Discovery at the Cosmic Frontier:

Canadian Astronomy Long Range Plan

2020-2030

Canadian Astronomical Society (CASCA)

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LRP2020 | PLT2020

COVER
Joined by bright Jupiter and fainter Saturn, the summer Milky Way shines above the Atlantic coast of Nova Scotia.

Canadian astronomy is poised to make great discoveries about the cosmos, and to deliver substantive benefits to Canada and to the world.

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Preface

On behalf of Matt Dobbs, Jeremy Heyl, Natasha Ivanova, David Lafrenière, Brenda Matthews and Alice Shapley, we are pleased to present the final report of the Canadian Astronomical Society's 2020 Long Range Plan for Canadian Astronomy (LRP2020). This report presents a roadmap for Canadian astronomy over the next decade and beyond, reflecting Canadian astronomers' aspirations and passion for understanding the Universe. The LRP2020 report is the work of not only the eight LRP panel members, but also the hundreds of researchers who contributed white papers, reports, ideas, detailed critiques, ideas and commentary, the dozens of staff members from funding agencies and other organizations who participated in consultations and provided feedback, and the many colleagues from around the world who responded to our requests for information. We are grateful to all of these individuals for their participation, to the agencies whose financial support enabled the LRP2020 process, and to the CASCA Board for entrusting us with the leadership of this exercise. We look forward to seeing the recommendations enacted and the discovery potential of Canadian astronomy fulfilled.

Pauline Barmby and Bryan Gaensler
Co-Chairs, 2020 Long Range Plan for Canadian Astronomy
December 2020

Chapter 1

Executive Summary

Canada has played a leading role in exploring the Universe for more than a century, with many spectacular discoveries over the last decade. Canadian astronomers now have exciting plans to further expand our horizons and our cosmic understanding, centred around four core questions:

1. **How did the Universe begin and what is it made of?**
2. **How have stars and galaxies changed over cosmic time?**
3. **What are the extreme conditions of the Universe?**
4. **Why are planetary systems so diverse and could other planets host life?**

In order to answer these questions and then to share these discoveries with the public, Canadian astronomers will need access to a wide range of powerful telescopes and supercomputers, paired with new ways of interacting with data, with each other, and with the broader community. In this **2020 Long Range Plan for Canadian Astronomy**, we set out priorities and recommendations that will ensure that Canadian astronomy sits at the forefront of knowledge and discovery over the next ten years, that the associated community of scientists, staff and students will succeed and flourish, and that this work benefits the Canadian economy and Canadian society.

Large telescopes in remote locations are the core component of modern astronomy. We recommend that the Canadian astronomical community develop and adopt a comprehensive set of guiding principles for the locations of astronomy facilities and associated infrastructure, to be applied to *all* future Canadian participation in astronomy projects. These principles should be centred on consent from relevant Indigenous Peoples and traditional title holders, and should reject the use or threat of force for developing or accessing an astronomical site.

Over the next decade, Canada's highest priorities for large investments (>$30M) in ground-based telescopes are a very large optical telescope (VLOT) and participation in Phase 1 of the Square Kilometre Array (SKA1). These were also the highest ground-based priorities in the 2010 Long Range Plan, and are anticipated to move forward in the next two to three years. Two future projects, the Maunakea Spectroscopic Explorer (MSE) and the Next Generation Very Large Array (ngVLA), represent compelling future opportunities for Canada and should be further developed. Mid-scale investments ($5M–$30M) in ground-based facilities are also of key importance. Significant scientific returns lie ahead for several of Canada's existing telescopes: Canada should continue to support the Atacama Large Millimeter/submillimeter Array (ALMA), the Gemini Observatory, and the Canada-France-Hawaii Telescope (CFHT). Canada should also make new mid-scale investments in future facilities, specifically in the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD), the Cosmic Microwave Background Stage 4 experiment (CMB-S4), and the Legacy Survey of Space and Time (LSST).

Space astronomy missions provide unique information not available from telescopes on the ground. Participation in multiple new space astronomy missions is needed to maintain Canada's expertise and skill base, and to address the broad scientific needs of the Canadian astronomy community. The highest priority for very large (>$100M) investments in space astronomy is the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR), an outstanding prospect for Canada's first marquee space astronomy mission. Participation in NASA's next flagship astronomy mission is also a high priority in this category. The community's highest priority for large ($25M–$100M) investments in space astronomy is participation in the Japanese-led Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD), followed by pursuing opportunities for substantive participation in a large, cooled, infrared international space telescope. The highest priorities for additional (<$25M) investments in space astronomy are support for the James Webb Space Telescope (JWST) mission and for associated Canadian science for the entirety of JWST's lifetime, development of the Photometric Observations of Extrasolar Planets (POEP) mission, and scientific and technical participation in preparatory activities for NASA flagship missions.

As part of Canadian society, Canadian astronomy and Canadian astronomers have responsibilities to each other and to the broader community. All Canadian astronomers need to make a personal commitment to equity and inclusion, focused on making significant structural changes to their workspaces and communities.

The National Research Council of Canada's Herzberg Astronomy and Astrophysics Research Centre (NRC's HAA) has the mandate to operate and administer any astronomical observatories established or maintained by the Government of Canada. HAA plays a key role in Canada's partnerships in international observatories and in astronomy technology development. Returns from Canadian investments in astronomy infrastructure can be further enhanced if HAA and the university community obtain an additional ~$1M/year for Canadian astronomy, in order to appoint early-career science, technology, engineering and mathematics (STEM) personnel who can provide direct scientific and operational support for Canada's investments in mid-scale astronomical facilities and infrastructure. To allow Canada to maintain clear international leadership in astronomy, NRC and Canadian universities should also establish partnership programs to support the development, design and construction of university-led mid-scale initiatives, and to enhance the high-risk, high-reward innovation capabilities of university-based astrophysics laboratories.

Theoretical astrophysics is an essential part of modern astronomy. Canada has built a critical mass of world-leading theorists who study phenomena across the Universe, unified by the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto and its accompanying national program. As CITA now moves into its fifth decade, CITA's footprint should grow and decentralize, so that it can play a greater role in enhancing the national theoretical astrophysics profile on the world scene, and can contribute to a productive environment for astrophysics theory trainees across Canada. The upcoming renewal of CITA's federal research grant presents the opportunity to expand the CITA membership beyond the areas of traditional expertise, to strengthen the CITA fellowship program by increasing the support provided for theoretical research taking place outside the University of Toronto, and to improve regional diversity in the fellowship program to match the distribution of theory-focused astrophysics researchers across Canada. We also recommend that additional support for astrophysics theory across Canada come from a variety of other sources, including as part of the operational scientific support provided by the Canadian Space Agency and National Research Council of Canada, for Canada's space-based and ground-based astronomical facilities, respectively.

Answering the fundamental questions in astronomy and cosmology requires not just traditional observations or calculations, but also enormous data sets and large-scale computational simulations. The digital research infrastructure currently available in Canada *cannot meet the needs of Canadian astronomy in the next decade*, nor is it internationally competitive across computational disciplines more broadly. Without a commitment to sustained investment in computational infrastructure over the next decade and beyond, Canada's scientists will fall ever further behind their competitors. We recommend that Canada maintain its commitment to digital research infrastructure outlined in Budget 2018, through an initial investment of $375M plus an ongoing expenditure of $50M per year over the next decade. This major investment in Canada's New Digital Research Infrastructure Organization (NDRIO) is needed to revitalize and then sustain Canada's research capabilities across all disciplines.

High-performance computing for simulations, general-purpose computing for data-intensive observations, and support for individual compute-intensive facilities are all necessary to maintain Canadian leadership in astronomy.

As part of Canadian society, Canadian astronomy and Canadian astronomers have responsibilities to each other and to the broader community. All Canadian astronomers need to make a personal commitment to equity and inclusion, focused on making significant structural changes to their workspaces and communities. We recommend that the Canadian Astronomical Society (CASCA) make equity, diversity and inclusion in Canadian astronomy an explicit part of its ethics and values, that CASCA adopt an explicit long-term goal to have its membership better reflect the demographics of Canada, and that CASCA adopt foundational documents that can provide an appropriate and enforceable framework for these principles. Training on equity, inclusion and anti-racism should be required for all those serving in leadership positions in Canadian astronomy, and should also be offered at CASCA's annual meetings. We recommend that CASCA support and advance the needs of Indigenous astronomers and students, and should establish a new committee dedicated to facilitating engagement and relationships with Indigenous communities. CASCA should adopt and pursue five National Education and Public Outreach Pillars, which need to be overseen by a paid education and outreach coordinator. All members of the CASCA community should minimize air travel in their professional activities; the astronomy community should also thoroughly consider the climate impacts of both construction and operations when planning infrastructure.

Students and early-career researchers form a key part of the ecosphere of Canadian astronomy. It is vital that these trainees have productive and positive experiences as astronomers, and that they also gain the skills needed to be successful in their future careers in or beyond astronomy. Improvements to professional training and career development can lead to a more productive astronomy community and to better long-term outcomes for Canadian society. Astronomers and their institutions should develop opportunities for students and postdoctoral researchers to acquire a broad set of skills relevant to careers both in and beyond astronomy, should develop a coordinated, expanded and enhanced approach to student training, and should supplement training programs through industrial partnerships. We recommend that CASCA establish a committee to represent and advocate for astronomy postdoctoral researchers in Canada, that postdoctoral researchers in Canadian astronomy be paid at internationally competitive levels, and that CASCA develop and maintain a set of best-practice guidelines for postdoctoral recruitment and flexible employment. CASCA should also endorse a national mentoring strategy for early-career astronomers, and should incorporate the trajectories, current positions and contact details of former trainees into its membership database.

Astronomical research in Canada is fortunate to be supported by numerous federal and provincial agencies and private organizations. We recommend that the Association of Canadian Universities for Research in Astronomy (ACURA) take the lead in advocating for essential federal funding to these agencies, and that ACURA should work closely with CASCA's Long Range Plan Implementation Committee (LRPIC) to advance the suite of priorities identified in this report. We further specifically recommend that:

- The Canadian government provide the Canadian Space Agency (CSA) with A-base funding at the level of at least \$15M per year to support space astronomy missions and associated activities;
- The Canada Foundation for Innovation (CFI) identify ways to support full utilization of scientific infrastructure, with flexibility in the ratio of construction to operations costs for a project;
- The Natural Sciences and Engineering Research Council of Canada (NSERC) fund postdoctoral positions that can attract and retain the world's best early-career astronomers.
- These and other agencies should also increase coordination in how they fund astronomy, in order to enable better science, to reduce duplication of effort, and to avoid situations where responsibilities fall between agency mandates.

The 89 recommendations in this report aim to deliver powerful new observational facilities on the ground and in space; high-capacity computational facilities for both theoretical calculations and data processing; the human capital and technological capacity needed to exploit all these capabilities; and inclusive and respectful relationships within and beyond astronomy. With these foundations in place, Canada can lead the world in astronomical discovery over the next decade, strengthening Canada's economy and society while also providing fundamental advances in our understanding of the Universe.

Chapter 2

Scope and Purpose of This Report

Astronomers are engaged in a grand adventure: a quest to understand the Universe and our place in it. The sky and its wonders have captivated people across history and cultures, and humanity is now on the verge of answering questions that we have pondered for millenia: How did the Universe begin, and how has it changed over time? What is the cosmos made of, and what are its extremes? Do other planets, besides our own, host life? Canadian astronomers not only aim to answer these questions, but at the same time to produce the advanced data analysis techniques and technically skilled people that allow Canada to lead the world in discovery and innovation.

Over many decades, Canadian astronomers have performed complex calculations, collected the faint signals that reach us from the heavens, and have developed new technologies and computer simulations that have pushed our understanding ever deeper. Under one sky, we exchange knowledge with researchers from around the globe, and share our passion for understanding the Universe with Canadians from all walks of life. Canadian astronomers are fortunate to be part of a nation that values scientific research and discovery. In return, we aim to push the boundaries of technology, capture imaginations, enrich our culture, and make Canada and the world a better place through discovery and inspiration.

Modern research in astronomy is not an individual endeavour. The shared computational and observational facilities needed to address burning scientific questions are large and complex, requiring international teams of skilled personnel, along with physical installations that can span multiple continents. Improving astronomy's connections with broader Canadian society—in knowledge translation, education and training, and reconciliation with Indigenous peoples—likewise requires a team approach.

In Canada, as in other countries, the research community works together to determine goals for the field and to decide which new and upcoming opportunities to pursue.

This report, the **2020 Long Range Plan for Canadian Astronomy (LRP2020)**, is the result of the third long-range planning exercise undertaken by the Canadian Astronomical Society (CASCA), the professional organization of Canadian astronomers, following the LRP2000 and LRP2010 reports of preceding decades. The goals of this process are to communicate the strengths of Canadian astronomy and its benefits to Canada, to identify the critical present and future science questions, and to develop a community-supported and realistic vision for the infrastructure needed to advance the field. Our aim is to recommend a set of facilities and programs that reflects Canada's strengths and breadth, with a range of project sizes, time scales, science areas and degrees of Canadian participation, offering strong prospects for training of Canadian highly-qualified personnel, and providing specific tangible benefits to Canadians. Where appropriate and feasible, our recommendations are aligned with the priorities of government and funding agencies and with the recommendations of the two previous Long Range Plans.

This cohesive and community-developed vision for Canadian astronomy makes the case for the resources required to carry out our community's exciting science vision. The primary audience for LRP2020 is the leadership and staff of organizations whose funding and support enables Canadian astronomy research. These include Innovation, Science and Economic Development Canada and several of its agencies (the Canadian Space Agency, National Research Council Canada, and Natural Science and Engineering Research Council), independent agencies such as the Canada Foundation for Innovation and CIFAR, provincial research ministries and organizations, and the universities at which most Canadian professional astronomers perform research and train students. The exciting future for Canadian astronomy that this report sets out will require support from and coordination between all these entities.

Additional audiences for the LRP2020 report include the Canadian public and the Canadian astronomical community. By holding a mirror up to the field, we aim to highlight its successes and the excitement of its future plans. Sharing this knowledge with Canadians, whose public support and tax dollars enable this work, is an important obligation. We also aim to describe opportunities to make Canadian astronomy more equitable, diverse, inclusive, fair and transparent, and to fulfill the field's social responsibility to the broader society. These goals require professional action on both the collective and individual levels: although less tangible than a new telescope or computer cluster, they are equally important to the future of the field.

The LRP2020 process has benefited from financial and logistical support from many of the agencies listed above, and we are grateful for these contributions. However, it is important to note that LRP2020 is a community-driven effort led by CASCA. As such, our recommendations are not binding on the agencies, the Society or its members. External circumstances change, and the future directions of astronomy may change as well. It will undoubtedly be necessary to show flexibility in implementing the recommendations contained herein, while continuing to push the field forward.

This report can hardly fail to acknowledge the COVID-19 pandemic—a circumstance external to astronomy that has nevertheless changed everyone's lives. The international nature of astronomy research means that many astronomers were already accustomed to collaborating remotely, but like everyone else, our work was disrupted by the need to care for family and community. Astronomical research was and is rightfully a lower priority than protecting the health and safety of communities; temporary closure of observatories and slowdowns of research are to be expected and will likely have effects for years to come. Non-medical curiosity-driven research is not among the current top priorities of any government or funding agency, for completely understandable reasons. So why release the LRP2020 report now?

The pandemic and our response to it are the defining events of a generation. Although it is clear that the world is never going to be the same, exactly what life will look like in five years is hard to imagine. Around the world, citizens will look to universities and research as enduring institutions to lead our communities through this crisis. Astronomy research, with a focus on the cosmos and its mysteries, is a long-term effort that can serve to lift our eyes from the grind of near-term challenges and remind us that there is a future beyond lockdowns, masks, and vaccines. Investing in the future of astronomy research means investing in the capability to answer ancient questions and uncover new ones. It means discovering new wonders and inspiring the next generation. It means placing our planet, our environment, and our species in their cosmic context. Investing in the future of astronomy research is an investment in the future of Canada and Canadians.

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Chapter 3

A society with a strong science culture will support the use of scientific knowledge and methodology, will encourage the education and training of a highly skilled workforce, and will foster the development of an innovative knowledge-based economy.

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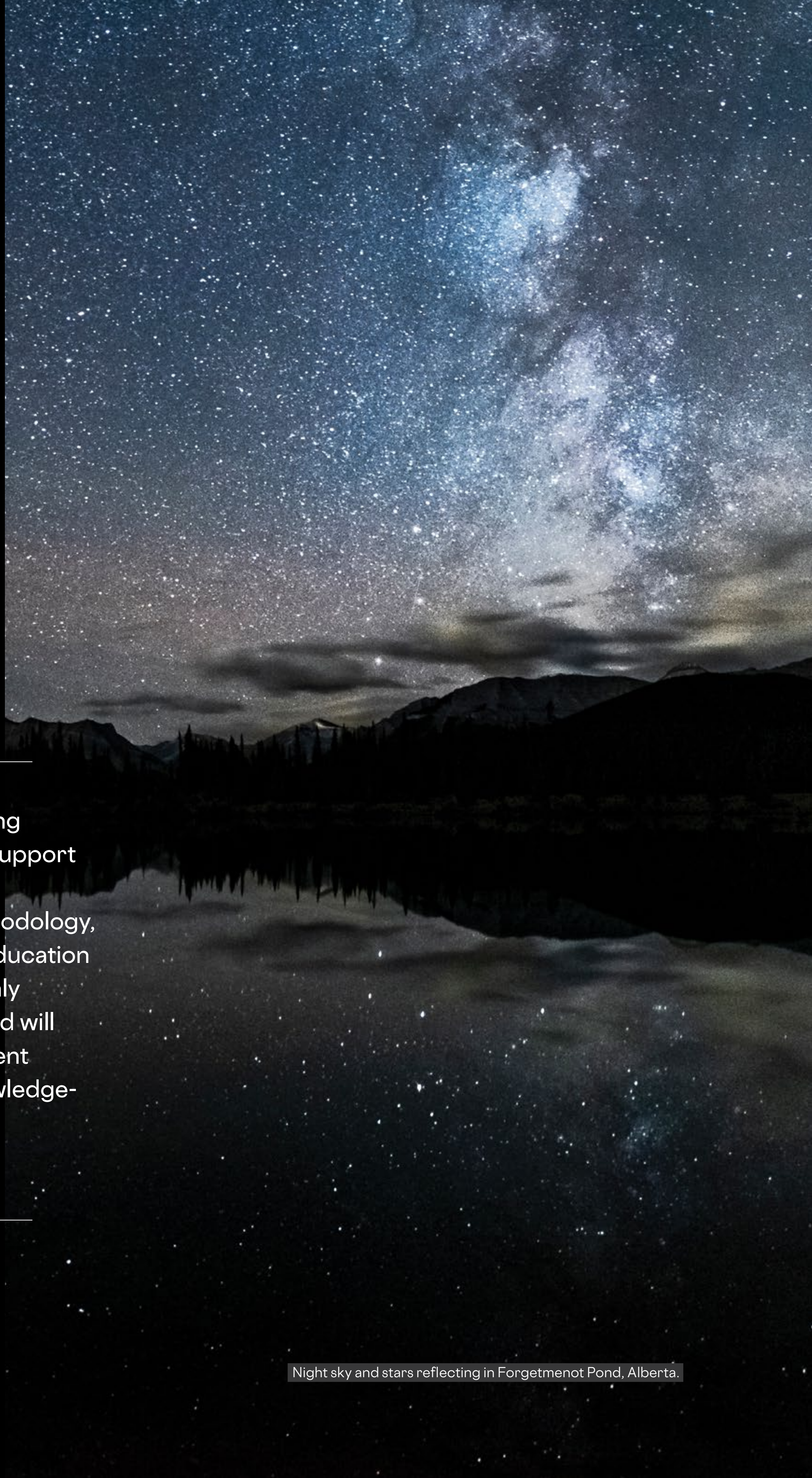

Night sky and stars reflecting in Forgetmenot Pond, Alberta.

The State of Astronomy in Canada in 2020

Over the last ten years, Canadian astronomers have made major discoveries, built world-leading facilities to enable the next epoch of discoveries, and trained a new generation of highly-qualified personnel (HQP) who are now contributing to discovery and innovation in Canada and around the world. The excitement of the science—from distant galaxies to black holes and planets around other stars—inspires Canadians and brings new talent to the field and to Canada. In this Chapter, we highlight some of the exciting astronomical discoveries of the past decade, and describe the people, organizations and technology that enabled this work. We begin by describing the newest facilities and some of the discoveries they made possible, then provide some snapshots of the people who make such astronomical discoveries and who drive technological innovation. We describe the many supporting organizations, partnerships and advanced technology without which Canadian astronomy would not be possible. This Chapter closes by outlining the benefits of astronomy to Canadian society, including astronomers' efforts to engage with the broader community.

Astronomy and astrophysics have long been highly international fields: the International Astronomical Union (IAU) is one of the oldest international scientific societies. Although every nation on Earth has a view of the sky, achieving the most complete view requires combining observations made from multiple latitudes and longitudes and hence international cooperation. Local, regional, and national observatories are found in many countries. Most of the world's largest observatories are operated as international partnerships: as technology and capabilities continue to advance, costs increase and these one-of-a-kind facilities have become too expensive for any one nation to construct and operate alone. Some observational facilities are available for use only by researchers affiliated with their sponsoring entities (from universities to nations); others maintain an "open skies" policy in which any qualified researcher can request their use.[1] It is extremely common for research in astronomy and astrophysics to be carried out by a team comprising people from multiple countries; international teams are common even in theoretical astrophysics research, which can be less reliant on shared facilities.

Astronomical research is carried out in most developed and many developing countries. The number of IAU members provides a very rough indicator of the number of astronomy researchers: the United States hosts the largest membership, with approximately 3100 of the IAU's 14,000 individual members. France, Germany, Italy, Japan, the UK and China each have 700–900 members; Russia and Spain 400–500 each, and Canada, Australia, India, and the Netherlands each have 300–400. Excepting Russia, the European countries listed comprise six of the sixteen members of the European Southern Observatory (ESO), an intergovernmental treaty organization that operates several observatories in northern Chile. Chile's topography and climate make it highly suitable for siting telescopes, and it also hosts a number of other international observatories. Other international locations hosting multiple major observatories include Hawaiʻi and Arizona (USA), the Karoo region (South Africa), Murchison Shire (Australia), and the South Pole. Astronomy from space is supported by the world's space agencies, often working together in partnership. The major agencies participating in space astronomy are NASA, ESA, and JAXA (USA, Europe, Japan, respectively), with smaller contributions from the Canadian Space Agency and ISRO (Canada, India), and national agencies from Europe (e.g., CNES in France, ASI in Italy, and Roscosmos in Russia).

Highlights and Achievements of the Last Decade

Infrastructure

Two major ground-based facilities with Canadian involvement began operation over the past decade: the Atacama Large Millimeter/sub-millimeter Array (ALMA) and the Canadian Hydrogen Intensity Mapping Experiment (CHIME). The first was a key priority in LRP2000, and the second in LRP2010.

ALMA is a multi-national, multi-user observatory, consisting of 66 radio dishes located on a plateau 5,000 metres above sea level in northern Chile. With operating wavelengths from 3 millimetres to 350 micrometres and angular resolution from a few arcseconds to tens of milli-arcseconds, ALMA is one of the world's most powerful telescopes. Canada is a partner in ALMA, and in collaboration with the United States and Taiwan forms the North American region of ALMA. Canada contributed to ALMA construction by building the Band 3 receivers for all 66 dishes and by contributing to the development of software, primarily in the areas of off-line data reduction and the archive. The total Canadian contribution to ALMA construction was US$20M (in 2000-dollars). Canada also contributes annually to ALMA operations, both in cash and in-kind; the Millimetre Astronomy Group at the National Research Council Canada's Herzberg Astronomy and Astrophysics Research Centre (NRC-HAA) collaborates with the US National Radio Astronomy Observatory in supporting ALMA operations through the North American ALMA Science Center.

CHIME is a Canadian-led experiment that represents a new paradigm of radio telescope, relying heavily on computational power rather than expensive mechanical structures and cryogenic receivers. It was the highest priority medium-scale ground-based astronomy project recommended in LRP2010. CHIME achieved first light in 2017. It is the first major research telescope to be built on Canadian soil in more than 30 years and is now the largest radio telescope in continental North America. CHIME's main scientific goal is to map the 21-centimetre emission of neutral hydrogen from redshifts 0.8 to 2.5. The resultant three-dimensional map of hydrogen structure in the Universe will be the largest map of the cosmos ever made, encompassing the critical period when Dark Energy began to dominate the expansion of the Universe.

1 The process of allocating use of astronomical observatories is generally based on scientific merit and not on the ability of an individual researcher or group to pay a fee; operating costs are borne by the facility's sponsors.

Over the past decade, Canadian investments in astronomy from space have paid off with Canadian participation in eight space missions, exploring the Universe from the Solar System out to the most distant galaxies and the beginning of the Universe itself.

CHIME also received funding from the Canada Foundation for Innovation (CFI) and partners in 2015 to enable searches for transient radio signals from pulsars and fast radio bursts, making it a multi-purpose experiment well suited for a variety of ancillary science objectives.

Canada has been deeply involved in new instrumentation deployed on the Gemini Observatory telescopes, both over the last decade and in development for the 2020s. The Gemini Planet Imager (GPI) and Gemini Remote Access to CFHT/Espadons (GRACES) both began operating in 2015, providing high-contrast imaging and high-resolution spectroscopy on Gemini South and North, respectively. The Gemini High resolution Optical SpecTrograph (GHOST) is scheduled to begin operations in 2021, and the Gemini Infrared Multi-Object Spectrograph (GIRMOS) is under development as a visitor instrument for Gemini and a precursor for thirty-metre telescope instruments. These instruments were developed by consortia that include multiple Canadian universities and NRC-HAA in Victoria, with funding provided by Gemini, the National Research Council Canada (NRC), CFI and provincial research agencies.

Canadians have also led important upgrades to the instrumentation suite of the Canada-France-Hawaii Telescope (CFHT). The GRACES instrument mentioned above is the result of a unique collaboration between Gemini and CFHT, transporting light from the Gemini-North telescope to the CFHT building where it is analyzed with the ESPaDOnS instrument. Operating since 2016, the SITELLE instrument was built by a consortium led by Laval University and including Québec City firm ABB. It provides imaging spectroscopy over a wide field of view ideal for the study of nearby galaxies and star-forming regions. A number of Canadian universities are involved in CFHT's SPIRou instrument, a high-resolution near-infrared spectropolarimeter, optimized for the study of exoplanets. SPIRou began operations in 2019.

Canadian astronomers continue to harness the power of the SCUBA-2 instrument, installed at the James Clerk Maxwell Telescope (JCMT) on Maunakea in 2013. Although as of 2015, Canada is no longer a national partner in JCMT, this facility remains the largest single dish submillimetre telescope in the world. Canada played a key role in the development of SCUBA-2 and its two ancillary instruments. In particular, the Canadian-led POL-2 polarimeter has emerged as a unique and highly oversubscribed facility instrument, enabling the highest resolution surveys of the morphology of magnetic fields across entire star-forming regions. SCUBA-2 surveys of the deep extragalactic sky and nearby galaxies have enabled a wide range of transformative science, leading to large ALMA allocations for follow up and spectacular, often paradigm-shifting results.

One method to track the productivity of observatories is the number and impact of scientific publications resulting from their use. An analysis for LRP2020 of the science output of ground-based observatories worldwide, including but not limited to those in which Canada is a partner, finds that the observing facilities that Canada supports financially are amongst the high-performing, both in productivity and impact, of facilities world-wide, and that scientific publications from Canadians have consistently higher impact than average.

Over the past decade, Canadian investments in astronomy from space have paid off with Canadian participation in eight space missions, exploring the Universe from the Solar System out to the most distant galaxies and the beginning of the Universe itself. These projects all began during the first long-range plan (LRP2000) or even earlier.

The Canadian NEOSSat mission and the Canadian-led BRITE constellation build upon the technology developed for Canada's first space telescope, MOST. Both NEOSSat and BRITE were launched in 2013 and continue to yield scientific data for the Canadian community. NEOSSat resulted from a novel partnership between the Canadian Space Agency and Defence Research and Development Canada. NEOSSat serves a dual role to monitor space debris near the Earth and to observe small bodies in the Solar System. Furthermore, NEOSSat has opened a guest observer program for Canadian astronomers which has focussed so far on photometric monitoring of nearby dwarfs, asteroids and comets. The BRITE constellation further exploited the Canadian expertise in small satellite busses to build the first constellation of nanosatellites for astronomy.

The ESA missions Planck and Herschel were launched together in 2009 and have since completed their missions. The Canadian Space Agency funded Canadian contributions to both missions in instrument components, calibration and data analysis. Planck operated as an experiment, making precise measurements of the cosmic microwave background. These yielded better constraints on the structure and evolution of the Universe as well as a more precise understanding of dust and magnetic fields within our Galaxy. The Canadian Planck team was led by Douglas Scott (University of British Columbia) and J. Richard Bond (University of Toronto) and included additional members from UBC and UofT as well as the University of Alberta, Université Laval and McGill University. The far-infrared and submillimetre telescope Herschel provided imaging and spectroscopic capabilities enabling the study of the cold Universe, including early galaxies, galaxy evolution and galactic star forming regions, and the earliest stars. Led by Michel Fich (University of Waterloo) and David Naylor (University of Lethbridge), the Canadian Herschel team involved members at the Universities of British Columbia, Calgary, Toronto, and Victoria, at Western and McMaster Universities, and at the National Research Council Canada.

Canada partnered with the Indian Space Research Organization (ISRO) to provide detectors for the Ultraviolet Imaging Telescope (UVIT) on the multiwavelength mission AstroSAT, and with Japan to provide the metrology system for the X-ray observatory Hitomi. These are Canada's first forays into instrumentation for high-energy astrophysics, and were launched in 2015 and 2016, respectively. The AstroSat contribution led to Canada receiving a 5% share of the telescope time; Canadian astronomers have made use of this share and principal investigators of successful proposals are currently supported by grants from the Canadian Space Agency (CSA). Unfortunately, Hitomi experienced a hardware failure a month after launch, ending the mission. However, Canada's contribution to Hitomi has guaranteed a Canadian role in Hitomi's successor XRISM.

LRP2000 identified a Canadian contribution to the James Webb Space Telescope (JWST) mission as Canada's top priority for space astronomy. At that time, the launch date for JWST was expected to be less than ten years away. Canada built the fine-guidance sensor (FGS) and the Near Infrared Imager and Slitless Spectrograph (NIRISS) instrument for JWST, and delivered these instruments in 2012 in anticipation of a 2018 launch. This has been the largest astronomy investment completed in Canada to date. NIRISS and FGS form an integral part of JWST, and the CSA is one of three key partners in the mission, along with NASA and ESA. Although the launch of JWST has been delayed to October 2021, Canada's contribution earned the Canadian astronomical community an outsized portion of JWST observing time, and an international team led by Canada's Els Peeters built a successful observing program chosen for Early Release Science with JWST; furthermore, several Canadian teams also have guaranteed time on this flagship mission.

Knowledge

The last decade has seen many astronomical discoveries in which Canadian astronomers made significant contributions to knowledge, instrumentation, observational techniques or data analysis. Below we highlight just a few of these, with emphasis on Canadian-supported facilities and instruments that have seen first light during the decade 2010 to 2020. Canadian astronomers have made crucial contributions and provided strategic leadership to all of these facilities.

A Dragonfly's Eye on the Sky

The Dragonfly Telephoto Array is an innovative telescope that uses an array of commercial telephoto lenses with special coatings that allow it to image the very faint diffuse light in the outskirts of galaxies. Its digital images are processed with the Canadian Advanced Network For Astronomical Research's advanced astronomical computing facility. Led by the University of Toronto's Roberto Abraham, Yale University's Pieter van Dokkum, and Charlie Conroy of Harvard University, Dragonfly is the world's largest all-refracting telescope. Sited in New Mexico, the project began taking images in 2013 and has discovered faint diffuse galaxies composed almost entirely of dark matter and some that appear to lack dark matter altogether.

Figure 3.1: Hubble Space Telescope image of Dragonfly telescope discovery NGC 1052-DF2, an ultra-diffuse galaxy lacking dark matter.

Credit: NASA, ESA, and P. van Dokkum (Yale University)

Discovery of A Fast Radio Burst from a magnetar in the Milky Way

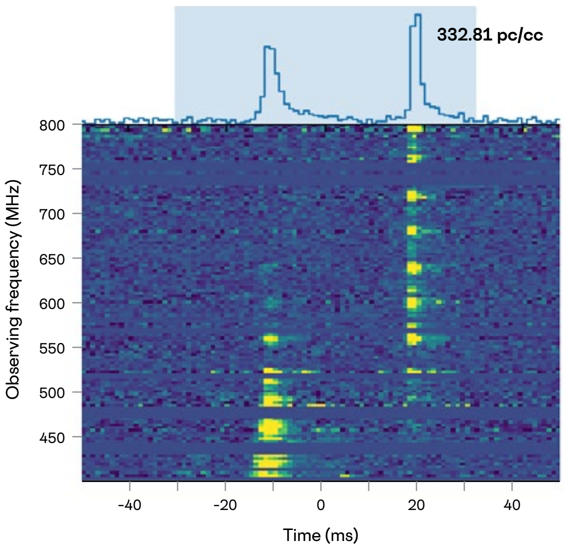

Figure 3.2: Twin bright radio flashes from a magnetar in the Milky Way. The signals closely resemble those previously seen from distant fast radio bursts.

Credit: CHIME Collaboration, 2020

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a set of half-pipe shaped radio telescopes in Penticton, British Columbia. The telescope has no moving parts, and watches the swath of sky directly above the telescope with more than four thousand individual antennas. Massive supercomputers on site combine the signals from each of these antennas to form an image of the entire northern sky, and to see how it changes over time. Although it will take many years to build the sensitivity required to create the largest map of structure in the Universe (one of the key missions of CHIME), CHIME's all-sky view means that it has already made many startling discoveries about FRBs, including discovering far more of these events than every other telescope combined.

On 28 April 2020, CHIME observed a closely-spaced pair of millisecond-timescale bursts that were briefly as bright as the Sun at radio wavelengths. The source of the bursts was determined to be a magnetar (an especially strongly magnetized neutron star) in our Milky Way Galaxy known as SGR 1935+2154. Scientists had long proposed magnetars in distant galaxies as one possible source of FRBs, and the discovery of FRB-like events from a known magnetar now appears to have confirmed this possibility.

Locating Fast Radio Bursts

First discovered in 2007, fast radio bursts (FRBs) are bright, broadband bursts of radio emission that last a few milliseconds. During these fleeting moments, an FRB can be more than 200,000 times more luminous than a typical star. Understanding where FRBs come from requires locating the source of radio emission in three-dimensional space—a difficult task when a burst is so brief. In 2017, a team led by McGill University's Shriharsh Tendulkar used the Gemini-North telescope to make the first ever image of an FRB's host galaxy, after observations made with the Karl G. Jansky Very Large Array radio telescope in New Mexico pinpointed the burst's location on the sky. The Gemini observations enabled the measurement of the host galaxy's distance from Earth. Surprisingly, the FRB host is a galaxy much smaller than the Milky Way but is forming stars at a rapid rate, suggesting that special conditions are needed to produce FRBs.

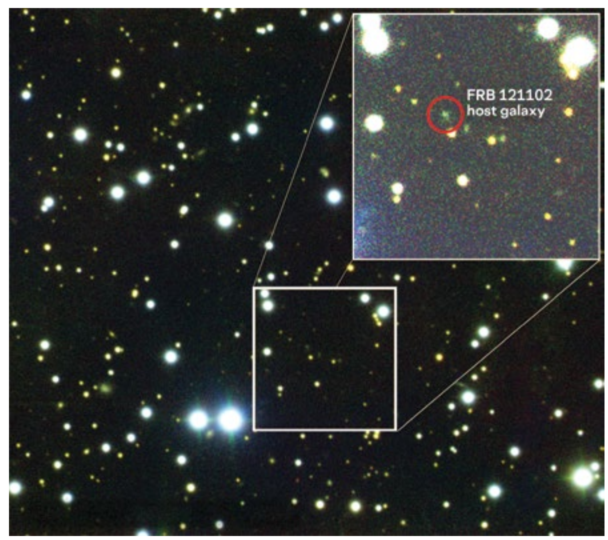

Figure 3.3: Gemini-North telescope image of the first known host galaxy of a fast radio burst.

Credit: Gemini Observatory/AURA/NSF/NRC

Imaging A Black Hole

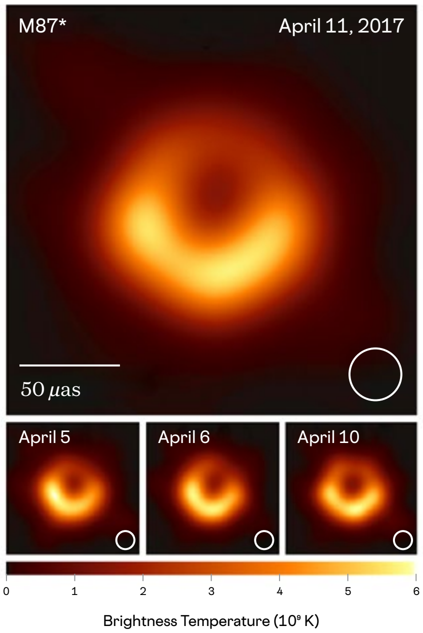

Figure 3.4: Event Horizon Telescope image of the black hole at the centre of the galaxy M87. Canadian astronomers led the analysis that enabled measurements of the black hole mass and spin from that image.
Credit: Event Horizon Telescope Collaboration

In 1967, scientists from NRC, Queen's University and the University of Toronto synchronized signals from the Dominion Radio Astrophysical Observatory in British Columbia and the Algonquin Radio Observatory in Ontario to create a virtual telescope with the resolving power of a telescope nearly as large as Canada. This technique, known as Very Long Baseline Interferometry, led directly to the first image of a black hole released in 2019. The image was made with the Event Horizon Telescope (EHT), an ensemble of eight radio telescopes spanning the globe whose signals can be combined to yield images with unprecedented angular resolution. Canadian researchers at the Perimeter Institute for Theoretical Physics and University of Waterloo led the complex theoretical calculations required to analyse the EHT images, and three of the eight EHT facilities (JCMT, ALMA, and SPT) have Canadian connections. The stunning scientific effort from the EHT team was recognized with the 2020 Breakthrough Prize in Physics.

Seeing New Solar Systems Form

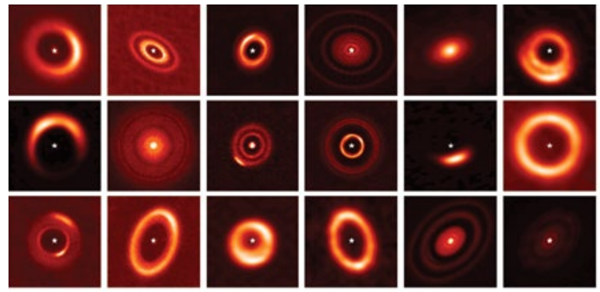

Figure 3.5: ALMA survey of proto-planetary disks to search for systematic variation in spacings of rings and gaps. All the disks are shown at the same angular scale.
Credit: Nienke van der Marel (NRC-HAA/University of Victoria)

Protoplanetary disks of gas and dust are found around young stars up to about ten million years old. ALMA is designed to detect the radiation from dust and gas in these disks with unprecedented sensitivity and resolution. Nienke van der Marel (NRC-HAA and University of Victoria) has used ALMA data to reveal a variety of complex disk structures that do not systematically vary with temperature profiles or snowlines; the presence of such substructures in these young disks may provide evidence that the onset of planet formation occurs at much earlier times in the evolution of a protoplanetary disk than previously thought.

Colossal Galaxy Clusters Take Shape

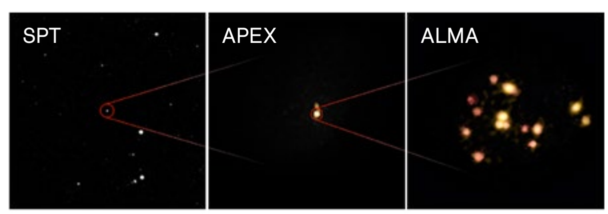

Figure 3.6: Dense concentrations of galaxies that are poised to merge, forming the cores of what will eventually become colossal galaxy clusters.
Credit: ESO/ALMA (ESO/NAOJ/NRAO)/Miller et al (2018)

A collaboration led by Tim Miller and Scott Chapman (Dalhousie University) discovered startlingly dense concentrations of galaxies that are poised to merge, forming the cores of what will eventually become colossal galaxy clusters. This discovery shows that the epoch of the formation of galaxies and especially large galaxy clusters occurred very early on in the Universe's history, not long after the Big Bang. A survey of one tenth of the Southern sky with the SPT found the intense submillimetre emission from these rapidly star-forming galaxies, using transition-edge sensor bolometers built at McGill University. Miller and his team then followed up with high-resolution images from ALMA, to reveal one of the most massive bound structures in the Universe. The formation of such massive structures so early in cosmic history is surprising, and presents a challenge to our understanding how galaxies and galaxy clusters form in the Universe.

Direct Imaging of Extrasolar Planets

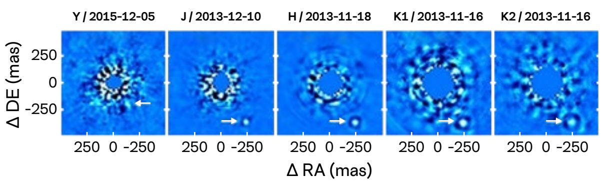

Figure 3.7: Exoplanet beta Pictoris b, imaged with the Gemini Planet Imager. The arrows in the four rightmost panels indicate the location of the planet.

Credit: J. Chilcote (University of Toronto) and collaborators

The Gemini Planet Imager (GPI) instrument on the Gemini South telescope is optimized for the study of planets around other stars, and features in many science highlights of the past several years. The GPI instrument is designed to suppress the light of stars to detect orbiting planets and disks. A team led by Jeffrey Chilcote (University of Toronto) used early GPI observations to target the nearby star beta Pictoris, and to detect the planet at multiple wavelengths in order to measure its colour. Colour measurements of beta Pictoris b suggest that its atmosphere is more like that of a brown dwarf than that of a gas giant planet, providing important data for constraining models of planetary formation and evolution.

New Dwarf Planet Beyond Neptune

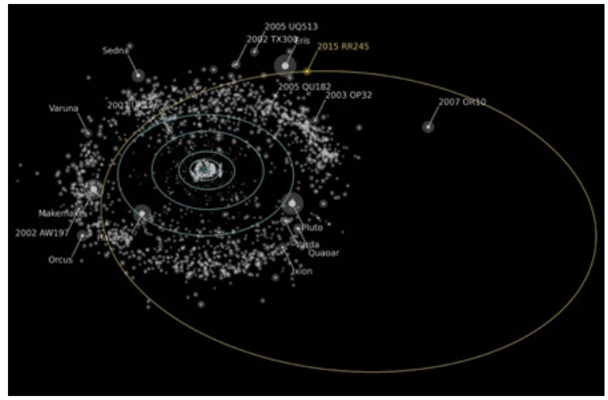

Figure 3.8: The distant orbit of RR245, a new dwarf planet discovered using the Canada-France-Hawaii Telescope as part of the Outer Solar System Origins Survey. The orbit of RR245 (orange line) takes it much farther from the Sun than most other small worlds in the outer solar system (white dots); it is currently at twice Neptune's distance.

Credit: A. Parker & OSSOS team

A new, distant dwarf planet beyond Neptune was discovered by the Outer Solar System Origins Survey (OSSOS) using the Canada-France-Hawaii Telescope on Maunakea, Hawai'i. RR245 is the only dwarf planet found by OSSOS, which has discovered more than five hundred new trans-Neptunian objects. Postdoctoral researcher Michele Bannister (University of Victoria) and the OSSOS team first sighted RR245 in February 2016 in images taken with CFHT's Megacam instrument in September 2015. After hundreds of years in the very outer solar system, RR245 is currently travelling towards its closest approach to the Sun (5 billion km, still farther than the orbit of Neptune) which it will reach in around 2096. Studying these icy worlds lets us piece together the history of our Solar System, but almost all of them are small and faint, spending most of their orbits beyond the detectability of current instrumentation: projects such as OSSOS must be carefully designed to extrapolate our understanding of the nature and distribution of the Solar System's most ancient objects from those few detectable at any given time due to their relative proximity to the Sun.

New Stars at a Galaxy's Heart

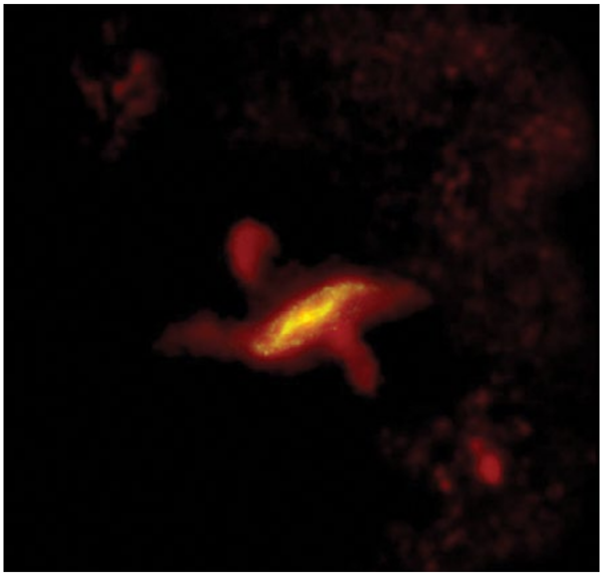

Figure 3.9: Far-infrared images of the galaxy NGC 5128 made with the Herschel Space Observatory, showing evidence for intense star birth towards the centre of the galaxy along with two jets emanating from the galaxy's core—one of them 15 000 light-years long.
Credit: ESA/Herschel/PACS/SPIRE/C.D. Wilson.

The nearby galaxy NGC 5128 is the closest elliptical galaxy to our own Milky Way and is well-known as a source of intense radio emission. Images made in visible light show a dark dust lane across the centre of the galaxy, indicating that the galaxy may be the result of past cosmic collisions between multiple galaxies. A team led by astronomer Christine Wilson (McMaster University) imaged NGC 5128 with the Herschel Space Observatory, providing evidence for intense star formation at the dark heart of this mysterious galaxy.

Through 2010–2018, approximately

340 MSc and 290 PhD

degrees in astronomy were granted in Canada

Echo of the Big Bang

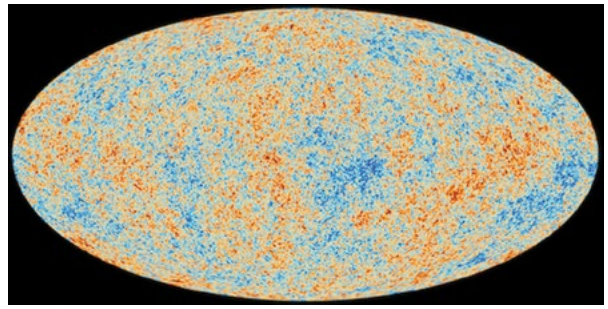

Figure 3.10: The remnant radiation from the Big Bang, also known as the Cosmic Microwave Background, as seen by ESA's Planck satellite.
Credit: ESA and the Planck Collaboration

ESA's Planck mission was launched in 2009 and released its final data set in 2018. Canadian scientists from five universities played important roles in constructing the most detailed all-sky map ever made of the cosmic microwave background radiation from the Planck observations. This map spectacularly confirmed the "standard model" of cosmology while generating a new mystery: the Universe's expansion rate as measured by Planck is incompatible with measurements of the rate by other means, for reasons that are not yet understood. ESA describes the situation as "the best of both worlds… the mission has given researchers confirmation of their models but with a few details to puzzle over."

Capacity

Canadian astronomy produces large numbers of highly-qualified personnel. Over the period 2010–2018, approximately 340 MSc and 290 PhD degrees in astronomy were granted in Canada. While the long-term career outcomes of these graduates are usually not yet known, at the present time roughly half of these graduates work at postsecondary institutions, one third in the private sector, and the remaining sixth in the (non-postsecondary) public sector. Beyond astronomy, example careers of PhD graduates include entrepreneurs (Olivier Daigle, highlighted in case study on page 25), data scientists, software developers, and remote sensing experts.

A database maintained by Dennis Crabtree (NRC-HAA) tracks university professors in Canadian astronomy, who comprise most of the permanent researchers in the field. The overall fraction of women in this sample of researchers is 21%. This value is consistent with statistics of applicants to NSERC Discovery Grants, for which physics (which includes astronomy), geosciences, and mathematics all have very similar fractions of women applicants at 22%; life sciences have a somewhat larger fraction (~31%) and chemistry and computer sciences have lower fractions (~18%). The gender distribution of astronomers has moved closer to parity over the past decade, as shown in Figure 3.11, and should continue to do so: for Canadian faculty hires who received PhDs after 2011, women outnumber men. Demographic information for Canadian astronomers along other axes of marginalization is largely unavailable; Chapter 7 makes recommendations to address this issue.

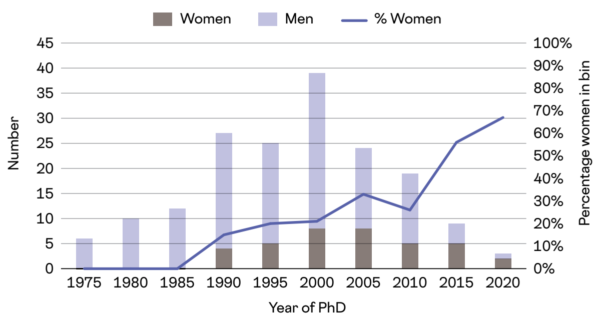

Figure 3.11: Experience and sex-disaggregated distribution of Canadian astronomy faculty

Data courtesy of Dennis Crabtree

Canadian astronomy has broad impact and world-renowned expertise, well beyond individual award-winners or science highlights. A 2018 report for the Government of Canada, prepared by an expert panel convened by the Council of Canadian Academies, reviewed the state of science and technology and industrial research and development in Canada. The report provides an assessment of the latest evidence of Canada's R&D and innovation performance, combining up-to-date data on research output, impact, and strength across all disciplines, with expert insights and analyses, and benchmarking against the performance of other countries. Physics and astronomy is one of only five research fields in which Canada ranks among the top five countries. The subfield of astronomy and astrophysics was ranked "much higher than the other subfields" in physics and astronomy—in fact, Canadian astronomy and astrophysics was listed as in the top 1% in the world, and was the only STEM field in Canada to be so highly ranked.

Individual Canadian astrophysicists have been frequently recognized over the last decade for their contributions to research through national and international prizes, including the Gruber Prize for cosmology (2012: the WMAP team, including Mark Halpern, Kendrick Smith and Gary Hinshaw; 2014: Sidney van den Bergh; 2018: the Planck Scientist Collaboration, including ten Canadians); the American Astronomical Society's Warner and Rubin Prizes (2019, Jo Bovy), the Breakthrough Initiative's New Horizons in Physics Prize (2020, Kendrick Smith), NSERC Herzberg Gold Medal (2016, Victoria Kaspi), and the Governor General's Innovation Award (2020, CHIME collaboration).

Theoretical Astrophysics

Theoretical astrophysics is an essential part of modern astrophysics and serves many purposes. On a practical level, theory is critical for making future predictions for what telescopes will see, designing the detailed experiments and observations to be performed, and then for interpreting these measurements, discriminating between competing models, and learning about the Universe. On a more abstract level, an important aspect of theoretical studies is the free, creative exploration of new ideas about physical concepts that eventually leads to new insights about how the world works. Theory is also crucial for responding to unexpected discoveries, by providing possible explanations for observed phenomena. Furthermore, because the timescales and physical conditions of many astrophysical processes cannot be replicated in Earth-based laboratories, theoretical calculations and computational simulations are often the only way to advance knowledge.

Canadian theoretical astrophysics has a long and successful history, highlighted by the establishment in 1984 of the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto and its accompanying national program in theory, through a peer-reviewed process overseen by the Natural Sciences and Engineering Research Council (NSERC). Supported in roughly equal measure by NSERC and the University of Toronto, CITA's primary missions are to foster interaction within the Canadian astrophysics community and to serve as an international centre of excellence for theoretical studies in astrophysics. CITA trains graduate students, postdoctoral prize fellows, and research associates, directs a program of national postdoctoral fellowships held at other Canadian universities, sponsors conferences and workshops, and hosts a vibrant and renowned visitor program. As one measure of its success, alumni of CITA's postdoctoral programs hold distinguished scientific positions across Canada and around the globe. The 70 national members of "CITA Inc." include faculty at universities spread across Canada. These full-time members are a significant fraction of astronomy faculty members. The theoretical astrophysics community also includes dozens of postdoctoral researchers, generally concentrated in centres such as CITA and the Perimeter Institute for Theoretical Physics, and hundreds of graduate students.

Theoretical astrophysics in Canada also has strong ties with many other fields, notably mathematics, engineering, earth and space science, and high energy and nuclear physics, but also more recently computing, statistics, data science and machine learning. Theoretical work provides astrophysics with an important connection to these other disciplines, fostering innovation and the development of centres of excellence through interdisciplinary work. One consequence of these cross-disciplinary links is the increasing importance to theoretical astrophysics of the Perimeter Institute. Cosmology has become a central part of Perimeter's focus, and in 2017 Perimeter launched its new Centre for the Universe, supporting named postdoctoral fellowships and chairs as well as distinguished visiting research chairs.

Current Facilities: Ground-based Telescopes

Canada's current ground-based facilities are summarized below. Further details are in several LRP2020 reports including those by the ground-based astronomy committee, long-range plan implementation committee, ACURA-CASCA advisory council on the SKA, CASCA-ACURA TMT advisory committee, and in white papers on individual facilities.[2] Many of the facilities in Table 3.1 are discussed in Chapters 5 and 6 of this report; here we briefly describe those not discussed elsewhere.

Most of the large optical/infrared/ultraviolet telescopes for which there is national Canadian access are located on Maunakea, Hawaiʻi. Continued access to these facilities is heavily dependent on the renewal of the Maunakea master lease under which astronomical use of the mountain is managed by the University of Hawaii, which ends in 2033. It is beyond the scope of this report to consider this issue in detail, but it will become a major and urgent focus for the anticipated Mid-Term Review of Canadian astronomy to take place in 2025 (MTR2025).

The Dominion Astrophysical Observatory (DAO) in Saanich, BC hosts 1.8-metre and 1.2 metre telescopes, which offer optical imaging and spectroscopy and also serve the local community for astronomy outreach events. The telescopes support approximately 12 programs per year among 20–35 researchers on topics including minor planets, binary stars, magnetic fields in faint stars, and supernovae.

The Dominion Radio Astrophysical Observatory (DRAO) in Penticton, BC hosts CHIME and also operates two telescopes onsite. The 26-metre Galt telescope, a single-dish radio antenna, is now nearing completion of a major upgrade that will enable new science in the areas of pulsars, the interstellar medium, and very long baseline interferometry. The DRAO Synthesis Telescope (ST) is the premier telescope in the world for imaging of large-scale neutral hydrogen and polarized radio continuum emission at arcminute resolution and continues to operate as a fully subscribed national facility. DRAO and university partners have developed a new vision for the DRAO ST as a forefront scientific instrument, an engineering testbed for new technologies, and a training ground for future Canadian and global radio engineers and astronomers.

The Murchison Widefield Array (MWA) is a low-frequency (80–300 MHz) radio interferometer in the Australian desert that uses 256 antenna tiles and no moving parts to achieve a field of view of more than 1,000 square degrees, sub-arcminute resolution, and exquisite surface brightness sensitivity. The MWA is a designated Square Kilometre Array precursor facility, and has been fully operational since 2013. The MWA has so far accumulated more than 35 petabytes of data on the Epoch of Reionization, Galactic and extragalactic sky surveys, time-domain science, and heliospheric/ionospheric studies, and has been recently upgraded to greatly increase its resolution and sensitivity. The University of Toronto joined the MWA consortium in 2016 and offers investigator slots for astronomers and students at other Canadian institutions; the current MWA principal scientist is based at UofT.

The South Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT) are two separate radio telescopes focused on observing the cosmic microwave background. Canadian astronomers participate in both, with involvement centred at UBC, the University of Toronto, CITA and McGill. Compute Canada support has enabled Toronto to be a site for much of the map-making and analysis of ACT and SPT data. Instrumentation laboratories at Toronto and McGill actively contribute to the development of hardware for SPT.

2 The LRP2020 community paper on "Indigenizing the next decade of astronomy in Canada" notes that "white paper" has negative historical connotations for Indigenous peoples in Canada; we were unaware of this when using the term as part of LRP2020. We retain it here to avoid confusion but suggest that it not be used in future.

Table 3.1: Ground-based telescopes with Canadian participation, ordered chronologically by operational date.

Facility	Description	Location	Managing Organization, Partners	Status
Dominion Astrophysical Observatory	1.8-m and 1.2-m optical telescopes	Saanich, BC	NRC-HAA	Operational since 1918, 1961
DRAO Synthesis Telescope and Galt telescope	7-element radio interferometer and 26-m single-dish radio antenna	Penticton, BC	NRC-HAA	Operational since 1960
CFHT	4-m optical/near-infrared telescope	Maunakea, Hawai'i, USA	CFHT Corporation (Canada, France, Univ. Hawaii)	Operational since 1979
JCMT	15-m submillimetre antenna	Maunakea, Hawai'i, USA	East Asian Observatory (Canada former member)	Operational since 1987
Gemini	2x8-m optical/near-infrared telescopes	Maunakea, Hawai'i and Cerro Pachón, Chile	Gemini Observatory (run by AURA for multi-national partnership)	Operational since 2000
Atacama Cosmology Telescope Polarization (Advanced ACTPol)	6-m single-dish radio antenna; cosmic microwave background experiment	Atacama, Chile	US-led consortium experiment	Operational since 2007; current upgrade since 2016
SPT	10-m single-dish radio antenna; cosmic microwave background experiment	Antarctica	US-led consortium experiment	Operational since 2010; current upgrade since 2017
ALMA	Millimetre-submillimetre interferometer (66 antennas)	Atacama, Chile	Joint ALMA Observatory (Europe, N. America, Asia)	Operational since 2011
Murchison Widefield Array (MWA)	Low-freq (metre-wavelength) radio interferometer; SKA precursor	Western Australia	International collaboration including Canada; operated by Curtin Univ.	Operational since 2013; upgraded in 2017
CHIME	Computational radio telescope; SKA precursor	Penticton, BC	Canadian-led consortium experiment	Operational since 2017

Current Facilities: Space Telescopes

Observations from space are an expensive but key component of astronomy for the well-known reasons of freedom from atmospheric weather, absorption and distortion. Canada's current and funded future space-based facilities, all funded and supported through the Canadian Space Agency, are summarized below. Completed missions not included here include Herschel, Planck, and MOST; see the LRP2020 report from the CASCA-CSA joint committee on space astronomy (JCSA) for information. Future missions in various study phases (CASTOR, Colibrì, ÉPPÉ, LiteBIRD, POEP, SPICA) are discussed in the JCSA report, in LRP2020 white papers on individual missions or science areas, and in Chapter 6.

The CSA also supports balloon astrophysics in Canada. An LRP2020 white paper describes the use of stratospheric balloon missions to advance the technology readiness level of key systems for future space missions and to provide opportunities for HQP training. Successes enabled by this program include Canadian contributions to the BLASTPol and EBEX experiments and the SuperBIT project (see case study on page 97). Table 3.2 summarizes current space and balloon astronomy projects.

The LRP2020 white paper on space astronomy summarizes Canadian space astronomy over the past decade, and notes that the CSA budget for space science has eroded over the past decade or more, to the point of major concern. During the period of LRP2010, CSA has funded one very minor new facility. The remaining LRP2010 priorities remain uncommitted, in spite of widespread interest and detailed studies. Of particular concern to the community are the unsuccessful attempts for substantial participation in the Roman Space Telescope (formerly known as WFIRST) and Euclid missions, either one of which would have fulfilled LRP2010's top space priority. No mechanism for participation in the Advanced Telescope for High-ENergy Astrophysics (Athena) or International X-ray Observatory (IXO)[3] X-ray astronomy missions was found. CASTOR and LiteBIRD were two other missions recommended in LRP2010 or its mid-term review (MTR2015) that both have imminent decision dates, but at present have no identified source of future CSA funding. Although Canada has the potential and the initiative to lead space astronomy missions, the CSA's limited budget for space science—in which astronomy must compete with other space science areas—does not currently allow for Canadian leadership. Recommendations on this topic are made in Chapter 7.

Instrumentation and Technology Development

Astronomy has been a technology-driven science for more than 400 years: new discoveries almost always require the advent of new instrumentation. Recent examples include transition edge sensors for millimetre and submillimetre radiation, which enabled the era of precision cosmic microwave background experiments such as the SPT and ACT; ultra low-noise room temperature amplifiers that made possible radio telescopes with large arrays of antennas such as the MWA and CHIME; and electron-multiplying charge-coupled devices (emCCD) that permit astronomical cameras to capture rapidly-changing phenomena and even count individual photons from faint celestial objects.

Canada's astronomical facilities are enabled by new technology developed in Canadian laboratories. Fueling these developments is a healthy and vibrant community of astronomical instrumentation scientists and engineers within Canada, who have been at the core of cementing Canada's international reputation for new discoveries. These teams include large, federally funded programs at NRC-HAA (Victoria, BC and Penticton, BC), along with many university-based laboratories.

NRC laboratories typically invest in long-timescale, large-scale instrumentation, and they have been essential in driving Canada's contributions to world observatories and national facilities. Critical contributions for ALMA, including the Band 3 receivers, were developed and provided by HAA-Victoria. DRAO-Penticton is renowned for its contributions to technology, including low-noise amplifiers for radio astronomy and the state-of-the-art WIDAR correlator for the Karl G. Jansky Very Large Array. Presently, NRC-HAA labs are working on technologies necessary for the success of future international observatories, including adaptive optics for very large optical telescopes (NRC leads the development of the sophisticated adaptive optics system NFIRAOS for the Thirty Meter Telescope), aperture array digital signal processing (NRC led the design of the Central Signal Processor element for the Square Kilometer Array), and composite reflector antennas (a possible contribution to the Next-Generation Very Large Array).

3 IXO was not selected by NASA to move beyond the study phase; however the most important elements of IXO were incorporated into ESA's Athena mission.

CASE STUDY

New Astronomy Techniques Lead to Nüvü

Astronomy collaboration creates an innovative start-up

↑ **The Nüvü Camēras team includes scientists and engineers from diverse fields beyond astronomy.**
Image credit: Nüvü Camēras

Astronomy is not the only field that requires super-sensitive cameras: medical imaging and national defence surveillance are examples of other fields that greatly benefit from advances in camera technology.

Nüvü Camēras is a Montréal-based startup derived from new techniques for astronomical imaging, using technology developed by astronomer **Olivier Daigle** and his collaborators. Daigle partnered with Marie-Eve Ducharme, who was embarking on her second successful start-up endeavour, to create Nüvü Camēras in 2010.

The increased sensitivity of the Nüvü electronics allows for very rapid exposures or for images to be taken in extremely low lighting conditions. Nüvü's roots are modest—the first prototype of Nüvü Camēras technology was developed by Daigle during his PhD at the **Université de Montréal**. The fledgling start-up spent its first half decade immersed in the academic environment at the Université de Montréal and École Polytechnique. Today Nüvü is located in downtown Montréal at the INGO Innovation Centre, providing instruments for high tech applications around the world. ◆

↑ **Dr. Olivier Daigle, CTO of Nüvü Camēras.**
Image credit: Nüvü Camēras

Table 3.2: Space and balloon-borne astronomy missions with Canadian participation, ordered chronologically by operational date.

Mission	Description	Managing Org, Partners	Status
NEOSSat	Photometric obs of solar system and exoplanets	CSA/DRDC	Launched 2013, operational
BRITE	Nanosat constellation monitoring brightest stars	CSA, w/universities in Austria, Poland	Launched 2013, operational with funding challenges
ASTROSAT-UVIT	General-purpose 2 x 38-cm telescopes (visible/NUV, FUV)	ISRO, w/CSA	Launched 2015, operational
JWST	6.5-m general-purpose optical/infrared observatory	NASA, w/ESA, CSA	Launch scheduled for 2021
XRISM	X-ray imaging and spectroscopy, Hitomi replacement	JAXA, w/ NASA, ESA, CSA	Launch scheduled for 2022
EBEX	Balloon-borne radio polarization mapping experiment	NASA	Flew in 2009 from New Mexico, 2013 from Antarctica
BLASTPol	Balloon-borne far-infrared/sub-mm polarimeter	NASA	Flew in 2010, 2012 from Antarctica
BLAST-TNG			Flew in 2020 from Antarctica
SPIDER	Balloon-borne mm-wavelength polarimeter	NASA, CSA	Flew in 2015 from Antarctica
SuperBIT	Balloon-borne wide-field optical/infrared/UV telescope	NASA, CSA	Test flights from Canada (2015), US (2016, 2018); awaiting 2021 long-duration flight
HiCIBaS	Balloon-borne high-contrast optical telescope	CSA	Flew in 2018 from Timmins, ON
HELIX	Balloon-borne particle spectrometer	NASA	Awaiting flight in late 2021/2022

There are several world-class university-based astronomical instrumentation laboratories in Canada. University laboratories often specialize in high risk, fast timescale instrumentation that seeds further development in a particular niche in the international scene—see Table 3.3 on page 27 for example areas. The McGill University, University of British Columbia, and University of Toronto laboratories conceived, developed, and built CHIME. The University of Lethbridge is a world leader in building Fourier transform spectrometers, bringing this instrumentation to both ground- and space-based platforms. The University of Calgary develops world-class low-noise amplifiers. The Université de Montréal has developed novel coronagraph instruments. The University of British Columbia and McGill University labs develop and build multiplexing detector readout electronics for essentially all of the world's millimetre and submillimetre radio telescopes that use transition edge sensor detectors. The University of Toronto develops world-class stratospheric balloon payloads. In addition to their technology output, these instrumentation groups produce a tremendous number of highly skilled technologists who go on to academic, military, medical, and industrial careers in Canada and abroad.

As noted by LRP2010 and MTR2015, university-based instrumentation laboratories face significant challenges, notably difficulties in maintaining adequate and broad technical support through the "boom and bust" cycle of project-linked funding. Recommendations on this topic are made in Chapter 7.

Table 3.3: Example areas where Canadian astronomical instrumentation laboratories exhibit world leadership.

Laboratory(ies)	Key Technology	Facilities (Present or Future)
McGill University and UBC	Multiplexed Transition Edge Sensor detector readout electronics	SPT, ACT, SCUBA-2, Simons Array, BICEP/Keck, LiteBIRD
NRC-HAA Penticton	Composite radio telescope dishes	CHORD, ngVLA, HIRAX
NRC-HAA Penticton, McGill, University of Toronto	Large-N radio interferometers and large radio correlators	VLA, ALMA, CHIME, CHORD, HIRAX, SKA1
NRC-HAA Victoria, University of Toronto	Millimetre receivers, optical/infrared spectrographs, adaptive optics	ALMA, Gemini, TMT
Université Laval	Optical design, advanced optics	CFHT/SITELLE, Gemini/GIRMOS, CFHT/SPIRou, ESO/NIRPS
University of Lethbridge	Fourier transform spectrographs	Herschel, JCMT/SCUBA-2 FTS
Université de Montréal	Infrared detectors, cryogenic optics and instruments, infrared precision radial velocity spectrographs	JWST/FGS-NIRISS, Gemini/GPI, CFHT/SPIRou, CFHT/WIRCAM, ESO/NIRPS, TMT, E-ELT
University of Toronto and Canadian industry	Stratospheric balloon and microsatellite pointing and stabilization	SPIDER, SuperBIT, MOST, BRITE

Research Computing Infrastructure

At the time of writing, research infrastructure for high-performance computing (HPC) and data storage in Canada is managed and operated by Compute Canada (CC) via support from federal and provincial governments. Compute Canada manages a common national model for access to systems, account management and resource allocation, and works closely with the regional consortia (e.g., WestGrid, SHARCNET) that manage the systems and provide front-line services to researchers. Going forward, Innovation, Science and Economic Development Canada (ISED) has decided to shift responsibility for digital research infrastructure from Compute Canada to a so-called "New Digital Research Infrastructure Organization" (NDRIO). Most Canadian universities are primary members of NDRIO; CASCA and CADC are associate members. The transition to this new non-profit organization is expected to run until 2021. The initial Board of Directors has been constituted and an interim executive is in place. NDRIO's Researcher Council was launched in September 2020 and includes a Canadian astronomer among its 22 members. Canada's research networks are managed by CANARIE, which will maintain an independent role alongside NDRIO. CANARIE's networks currently offer speeds of 100 gigabits/s (i.e., 80 seconds to transfer 1 TB of data).

The 2018 federal budget included $572.5M over five years, with $52M per year ongoing, to develop and implement a Digital Research Infrastructure (DRI) strategy. This includes $50M for the immediate expansion of advanced research computing capacity, $145M for CANARIE, and up to $375M for NDRIO to advance and invest in data management, research software and advanced research computing. These investments represent a new funding model in which 60% of total expenditures are federal funding for the national layer of the DRI ecosystem, and 40% of total expenditures are from regional and institutional funding.

Much of theoretical astrophysics relies on access to HPC for numerical simulations and model testing, and theoretical astrophysicists in Canada have been at the forefront of developing both hardware and software infrastructure. Current simulations have expanded to exceptional scales, representing millions of hours of CPU time and generating petabytes of data. The Canadian-led "TianNu" simulation ran on over 13,000 nodes in China, reflecting the unfilled need for capability computing and a less-than-optimal match between the CC model (a uniform share of resources allocated over the year) to initiatives which require concentrated resources for short sprints.

HPC capacity in Canada has been previously supported by special competitions for cyberinfrastructure run by CFI. Unfortunately these have not run regularly, leading to a boom and bust cycle whereby Canada's academic HPC capacity temporarily becomes comparable with other G20 nations and then gets overtaken, until the next refresh several years later. As of November 2020, Canada's most powerful supercomputer is only ranked 82nd in the world. In terms of supercomputing resources relative to GDP or population, Canada is well behind many other countries and ranks *last in the G7*, lagging the United Kingdom by a factor of two and the United States by a factor of four, as shown in Figure 3.12. The US-based Summit supercomputer alone (online since 2019) offers comparable capacity to what will be needed by Canadian astronomy by 2025 (see Chapter 6), and Summit is one of many US supercomputers now available for academic research.

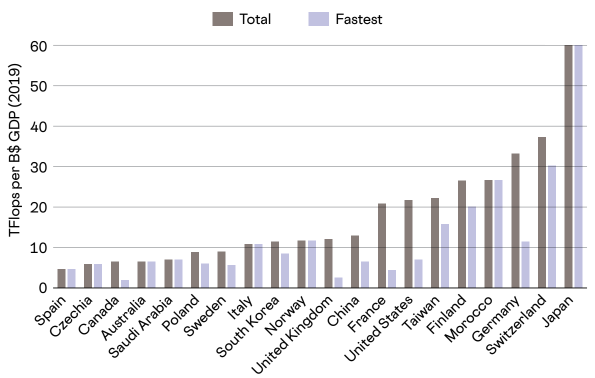

Figure 3.12: Supercomputing power (from data at top500.org as of November 2020) versus 2019 GDP. Top 20 countries are shown; Japan is off-scale at values of 115 (total), 87 (fastest).

The creation and maintenance of research software and long-term archival preservation of data are challenges for many scientific fields. Data archiving is particularly important in astronomy, since observations are expensive to make and potentially irreproducible for time-varying celestial phenomena. In Canada, the Canadian Astronomy Data Centre (CADC), part of NRC-HAA and also supported by CANARIE and the CSA, comprises the largest concentration in Canada of computing expertise related to astronomical data. The CADC maintains archives of data from telescopes including Hubble, CFHT, Gemini and many others, provides Canada's interface to the International Virtual Observatory Alliance, and supports more specialized projects (e.g., CIRADA). CADC is a unique resource, and the services and expertise that it provides enable Canadian astrophysicists to better exploit the data from observational facilities. In 2008, CADC helped establish the Canadian Advanced Network For Astronomical Research (CANFAR) to serve the data-intensive storage, access, and processing needs of university groups engaged in astronomy research. CANFAR's primary goal has been to build on top of the CC infrastructure to provide the specific service offerings (e.g., customized virtual machines, managed storage, batch processing using virtual machines, group access rights) needed for astronomy research. A challenge in continuing to evolve CANFAR has been to find an appropriate mix of funding through NRC and CFI.

Funding and Organizations

Canadian astronomy research is supported by a number of different agencies, each with specific mandates:

- The mandate of the **National Research Council (NRC)** includes the responsibility to "undertake, assist or promote scientific and industrial research"; in particular it is charged to "operate and administer any astronomical observatories established or maintained by the Government of Canada" and does so through its **Herzberg Astronomy and Astrophysics Research Centre (HAA)**.
- The mandate of the **Canadian Space Agency (CSA)** is to "promote the peaceful use and development of space, to advance the knowledge of space through science, and to ensure that space science and technology provide social and economic benefits for Canadians."
- The mandate of the **Canada Foundation for Innovation (CFI)** is to make financial contributions to Canada's universities, colleges, research hospitals and non-profit research organizations to increase their capability to carry out high quality research. CFI, together with matching contributions from provincial research agencies, is the main source of funding for university-led infrastructure projects in Canadian astronomy.
- The mandate of the **Natural Sciences and Engineering Research Council (NSERC)** is to "promote and assist research in the natural sciences and engineering" and it accomplishes this through grant and scholarship support to individual researchers and research programs.
- **Compute Canada** provides and manages the computing resources needed for advanced research computing, involving supercomputers that allow researchers to analyze massive amounts of data. Its successor **NDRIO** will take over this responsibility and will have a mandate to coordinate and fund activities in advanced research computing, data management and research software, working collaboratively with all stakeholders across Canada.

This diversity of funding sources has both strengths and weaknesses. It allows astronomers access to a large pool of available resources, in competition with researchers from other fields. However, astronomy projects can also suffer from gaps between agency mandates, for example where construction and operations funding for a facility must each be requested from different agencies, or when operations funding does not include necessary computational resources. Canadian funding for large international astronomy projects generally flows through NRC or CSA. Operations funding may support staff based at Canadian institutes and/or be transferred directly to international partners who operate the facilities. Construction funding usually involves at least some spending in Canada, for example through contracts to industry for specific components. Routes to construction and operations for smaller facilities are less well-defined. Chapter 7 makes a recommendation on coordination of funding agencies.

The funding situation in astronomy is quite different from that in the closely-related field of high-energy physics, which is supported by envelope funding from NSERC. Envelope funding has served the high-energy physics community very well over the last twenty years, in part because the envelope was enacted when that field was peaking in investment. This may not apply to astronomy, where we argue that growth in federal investment can be justified.

As one of NRC's Research Centres, HAA is part of NRC's Emerging Technologies Division and the HAA Director General reports to the corresponding NRC Vice-President. Both a 2016 evaluation of HAA and MTR2015 recommended the re-establishment of an HAA Advisory Council. This group, comprising primarily Canadian astronomers, was established in 2019 and has provided its first confidential report to HAA and NRC management. As the official representative for Canadian participation in international observatories, NRC-HAA manages the Canadian Time Allocation Committee (CanTAC) that awards Canadian observing time on CFHT and Gemini. A report to LRP2020 by CanTAC describes the proposal process and oversubscription rates. NRC also appoints Canadian representatives to governance bodies for ALMA, CFHT, Gemini, SKA, and TMT. The ACURA-CASCA Advisory Council on the SKA (AACS) and the CASCA-ACURA TMT Advisory Committee (CATAC) provide advice on SKA and TMT, respectively, and also contributed reports to LRP2020. Although there are some space astronomy-related activities at NRC-HAA, space astronomy is not explicitly within the mandate of NRC.

Like NRC, the Canadian Space Agency is part of the federal government through ISED. CSA supports Canadian astronomy through its Space Exploration division, making contributions to space astronomy missions through, for example,contracts for hardware development, the science and technology development program (STDP), and the flights for the advancement of science and technology (FAST) program. Advice to the CSA on space astronomy is managed through the Joint Committee on Space Astronomy (JCSA) and also through the Science Advisor to the CSA President who consults with the community directly and through CASCA (currently this post is held by astronomer Sarah Gallagher from Western University). The JCSA plays a key and effective role, meeting with the members of the space astronomy team at the CSA on a regular basis to provide feedback and advice on CSA programs. The CSA facilitates regular Canadian Space Exploration Workshops[4] for the community to develop priorities in space astronomy. In the space sector more broadly, ISED sponsors the Space Advisory Board to advise the Government of Canada on long-term objectives for space and to engage with Canadians. The Space Advisory Board advises the CSA at a strategic level and can advocate more broadly within and outside the government for space science and technology.

A focus of NRC and CSA investment has been the global observatories that were Canada's highest priority for LRP2010: TMT, SKA and JWST. These investments are still awaiting their corresponding science return, since the timescale for observatories of this scale is beyond a single decade. The timescales and returns on investment are very different for mid-scale facilities, which can often be conceived, built, and enable new science all within a decade. Since its inauguration, CFI has been the primary engine for funding mid-scale facilities in Canada. CHIME is a prime example, as a stand-alone observatory funded by CFI in 2012, with first light in 2017 and first science papers in 2019. Many other instrumentation projects mentioned earlier in this Chapter were also partially funded by CFI, and several of the future facilities described in Chapter 5 are, at the time of writing, the subject of pending CFI proposals.

NSERC supports Canadian astronomy research through many different programs that together form the main source of funding for research HQP.[5] The primary sources of support include Discovery Grants and Research Tools and Infrastructure Grants to individual faculty members, scholarships and fellowships awarded to students and postdoctoral researchers, faculty salary support through the Canada Research Chairs program, and a Discovery Institutes Support Grant that partially funds the Canadian Institute for Theoretical Astrophysics (CITA).

Additional support to Canadian astronomy comes from a number of other agencies, although the extent of this support is difficult to quantify. CIFAR supports long-term interdisciplinary collaboration across many research areas, including a program in "Gravity and the Extreme Universe" that includes many astrophysicists and cosmologists.

4 The report from the 2016 workshop is the most recent for space astronomy.

5 NRC supports trainees in-house, for example undergraduate co-op students and postdoctoral research associates, but has no external granting programs. CFI funding is not allowed to support research, and permits some limited support for operation of infrastructure. CSA provides some limited support for trainees through FAST and other programs but does not have the same kind of "data analysis" support programs as, for example, offered by NASA.

Mitacs supports trainees through its Accelerate, Globalink and Elevate programs; because most of these programs require matching contributions from industrial partners with relevant research problems, their uptake in astronomy is limited. Provincial research agencies such as the Ontario Research Fund and Fonds de recherche Québec – Nature et Technologies provide matching funds for CFI infrastructure proposals and, in some cases, individual grants.

Astronomy in Canada is also supported by universities, in some cases with substantial private funding. The Dunlap Institute for Astronomy and Astrophysics at the University of Toronto benefits from an endowment established by the Dunlap family, supporting efforts in instrumentation, training, and public outreach. The Perimeter Institute for Theoretical Physics uses both public and private funds to support research in theoretical physics, including cosmology and astrophysics. The Université de Montréal's Institute for Research on Exoplanets is also supported by donors, although on a smaller scale than Dunlap or Perimeter. Table 3.4 gives a broad overview of support to Canadian astronomy by the various agencies.

While a complete picture of spending on Canadian astronomy is not available, relatively complete information for NSERC, CSA, and CFI over the past decade is shown in Figure 3.13. Notable features include the large CSA spending on JWST at the beginning of the decade, which gradually declined as contracts were completed. CSA spending on space astronomy missions excepting JWST also declined significantly over the decade, from $9M in 2012–13 to $0.9M in 2017–2018. Non-mission spending at CSA (STDP, grants) saw more variability; in the last several years reported, it was higher than mission spending. The CFI spending varies over the decade because of the multi-year cycle of Innovation Fund calls; overall, the CFI spending on astronomy increased over the decade. Total NSERC spending was approximately constant over the decade. As the LRP2020 report on astronomy funding notes, this means that the inflation-adjusted value of individual grants and scholarships has declined. Finally, we note that, for the last several years, NRC contributions to international observatories (ALMA, Gemini, CFHT) have been only slightly less than the sum of all NSERC and CSA spending on astronomy.

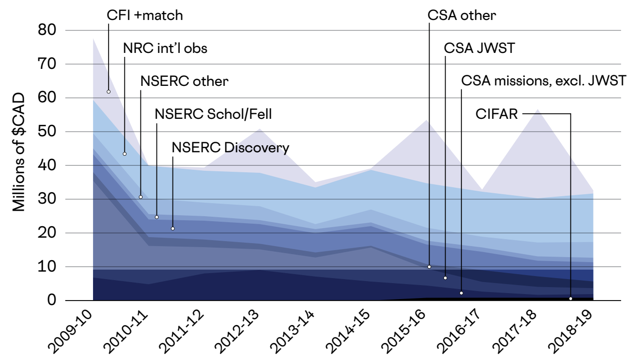

Figure 3.13: Available information on astronomy research spending in Canada, 2009-2018. All figures in in-year CAD. CIFAR data prior to 2015-16 are not available. Significant spending not captured here includes salaries for university faculty and HAA staff (est. $40M/yr total) and NRC-HAA internal research and development expenditures ($5.6M CAD/yr for 2020 and 2021).[6]

In the international context, comparing research funding between countries is far from straightforward. For ground-based astronomy, the LRP2020 report on astronomy funding compares cumulative astronomy funding from NSERC and CFI to the cumulative astronomy spending by the Australian Research Council, and concludes that, over the period 2002–2018, the totals for non-major projects are similar at approximately $250M. However, Australian funding for major projects over the same time period was roughly twice that for Canada.[7] Comparing space astronomy budgets is even more difficult (Australia is not an appropriate comparator as it has only recently been involved in space astronomy); for reference we note that the 2020 budget of NASA's Astrophysics division was roughly US$1.7B and the CSA's annual space astronomy spending (averaged from 2010–2011 to 2018–2019) was $12.6M.

6 "CSA other" includes FAST, STDP, Co-I, and preparatory activities.

NSERC Discovery includes Discovery Grants, Discovery Accelerator Supplement, Northern Supplement.

"NSERC Schol/Fell" includes Postdoctoral Fellowships, Canada Graduate Scholarships, Post-Graduate Scholarships, Banting Fellowships, EWR Steacie Memorial Fellowships, Industrial Research Chairs, Vanier Scholarships.

"NSERC other" includes Canada Research Chairs, CITA support, Collaborative Research and Training Experience, Research Tools and Instruments, Undergraduate Summer Research Awards.

"NRC intl observatories" is the sum of contributions to CFHT, Gemini and ALMA.

7 Both Canada's Fundamental Science Review ("the Naylor report") and LRP2010 recommended a change in the way that "Big Science" is funded in Canada, away from the current ad hoc process. To date this change has not been made and very large science programs, beyond the capability of individual agencies to support, are funded as separate line items in the federal budget.

Table 3.4: Funding for astronomy research in Canada.

Agency	Program	Purpose	Approximate $M/yr [2010-2019, not inflation-adj.]
CIFAR	Gravity and the Extreme Universe	Individual faculty research, collaboration, travel for 22 Canadian and 15 international members	0.8
CFI	Innovation Fund, JELF	Infrastructure construction, limited operations	0.2 [2014] to 10.5 [2017]
CSA	Missions	Hardware and software construction, launch costs	2.9 [2018-2019] to 16.2 [2010-2011]
	Other support (e.g., STDP, FAST, Co-I grants)	Mission preparation, science analysis	0.5 [2014-15] to 3.5 [2016-2017]
NRC	Flow through	International observatory support infrastructure contracts	11.5 Not available
	Internal research and development	Staff research, technology development	5.6
NSERC	Discovery Grants	Individual faculty research, primarily trainee support	5.5
	Scholarships/Fellowships	Individual trainee support	1.3
	CREATE	Research training, mostly individual trainee support	0.3
	Canada Research Chairs, CERCs	Faculty salary support, research support	2.7
	CITA	Postdoctoral fellow support	1.1
Private funding	Dunlap Institute, Perimeter Institute, foundations	Various	Not available
Provincial agencies	ORF, FRQNT, ERA, BCKDF, etc.	Matching contributions to CFI-funded projects; Individual research grants	Not available
Mitacs	Accelerate, Globalink, Elevate	Trainee support and training programs	Not available

Table notes:

1) For situations where year-to-year spending varies significantly (CFI Innovation Fund, CSA), ranges are given rather than averages.
2) Sources of support for astronomy research not included here: expenditures within universities (faculty and trainee salaries, internal research funding, research support), HAA staff salaries, NASA or other contract funding, and support of national and regional computing infrastructure. Of these, faculty and staff salaries (estimated at approx $40M/yr) are very likely to be the largest.

Table 3.5: Other astronomy-related organizations in Canada.

Organization	Description	Membership	Approx. Annual Budget
FAAQ: Fédération des astronomes amateurs du Québec	Non-profit amateur astronomy society	~2,000 individual members, 37 clubs, 9 corporations	$100k
RASC: Royal Astronomical Society of Canada	Non-profit amateur astronomy society	~5,000 individual members	$600k
CASCA: Canadian Astronomical Society/ Société Canadienne d'Astronomie	Non-profit professional society	~550 individual and 7 corporate members	$100k
ACURA: Association of Canadian Universities for Research in Astronomy/ L'Association canadienne d'universités pour la recherche en astronomie	Non-profit association	20 university members	$120k
CCA: Coalition for Canadian Astronomy/ Coalition pour l'astronomie canadienne	Lobbying group	CASCA, ACURA, industry	Not available

Other organizations relevant to Canadian astronomy are listed in Table 3.5. These groups organize, support, and/or advocate for astronomy in Canada. Unlike the research agencies described above, they typically have small budgets and do not distribute funding. The FAAQ and RASC are the two main amateur astronomy groups in Canada. These amateur groups work closely with professional astronomers on education and public outreach activities, and have occasionally joined forces to lobby government. CASCA is the professional society for Canadian astronomers; its membership demographics are discussed below. As a membership organization, CASCA is devoted to the promotion and advancement of knowledge of the Universe through research and education. CASCA is governed by a Board of Directors, all of whom are currently PhD astronomers. Its financial and paid human resources are small, and most of CASCA's activities rely on volunteer labour. CASCA can make recommendations related to the coordination and conduct of professional astronomers in Canada, but has no direct influence on hiring, research funding, or other aspects of the profession governed by individual universities. Many Canadian astronomers are also members of the American Astronomical Society (AAS), comprising about 5% of the 8,000 AAS members and corresponding to the largest non-US national membership according to the 2019 AAS annual report.

The Association of Canadian Universities for Research in Astronomy (ACURA) was formed in 2003, as an organization dedicated to the advancement of research and teaching in astronomy and astrophysics in Canada. Initially involved in coordinating Canadian participation in the Thirty Meter Telescope, it has since expanded to support Canadian involvement in Phase 1 of the Square Kilometre Array. Its activities are supported by membership fees paid by the member universities. ACURA's Executive Director reports to the ACURA Board of Management, which consults with the ACURA Institutional Council. Institutional representatives are a mix of professors and vice-presidents research. ACURA coordinates with other bodies in that the CASCA President, NRC-HAA Director General, and the chairs of several joint committees are *ex officio* members of the ACURA Board of Management.

The Coalition for Canadian Astronomy (CCA) is a lobbying group whose members are CASCA, ACURA, and representatives of Canadian industry relevant to astronomy. It was formed in 2000 to advocate for long-term sustainable funding for Canadian astronomical research and for the Canadian Astronomy Long Range Plan for Astronomy and Astrophysics from the Federal Government. The CCA has organized briefings on astronomy projects for Members of Parliament, ministerial staff and senior civil servants, has responded to pre-budget consultations on behalf of the Canadian astronomy community, and works with a government relations and communications firm to promote Canadian astronomy priorities to the federal government. The Coalition played a particularly pivotal role in securing federal funding for Canadian participation in the Thirty Meter Telescope.

People

The people who carry out astronomy research in Canada can be divided into three groups: trainees, university faculty members, and research staff employed in government, universities, or industry. Trainees include undergraduates, graduate students, and postdoctoral researchers.[8] An estimate of the size of the community can be made from the membership of CASCA, which has ranged from 500 to 570 over the past eight years. About half of the membership hold faculty or permanent staff positions, one-third are graduate students, one-tenth are postdoctoral researchers, and the remainder are associate or retired members. Some graduate student and postdoctoral researchers, and a smaller fraction of faculty members, are not CASCA members, and CASCA does not have an undergraduate membership category, so the true size of the research community is somewhat larger than the membership total.[9] The demographics and even the number of astronomy undergraduates in Canada are not well-known. Chapter 7 makes a recommendation to address this. The demographics most typically tracked in Canada (gender, race, Indigeneity, disability status, sexual orientation) are not well-known for Canadian astronomy researchers. The LRP2020 report by CASCA's Equity and Inclusivity Committee explains that attempts to collect this information from CASCA members on a voluntary basis have not been successful to date; Chapter 7 discusses this issue in more detail and makes recommendations to address it.

A report by NRC-HAA astronomer Dennis Crabtree describes the astronomy graduate students trained at Canadian institutions over the period 2010–2018 and their career trajectories. Relatively complete tracking is possible, since the number of individuals involved is small. The structure of astronomy graduate programs differs by institution: at some universities, the MSc and PhD are entirely separate, at others students begin as MSc students and transition into a PhD, while at others students enter the PhD directly from an undergraduate degree. Figure 3.14 shows that Canada produces an average of about 30 graduates at both the PhD and MSc levels astronomy per year, values roughly constant over the past decade. About two-thirds of the PhD graduates work at postsecondary institutions, one-quarter are employed in the private sector, and the remainder work in the (non-postsecondary) public sector. The relative order of employment areas is similar for Master's graduates but with different proportions: 44% in postsecondary institutions, 32% in the private sector, 11% in the public sector, and the remainder unknown.

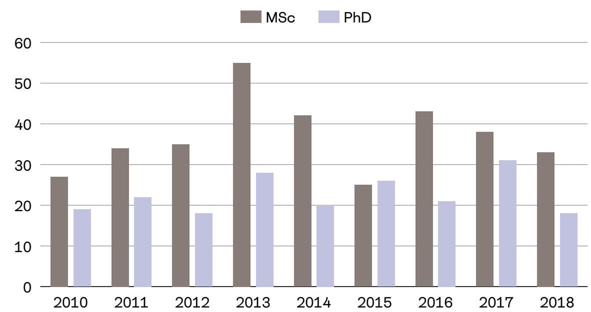

Figure 3.14: Annual numbers of PhD and MSc graduates in astronomy in Canada.
Data courtesy of Dennis Crabtree

Postdoctoral researchers in Canadian astronomy, like those in many other countries and research areas, can be difficult to track. The total number of postdocs in Canadian astronomy is not well-known. Postdocs are less likely to join CASCA because many are only in Canada for short periods; tracking them is difficult in part because of the short-term nature of their positions and in part because of the variation in their employment status across institutions. CASCA has had an average of about 50 members in its "postdoc" membership category since 2015 (compared to roughly five times as many faculty and staff members), but this almost certainly undercounts the total number. An informal survey of Canadian physics and astronomy department websites estimates that there are roughly half as many postdocs as faculty members, a ratio that is quite low compared to that in other countries.

Astronomy postdoctoral researchers in Canada work primarily in universities. Some are also employed at research institutes such as NRC-HAA and the Perimeter Institute for Theoretical Physics. They are highly effective researchers, as judged by their scientific publication output. The LRP2020 white paper reporting on Canada's telescope-linked publications finds that Canadian postdocs lead more papers than either students or faculty members, and that those papers also tend to have higher impact. However, as Figure 3.15 shows, publications led by Canadian-based researchers are declining in number relative to competitor nations. A plausible explanation for Canada's decreasing number of first-author papers compared to other countries is the lower relative number of postdocs in Canada, since almost 80% of Canadian first-author papers based on telescope data are authored by either students or postdoctoral researchers.

8 Although it can be argued that postdoctoral researchers should be considered early-career professionals, we note here that funding agencies generally categorize them as trainees.

9 A database of Canadians in astronomy maintained by Denis Laurin of the CSA uses broader criteria for inclusion and estimates this number at closer to 1,200.

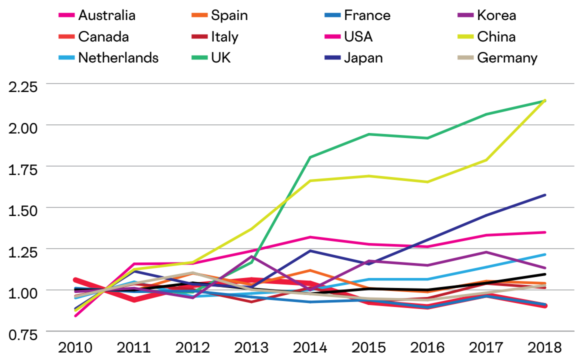

Figure 3.15: Number of telescope-linked publications by first-author affiliation country, relative to 2010–2011 average.

Data courtesy of Dennis Crabtree

University faculty members form another major group of people who carry out astronomy research in Canada. Because faculty positions are less transient than either trainees or staff, the demographics of faculty members are of particular importance in shaping the community. The demographics report prepared for LRP2020 shows that the number of astronomy faculty members per institution varies from 1 to over 20, with a median value of about 7. As might be expected given the small numbers of people at each institution, there is substantial demographic variation between institutions. Figure 3.1 shows that overall, the Canadian astronomy faculty cohort is relatively senior, with a median date of PhD in 1995. Most faculty hold PhDs from institutions in Canada and the United States, which also comprise the birthplaces of nearly 80% of faculty members. The overall fraction of women faculty is 21% and increasing with time. An LRP2020 white paper on astronomy research at smaller, comprehensive research universities highlights the opportunities and challenges particular to faculty members at these institutions; a recommendation on this topic is in Chapter 7.

The third group of people in Canadian astronomy are research staff employed in government, universities, or industry. The largest group of non-faculty PhD-level research staff in Canadian astronomy (approximately 30) is employed by NRC-HAA. An LRP2020 report by the HAA Science Council notes that HAA's science staff are more senior and more likely to be men than university faculty, although well within the distribution of these quantities for the relevant university departments. Some HAA research staff participate in teaching and student supervision through adjunct appointments and partnerships with universities and colleges. Unlike university faculty, their non-personal research activities usually include research support to the university community, for example through supporting use of international telescopes such as ALMA, facilitating proposals, building instruments, or assisting in data analysis via computing facilities such as the CADC.

HAA also employs the largest number of non-research staff at a single organization in Canadian astronomy. Approximately 40 staff members work in areas from computing support to engineering design, with roughly three-quarters of these in continuing positions. Staff members in equivalent positions at Canadian universities are typically employed on fixed-term contracts for instrumentation projects, such as the research staff members working on JWST at the Université de Montréal or on GIRMOS at the University of Toronto's Dunlap Institute. A small number of staff members work in on-or-near-campus observatories, of which Observatoire de Mont Mégantic in Québec is the largest. Canadian astronomical research is also supported by staff at core facilities within individual universities (e.g., libraries, computing centres, machine shops) who also support other fields of research. High-performance computing—for which astrophysics is a major user—is also facilitated by staff at the regional consortia that are currently part of Compute Canada (see above section on research computing infrastructure).

Other contributors to Canadian astronomy research include staff members at the Canadian Space Agency and at companies such as Honeywell, ABB, MDA, Magellan Aerospace, and Neptec that do astronomy-related work. As with non-research staff at NRC-HAA, these individuals do not perform astronomy research as their primary responsibility, but their work is a critical component of enabling astronomy research in Canada. There are about a dozen staff members involved in space astronomy at CSA. In industry, about 25 individuals in industry have led development projects in space astronomy; the total number of personnel involved in all of these projects is much larger, but counting them individually would be very difficult. Links between university researchers and industry have mostly been made through space missions and HAA instrumentation projects and, as discussed in Chapter 7, there is substantial room for these connections to grow.

Canadian Astronomy and Society

Public Engagement

A society with a strong science culture will support the use of scientific knowledge and methodology, will encourage the education and training of a highly skilled workforce, and will foster the development of an innovative knowledge-based economy. Numerous studies have confirmed that scientific education and public outreach (EPO) are crucial for establishing and maintaining this culture.

EPO presents complex research topics in an exciting and inspiring context, promotes logical and evidence-based reasoning, stimulates long-term science understanding and interest, and gives people the approaches and information they need to inform their purchasing decisions, medical choices, and voting intentions. Many educators, researchers, engineers and scientists, across a diverse range of fields, credit the beginnings of their career path in science, technology, engineering and mathematics (STEM) to an early science outreach experience. In particular, scientific EPO plays an important role in recruiting underrepresented groups into careers in STEM.

Astronomy is widely acknowledged as the "gateway" topic to all of STEM. Astronomy is synonymous with the wonder, excitement, and discovery of science, because of its accessible content, spectacular visual material, regular stream of new discoveries, and tremendous potential to capture the imagination. With its ambitious goals of explaining space, time, and life, astronomy plays a unique role in providing an appreciation of the importance of basic research, in raising awareness of scientific principles and of the scientific method, and in contributing to the creation of a technically capable and aware society. Even for those members of society without significant scientific literacy, astronomy resonates and inspires. Astronomy is a highly accessible window into what science offers and how science is done, and in addition can showcase local "made-in-Canada" discoveries to communities across the country.

The appetite for public consumption of astronomy is enormous. Planetariums, observatories, and viewing nights are some of the most popular events in the country for communities and families, while in the International Year of Astronomy in 2009 (IYA2009), more than a million Canadians looked through a telescope, many for the first time. Astronomical breakthroughs are no longer reserved only for professional researchers: astronomy has pioneered the burgeoning field of "citizen science," in which members of the public can make important discoveries about the Universe using their computers and smartphones. Nationally, CBC's *Quirks & Quarks* airs over 30 astronomy-related segments each year, with similar numbers of articles in the country's largest newspapers. More than 70,000 Canadians attend free outreach events organised by the professional astronomy community each year as summarized in Tables 3.6 and 3.7, in addition to the many other activities run by amateur astronomy groups, museums and science centres. In particular, Canada's two main amateur astronomy societies, the Royal Astronomical Society of Canada (RASC) and Fédération des astronomes amateurs du Québec (FAAQ), have a combined membership of around 7,000 (more than ten times that of CASCA), and make enormous contributions to astronomy EPO across Canada. Descriptions of the wide range of public-facing activities conducted by the RASC and FAAQ are beyond the scope of this report, but can be found on those organizations' web pages.

The professional Canadian astronomy community has greatly grown and expanded its scope of creative EPO activities over the last decade, some highlights of which are as follows (see Table 3.7 for a broader list):

Transit of Venus: In 2012, the transit of Venus gathered national interest and viewing parties were organized across the country. To help with observations, the Dunlap Institute, assisted by the RASC and FAAQ, distributed 43,000 pairs of eclipse glasses.

Solar Eclipse: The partial solar eclipse of August 2017 was the single largest astronomical public outreach event in the history of Canada. Many groups distributed their own eclipse glasses and viewing events were held in countless locations, leading to record-breaking crowds. For example, AstroMcGill and the Dunlap Institute distributed over 50,000 pairs of eclipse glasses, and hosted a combined total of 35,000 people at various viewing events.

Outreach by Research Institutes: Many Canadian astronomy or related institutions now include EPO as part of their mandate and/or have hired dedicated EPO staff. These include the Dunlap Institute at the University of Toronto, the Institute for Earth and Space Exploration at Western University, the Arthur B. McDonald Canadian Astroparticle Physics Research Institute at Queen's University, the Perimeter Institute for Theoretical Physics in Waterloo, and the McGill Space Institute and the Institute for Research on Exoplanets in Montréal.

Astronomy on Tap: Astronomy on Tap (AoT) is a series of free public outreach events featuring engaging science presentations combined with music, games, and prizes in a fun, interactive atmosphere. AoT events feature one or more presentations given primarily by local professional scientists and graduate students, but also by visiting scientists, undergraduate students, educators, amateur astronomers, writers, artists, and other astronomy enthusiasts. Events are held at social venues like bars, breweries, coffee shops, and art galleries. Since the first New York City event in April 2013, over 600 AoT-affiliated events have been held in over 50 locations worldwide. In Canada, Astronomy on Tap events have been organized by the Dunlap Institute (Toronto), AstroMcGill and iREx (Montréal), McDonald Institute (Kingston) and Western (London). Astronomy on Tap MTL / Astronomie en fût MTL in Montréal was the first bilingual AoT series, launching in January 2017, alternating monthly between English and French.

Discover the Universe / À la découverte de l'univers: As a legacy of IYA2009, a national and bilingual training program in astronomy was founded and offered its first online workshop in 2011: Discover the Universe / À la découverte de l'univers. The founding partners were CASCA, RASC and the FAAQ. Over the years, the program has grown and gained credibility and popularity with different audiences: K-12 teachers, different science centres and museums, STEM outreach organizations and even international individuals and institutions. Teachers, in particular, are an important target group for Discover the Universe since astronomy is present in all provincial science curricula but little training for teachers is available. In 2016, the program was adopted by the Dunlap Institute at the University of Toronto while still being supported financially by CASCA and the Centre for Research in Astrophysics in Québec (CRAQ). While this meant a reduced collaboration with the three original partners, Dunlap's contribution allowed the program to continue and grow. Discover the Universe is now stronger than ever, with many partnerships being forged and many projects underway. Discover the Universe is an unquestioned success story and a great heritage of IYA in Canada.

CASCA Westar Lectureship: The Westar Lectureship was established in the early 2000s and ran for a few years with limited success. CASCA decided to revive the program in the mid-2010s and the first lecture was given in 2017. A small committee was formed to run the program, which includes recruiting lecturers, sending the call for proposals to communities, screening proposals, matching winning proposals with lecturers and supervising the organization of the visits/lectures. As of 2020, six lectures have been organized in various locations across Canada, including extremely remote locations such as Igloolik, NU (see next section). The program continues to attract many proposals from communities to host lectures.

Indigenous Engagement: A variety of different activities relating to Indigenous engagement and Indigenous education have taken place over the last decade. Some of the highlights are as follows:

- The University of Calgary's Rothney Astrophysical Observatory (RAO) completed an online constellation guide project in 2016, blending contemporary Indigenous ways of knowing with the Western science perspective. RAO summer camp themes include traditional skills of wayfinding, time keeping and marking seasonal changes. The RAO also delivers educational programs to indigenous students from the Tsuu T'ina, Stoney and Siksika Nations.
- In 2017, an Indigenous astronomy workshop at the University of Toronto brought together astronomers, educators and Indigenous scholars to discuss methods for improving engagement with Indigenous communities and inclusivity in delivering Indigenous knowledge in the classroom.
- Western and McMaster Universities hosted a two-day Indigenous astronomy workshop in 2019. Key knowledge mobilization goals included hosting local, national and international Indigenous astronomy experts and local Indigenous community members for the purposes of sharing Indigenous sky knowledge, forming new collaborations within and between nations, and facilitating and furthering efforts to increase Indigenous astronomy knowledge documentation and dissemination through university courses and outreach programs.
- In 2019, the Mont-Mégantic Observatory received funding from the International Astronomical Union's Office of Astronomy for Development for a pilot program: Astronomy in Indigenous Communities. This program involves sending astronomers to visit schools on First Nations reserves to reach young Indigenous students and to bring a group of students to visit the Mont-Mégantic Popular Astronomy Festival.
- CASCA Westar Lecturers have visited several remote Indigenous communities. For example, in 2019 Stanimir Metchev visited Ataguttaaluk Elementary School in Igloolik, NU as a Westar Lecturer. Prof Metchev led activities with Inuk students and teachers, learned about Inuk sky knowledge, and helped a class of grade 7 students to build an igloo under the instruction of three village elders.

Within the landscape of increased public engagement, universities and astronomical institutions have correspondingly increased the time and resources they dedicate to communicating their astronomers' exciting results.

Awards: Following the International Year of Astronomy 2009, awards were created to recognize excellence in EPO. Three awards are given each year, one for each organization involved in the creation of the award: CASCA, RASC and FAAQ. CASCA's Qilak Award for Astronomy Communications, Public Education and Outreach includes a prize lecture at CASCA's annual science meeting.

Small Initiatives for Diverse Audiences: A few smaller Canadian initiatives for diverse audiences have gathered the attention of the international funding campaign led by the IAU's Office of Astronomy for Development. The SYSTEM Sounds project has received funding and international recognition for its original integration of science and art by turning science data into sound and music. This new approach is particularly interesting for people who are visually impaired.

Within the landscape of increased public engagement, universities and astronomical institutions have correspondingly increased the time and resources they dedicate to communicating their astronomers' exciting results. These organizations write press releases, solicit media interviews for their scientists and feature their research highlights on platforms such as social media and institutional websites. Most astronomers now consider the dissemination of their discoveries as part of their responsibilities as scientists to Canadians who fund so many of our scientific efforts and are more engaged with their local press officers and with science journalists across Canada. Building relationships with journalists is especially imperative as the number of journalists and writers who cover science and technology full-time has greatly decreased over the past decade.

Canadian astronomers also frequently contribute to larger, Canada-wide science outreach festivals and organizations, many of which were founded or have been significantly expanded since 2010. Some of the many programs in which Canadian astronomers participate include Skype a Scientist, Virtual Researcher on Call, DAO's ExoExplorations and CanYES, Exploring by the Seat of Your Pants, Science Odyssey, Science Rendezvous, 24 Hours of Science / 24 heures de science, Science Literacy Week, Eureka! Festival / Festival Eurêka!, Pint of Science Canada, Nerd Nite, and Let's Talk Science.

Science communication is experiencing an exciting upswell all over Canada and astronomers, especially early-career astronomers, are at the forefront of this movement. However, the lack of time and resources often stop astronomers from performing science communication, despite their desire to make a contribution. Furthermore, the fact that EPO activities are often not included in evaluation metrics for grants, tenure and academic positions means that astronomers are often forced to deprioritize their EPO activities. In Chapter 7, we make recommendations to address these concerns, and more broadly to advance the future of EPO in Canadian astronomy.

Table 3.6: Representative EPO activities across Canada directed toward different demographics.

Audience	Examples of Canadian Astronomy EPO
K-12	School visits by Astronomers Summer camps University of Alberta USchool McGill Space Explorers Let's Talk Science
K-12	Discover the Universe Alberta Science Network McGill Teacher Inquiry Institute
Girls and underrepresented youth	University of Alberta WISEST Dalhousie University Imhotep's Legacy Academy McGill Girls in Physics Day
Families with young children	Science Rendezvous Eureka! Festival
College and university students	McGill Physics Hackathon
Adults interested in science	Talks at RASC Centres Public Observing nights Planetarium shows on university campuses Western World Podcast York Universe Radio Show University of Toronto AstroTours AstroMcGill Public AstroNight
Adults not-so-interested-in-science	Sidewalk astronomy Astronomy on Tap Pint of Science Nerd Nite Large Public Events
Women and underrepresented adults	SYSTEM Sounds University of Alberta WISEST
Indigenous peoples	Westar Lectures ii' taa'poh'to'p, Rothney Astrophysical Observatory Astronomy for Canadian Indigenous People, Mont-Mégantic Observatory Indigenous astronomy workshops
Science centres, museums and Informal educators	Discover the Universe

Table 3.7: Astronomy and astrophysics outreach activities compiled from the websites of Canadian universities. Note that this table does not include EPO efforts from the RASC, FAAQ and other amateur astronomy groups, or from professional observatories, non-university affiliated planetariums, museums and science centres.

Canadian University Astronomy EPO Efforts

University	Department or Institute	Name of Outreach Group, Observatory or Planetarium	Activities
Brandon University		Brandon University Astronomical Observatory	Monthly public telescope observing nights
Dalhousie University	Physics and Atmospheric Science	Halifax Planetarium	Planetarium operated by RASC volunteers, school visits, week-long summer camps for youth
McGill University	McGill Space Institute	AstroMcGill	Monthly public lectures, Astronomy on Tap (with iRex), and 24 h des sciences
McGill University	Physics	Physics Matters	Monthly public lectures, primary school visit program, teacher workshops, hackathon for high school-undergrad students, girls in physics visit day
McMaster University	Physics and Astronomy	Physics and Astronomy Outreach At McMaster, W.J. McCallion Planetarium	Planetarium Planetarium shows, sidewalk astronomy, Online physics competition
McMaster University	Origins Institute		Public lecture series
Memorial University		Grenfell Campus Observatory	Occasional public observation sessions
Permineter Institute for Theoretical Physics			Public lecture series, arts and culture events, summer school program for senior high school students, games and videos for students, workshops and resources for teachers, research training for african students
Queen's University	Physics, Engineering Physics and Astronomy	The Queen's Observatory	Monthly public tours (short lecture + telescope observing), school tours
Queen's University	McDonald Institute		Visitor centre, Astronomy on Tap, public lectures
Saint Mary's University	Astronomy and Physics	Burke-Gaffney Observatory	Weekly public telescope observing, private tours for school and community groups, Robotic telescope open to authorized members of the public
Simon Fraser University		Trottier Observatory	Bi-weekly public telescope observing, partners with RASC Vancouver Centre

Table 3.7 (Continued)

Canadian University Astronomy EPO Efforts			
University	**Department or Institute**	**Name of Outreach Group, Observatory or Planetarium**	**Activities**
Université de Moncton	Physics and Astronomy	L'observatoire du campus de Moncton	Monthly public telescope observing
Université de Montréal	Institute for Research on Exoplanets (iREx)		Astronomer visits to schools K-12, talks in schools (primary school to university), virtual classroom visits, "Astronomer for a Night" contest at OMM, Artist in Residence program, day-long internships for high school and CEGEP students. Public lectures, Astronomy on Tap (with AstroMcGill), 24 h des sciences, Festival Eurêka
University of Alberta	Physics	UAlberta Observatory	Weekly public observing (solar and evening). Hosts visits from schools, summer camps, and other groups. Public lectures and teacher workshops
University of British Columbia	Physics and Astronomy	UBC Physics and Astronomy Outreach Program	Summer camps, science competitions, to teacher workshops and public lectures.
University of Calgary	Physics and Astronomy	Rothney Astrophysical Observatory	Monthly public Open House events with telescope observing. Curriculum targeted educational programming for all regional school boards
University of Guelph	Physics	University of Guelph Observatory Telescope	Observatory available for group tours
University of Manitoba	Physics and Astronomy	Ewen Campus Observatory, Lockhart Planetarium	Monthly astronomy Open House, hosted jointly with RASC (telescope observing + planetarium shows)
University of Saskatchewan	Physics and Engineering Physics	University of Saskatchewan Observatory	Weekly public telescope observing, private tours for school and community groups
University of Toronto	Astronomy and Astrophysics, Dunlap Institute		Frequent Planetarium shows, monthly public lectures (organized by graduate students), sidewalk astronomy, Ask an Astronomer, Astronomy on Tap, all-ages events
University of Toronto	CITA		Classroom visits

Table 3.7 (Continued)

Canadian University Astronomy EPO Efforts			
University	**Department or Institute**	**Name of Outreach Group, Observatory or Planetarium**	**Activities**
University of Victoria	Physics and Astronomy	UVic Astronomy	Weekly public telescope observing, private tours for school and community groups, yearly public lecture, high school outreach with cosmic ray detectors, Café Scientifique and Historique, Ask us (questions about physics and astronomy)
University of Waterloo	Physics and Astronomy	Gustav Bakos Observatory	Monthly public tours (short lecture + telescope observing), private tours for school and community groups, Science open house, Online physics competition
University of Winnipeg	Physics		Let's Talk Science, School Tours and Visits
Western University	Physics and Astronomy	Hume Cronyn Memorial Observatory	Weekly public telescope observing (May through August, otherwise monthly), program for school and community groups (lecture, hands-on activity, a tour of the telescope, and observing; in partnership with RASC), private observatory events, Science Rendezvous, Astronomy on Tap (with CPSX)
Western University	Centre for Planetary Science and Exploration (CPSX)		Primary school student workshops and activities, bi-weekly podcast, Science Literacy Week, Science Odyssey, 1-week camp for children several times throughout the year, Astronomy on Tap (with department of Physics and Astro)
York University	Physics and Astronomy	Allan I. Carswell Astronomical Observatory	Weekly public telescope observing, radio show, private tours for school and community groups, online public observing, scale model of solar system on campus, evening for high school teachers

Astronomy and Other Scientific Fields

In Canada, the strongest connection between astronomy and other research fields is that with physics. Nearly all astronomy faculty members at Canadian universities are members of academic departments that combine physics and astronomy (the University of Toronto is the exception, and is the only Canadian university with a separate department of astronomy and astrophysics); many teach both subjects. Astronomy, astrophysics and cosmology are research topics within NSERC's Discovery Grant Evaluation Group on Physics and there are numerous links between astronomy and physics. Condensed matter physicists may develop technologies used in astronomical instrumentation or make laboratory measurements used to interpret astronomical observations; astronomers may test predictions of physical theories under conditions not attainable on Earth; and the study of subatomic particles from space (astroparticle physics) is the mission of the Arthur B. McDonald Canadian Astroparticle Physics Research Institute at Queen's University.

Planetary science, solar physics, and space weather are also adjacent disciplines to astronomy. Researchers in these fields may have their academic homes in physics, astronomy, or geosciences departments, and may have their NSERC Discovery Grants evaluated by either the physics or geosciences evaluation group. Use of satellite and remote-sensing technology is one commonality between researchers in planetary science, space weather, and astronomy. There are clear parallels between planetary scientists who study planets in our own solar system and astronomers who study planets around other stars, as well as between solar physicists and stellar astrophysicists.

Industry-Astronomy Partnerships

Many Canadian companies have connections with Canadian astronomy, both as partners in technology development, and as receptors for the technical capacity built through research training. This engagement is often facilitated by NRC-HAA which, as noted by the LRP2020 white paper on Industrial Initiatives in Canadian Astronomy, has a deep understanding of Canada's astronomy infrastructure and a close relationship with its observatories, and is ideally positioned to facilitate between industrial capabilities and observatory and instrumentation project needs. That document contains a comprehensive description of industrial initiatives, engagement, and funding mechanisms; here we highlight some of the deepest, most long-lasting connections.

ABB Canada has headquarters in Montréal and more than 4,000 employees across Canada. ABB's Space and Defense Systems section in Québec City specializes in optical sensing and systems and has contributed to a number of Canadian astronomical instrumentation projects, providing critical elements at all phases from design to manufacturing. For example, ABB is the main industrial sub-contractor for optical systems associated with TMT/NFIRAOS, and ABB was the lead organization behind the CFHT/SITELLE instrument. ABB's instruments have been in space for over 25 years. More recently, ABB was awarded a contract for the emCCDs for the coronagraphic instrument on NASA's Roman Space Telescope in collaboration with Montréal-based Nüvü Cameras.

COM DEV Ltd (doing business as Honeywell Aerospace) has supplied communications hardware to the global satellite industry for the past 40 years. COM DEV has also supplied the majority of the optical and space science instrumentation that the Canadian Space Agency has flown in the last few decades. Its business is highly technical: of 800 Canadian employees, over 100 have advanced degrees. The company reports that graduates from programs in astronomical instrumentation, computation and big data surveys typically have a broad base of skills. A number of such graduates have become leaders in its technical staff.

MDA is a Canadian aerospace company doing business in next-generation space exploration, Earth observation, space awareness, and defence systems. Its space robotics expertise is perhaps the most familiar to Canadians through its development of robotic arms for the space shuttle and International Space Space Station. MDA also has a long-standing collaboration with NRC in central signal processing that provides a path for Canadian technological leadership roles in SKA1. MDA subsidiary Neptec provided design, fabrication, and calibration for the CAMS metrology system, the Canadian contribution to the Hitomi X-ray telescope.

Dynamic Structures Ltd (DSL) of Port Coquitlam, BC designs and builds large, complex steel structures and is well-known worldwide for its expertise in enclosures and telescopes for observatories. From its beginnings with work on CFHT, DSL has been involved with may other large telescope projects including in Spain (Isaac Newton Telescope, William Herschel Telescope), Chile (Gemini Observatory, Atacama Cosmology Telescope) and Hawaiʻi (Keck Observatory, Subaru Telescope). The company has designed the unique calotte enclosure for the Thirty Meter Telescope, which forms Canada's largest technical contribution to the project.

An LRP2020 white paper on New Space describes the expanding role that private industry plays in space use, with programs, initiatives, and services led by commercial operators. With an increasing number of launch opportunities at decreasing costs, space is becoming more accessible; this may be advantageous

Astronomy captures the imagination, enriches our culture, and pushes the boundaries of technology. It improves our understanding of the physical world and develops the advanced data analysis techniques and technically skilled people that allow Canada to lead the world in discovery and innovation.

for small-satellite astronomy missions. With increased access to space, however, new problems are expected to arise: space-based observatories will need to be cognizant of orbital debris, and all types of astronomical observations may become affected by satellite mega-constellations such as Starlink and OneWeb. If Canadian astronomers want to access space-based astronomy observations provided under a pay-for-use model, revisions to granting programs might be necessary. Space mining has the potential to be of significant scientific value, as it could accelerate efforts to sample the composition of many lunar locations and asteroids, but its legal basis is controversial and current law does not guarantee that the scientific value of samples will be preserved.

Benefits to Society

Canadian astronomy contributes to Canadian society in many ways. Astronomy captures the imagination, enriches our culture, and pushes the boundaries of technology. It improves our understanding of the physical world and develops the advanced data analysis techniques and technically skilled people that allow Canada to lead the world in discovery and innovation. Astronomy connects people across cultures as they ask and try to answer fundamental questions.

Astronomy is one of the most visible and captivating sciences. Public communication about astronomical discoveries demonstrates to Canadians that world-class science happens here and contributes to the development of a science culture in Canada. In its 2014 report *Science Culture: Where Canada Stands*, the Council of Canadian Academies defined a society with a strong science culture as one that embraces discovery, supports the use of scientific knowledge and methodology, and encourages the education and training of a highly skilled workforce and development of an innovative knowledge-based economy. Canadians were shown to have few public reservations about science, were interested in new scientific discoveries, enjoyed visiting science centres and museums, and demonstrated a good basic level of scientific literacy. The *3M State of Science Index* explored global attitudes towards science. When looking at the opinions of Canadians in this poll, attitudes towards science remain wholly positive and Canadians appear conscious of the importance and impact of science and technology in their daily lives. Informing and inspiring Canadians, especially Canadian youth, about the value of science is key to building the country's prosperous future.

Technology developed for astronomy research can be applied well beyond the field to improve everyday life. Perhaps the best-known example is the development by

Crowds enjoying the solar eclipse of August 2017. Image credit: Dunlap Institute for Astronomy & Astrophysics

Australian radio astronomers of critical technologies that enabled WiFi, but there are many others in areas from medical imaging to environmental monitoring. Notable Canadian successes in astronomical spin-off technology include Skaha Remote Sensing Ltd., a BC company that has developed sensor technology to measure soil moisture remotely over large areas. This technology uses CHIME feeds to measure the water content of soil in real time to make irrigation more efficient, maximizing crop yield and reducing water and energy usage. Blue Sky Spectroscopy Inc., grew out of research in far-infrared astronomy at the University of Lethbridge. This Alberta company develops custom terahertz technology for remote sensing applications.

A study prepared by Hickling, Arthurs and Low (HAL) for the Canadian Space Agency describes the Benefits and Return of Investment (ROI) from Canada's Participation in Space Astronomy. Over the period 1999–2019, government investment in space astronomy had a net present value of $379.49M and total impact of $891.35M, yielding an ROI of 2.35. The total employment impact was 3717 FTEs. Participation in space astronomy missions is also a source of prestige for participating companies, academic institutions, and for Canada overall, and increased visibility for participating companies allows them to leverage their experience and technologies developed for space astronomy missions to obtain other types of non-space and space-related contracts. A 2010 study by HAL on "Astronomy in Canada," covering both ground- and space-based investments, found a similar ROI.

Training in astronomy research develops a broad technical problem-solving skill set. Understanding everything in the Universe involves collaborating in teams, analyzing massive digital datasets that are often heterogeneous or incomplete, performing complex computer simulations of otherworldly processes, and interpreting the results in a physically meaningful way. Astrophysicists must employ flexibility to investigate multiple methods, creativity to determine how to obtain useful information, and computational expertise to solve problems on any scale. Trainees attracted to the field by intrinsic interest may not realize that they are developing the digital skills that Canadian businesses and entrepreneurs are looking for, including expertise in data analytics, programming, and web development. Astronomy trainees represent a diverse talent source complementary to software engineers, statisticians and computer scientists: they are interpreters who can turn data into knowledge and communicate complex concepts.

Finally, astronomy brings people together. The sky and its wonders belong to all people; astronomy both requires and inspires peaceful, worldwide cooperation. Celestial events such as eclipses and meteor showers can draw people from diverse backgrounds together for a common experience in a way that few other natural phenomena can. Although it would be foolish to believe that astronomy exists independent of religion, politics, history, and the many other differences that can drive humans apart, it has the potential to reach across those divisions in the shared contemplation of fundamental questions: How did we get here? What is our relationship to the Universe? Are we alone?

The current state of astronomy in Canada provides a strong foundation for future discoveries. However, for all the successes of the last decade, there is much work to do before Canadian astronomy is prepared to address the exciting science questions outlined in Chapter 4, from building the new facilities and technical capabilities described in Chapters 5 and 6 to addressing inequities in the field and improving its connection with broader society, as described in Chapter 7.

Chapter 4

The coming decade will see the first attempts at establishing whether or not life exists elsewhere in the Universe.

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Star trails over western Vancouver Island.

Science Questions for the Next Decade of Astrophysics In Canada

Our understanding of the Universe has been completely transformed over the last decade. The direct detection of gravitational radiation was a stunning confirmation of Einstein's General Relativity, and has opened an entirely new way of studying the sky. The Kepler mission discovered more than 2,600 planets in other solar systems, while the Gaia satellite has measured the distances to around 100 million stars. Astronomers have discovered interstellar objects passing through our own solar system, have confirmed the existence of infant galaxies forming only a few hundred million years after the Universe's beginning, and have watched new planets begin to form around other stars. We have produced the first direct images of a black hole, have generated computer-simulated galaxies that are almost indistinguishable from the real thing, and have made extraordinarily precise measurements of the cosmos's age and composition.

Canadian astronomers have been at the forefront of these and other breakthroughs. Over the last ten years, Canadians made the first ever direct images of planets orbiting other stars, revealed the exotic processes that create the heavy elements in the periodic table, discovered more mysterious "fast radio bursts" than everyone else in the world combined (see Figure 4.1), showed that the Universe is full of carbon "buckyballs," performed the world's largest cosmological simulation, and pioneered the techniques now being used by astronomers worldwide to study the history of the Universe and its expansion.

Figure 4.1: The discovery of new fast radio bursts with Canada's CHIME radio telescope was featured on the cover of Nature magazine in February 2019.
Credit: Andrew Fyfe; Springer Nature

No single telescope or technique has delivered all these extraordinary advances. To make these exciting discoveries, astronomers have directed a huge range of instruments and approaches at the heavens: telescopes capable of gathering all types of electromagnetic and non-electromagnetic signals, observatories both on the ground and in space, innovative instrumentation that collects and manipulates light in new ways, and sophisticated calculations and simulations needed to predict or interpret a plethora of astronomical processes.

All this progress has brought us to the brink of a new and exciting frontier, but some of humanity's oldest and most fundamental questions remain. How did the Universe begin? How did the objects in the night sky form, and what is their future? Are there other planets like Earth? And is there any other life out there, maybe life like us? All these questions were once only philosophical but, incredibly, astronomy now has the power to answer them. Furthermore, we are committed to answering these questions not just in a broad sense, but in quantitative, specific detail.

Canadian astronomers accordingly have extremely ambitious science goals for the next decade. Having secured a position at the front lines of discovery, we now wish to not just maintain this standing, but to expand our horizons and endeavours. The full scope of plans envisaged by the Canadian astronomical community is enormous, and is comprehensively covered in the set of white papers submitted to the Long Range Plan process. In the rest of this Chapter, we highlight four central scientific themes that encapsulate the planned focuses of Canadian astronomy through to 2030:

1. **How did the Universe begin and what is it made of?**
2. **How have stars and galaxies changed over cosmic time?**
3. **What are the extreme conditions of the Universe?**
4. **Why are planetary systems so diverse and could other planets host life?**

These questions directly motivate the set of facilities and programs that we recommend as priorities for Canadian astronomy over the next decade, as set out in Chapter 5. The specific science areas in which each such recommendation will provide significant leadership for Canadian astronomy are listed in Table 4.1.

Table 4.1: Summary of Canadian astronomical capacities and facilities for 2020–2030 and their capabilities for science and discovery. The left-hand column lists the core programs and projects listed in Chapter 5.[10] The top row indicates the four main science questions that Canadian astronomers want to answer over the next decade. While many projects have broad science cases, a check mark indicates the expectation of significant Canadian leadership on a key science question using a given facility or resource.

	ALMA	CASTOR	CFHT	CHORD	CMB-S4	Computation	Cooled infrared space telescope	Gemini	HabEx[11]	JWST	LiteBIRD	LSST	LUVOIR[11]	Lynx[11]	MSE	ngVLA[11]	Origins[11]	POEP	SKA1	Theory	VLOT	XRISM
How did the Universe begin and what is it made of?		✓		✓	✓	✓				✓	✓	✓			✓				✓	✓	✓	
How have stars and galaxies changed over cosmic time?	✓	✓	✓			✓	✓	✓		✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
What are the extreme conditions of the Universe?	✓	✓		✓		✓		✓		✓		✓		✓	✓	✓			✓	✓	✓	✓
Why are planetary systems so diverse and could other planets host life?	✓	✓	✓			✓	✓	✓	✓	✓		✓	✓			✓	✓	✓	✓	✓	✓	

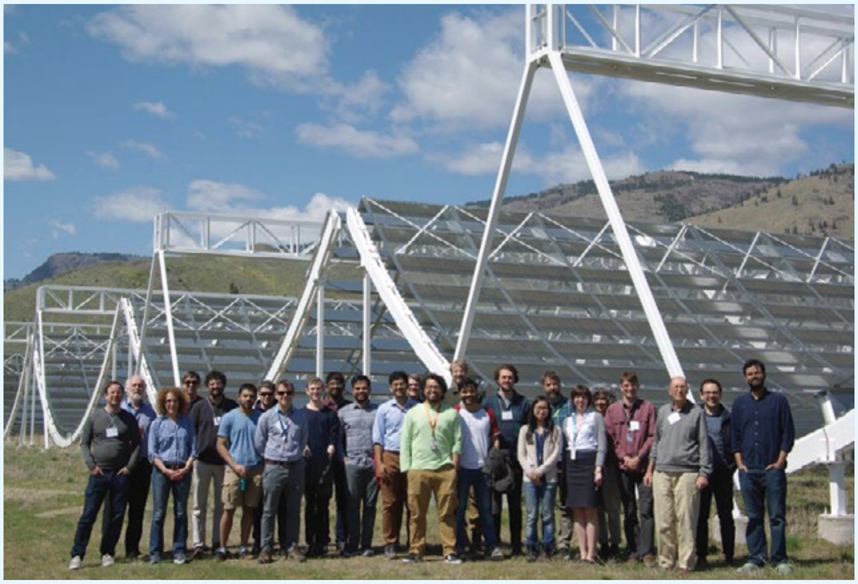
10 Along with the forthcoming XRISM mission in which Canada has previously invested as described in Chapter 6.

11 This facility or mission is awaiting a recommendation from the USA's Astro2020 decadal survey.

CASE STUDY

Unraveling a Cosmic Mystery with CHIME

A Canadian telescope is transforming our understanding of fast radio bursts



In its first two years of operation, CHIME has discovered

1,000+ FRB's

far more than every other telescope on Earth combined

← Deborah Good and Cherry Ng (sixth and eighth from right, respectively) with some of the rest of the CHIME team, in front of the CHIME telescope.

Image credit: Cherry Ng

"Fast radio bursts," or FRBs, are a new astrophysical mystery. FRBs are millisecond bursts of bright radio waves that come from random directions all over the sky, produced by unknown events or objects located hundreds of millions of light years away. FRBs have been a puzzle that has stumped some of the best minds in global astronomy. But a new telescope, the **Canadian Hydrogen Intensity Mapping Experiment**, or **CHIME**, is totally changing the game, and is on track to solve the FRB enigma.

CHIME is a recently constructed radio telescope located near Penticton BC, with an innovative design consisting of four huge half-pipe-like cylinders, and containing no moving parts. CHIME was initially designed to study Dark Energy, but Canadian astronomers subsequently realised that it could at the same time be a superb hunter of FRBs.

CHIME has indeed delivered: in its first two years of operation, it has discovered more than a thousand FRBs (far more than every other telescope on Earth combined), including dozens of FRBs that repeat, and one that even repeats at regular intervals. CHIME is rapidly building up a vast census of the FRB population, and is on track to figure out the origin of these mysterious distant radio flashes.

The search for FRBs on CHIME produces data at an astonishing rate, and a large team is required to process and understand these measurements. On the flip side, CHIME is a small enough project that early-career researchers can make important contributions throughout the lifecycle of the experiment, from planning and building through to observations and interpretation.

Cherry Ng is a postdoctoral researcher at the **University of Toronto**, who started working on CHIME while it was under construction. This gave Ng the unique opportunity both to build the hardware on the Penticton site and to develop the software pipeline to study pulsars and FRBs with CHIME. Ng also led the effort to discover new mode-switching and nulling radio pulsars with CHIME; these objects may hold the key to understanding how pulsars work.

Deborah Good is a PhD student at the **University of British Columbia**. She has worked on the calibration of the CHIME telescope, which is key to converting CHIME's FRB measurements into an estimate of how many FRBs are actually out there in the Universe. Good spent a significant amount of time at the Dominion Radio Astrophysical Observatory helping build CHIME, and considers this experience a formative part of her development as a scientist. Good loves that projects like CHIME allow students to see parts of science like building new instruments that might otherwise be hidden from them, and finds that having a personal connection to the telescope increases her investment in the project's success. Good is now using CHIME to study FRBs and radio pulsars. ◆

How Did the Universe Begin and What Is It Made Of?

How did the cosmos start, and what are its contents? These are questions that humanity has asked for thousands of years. However, only very recently has it become possible to provide scientific answers. Our basic understanding of cosmology, established around 50 years ago, is that the Universe is expanding from an earlier hot, dense state. This single concept can explain many properties of the cosmos, from the cosmic abundance of the elements to the faint relic background radiation that is seen in all directions.

While the basic picture of a "Big Bang" many billions of years ago has remained unchallenged, the situation has become considerably more complex over the last 25 years. We now know that the ordinary matter we can see with telescopes (galaxies, stars, planets, etc) comprises only around 15% of the total mass of the Universe: the rest is invisible "dark matter." Dark matter has dominated the ways in which galaxies and their spatial distribution have formed and evolved over cosmic time, but its nature remains a mystery. If that weren't enough to come to terms with, the Universe isn't even dominated by dark matter, but instead appears to mostly be "dark energy," an as yet unexplained phenomenon that is causing the Universe's expansion to accelerate.

Other mysteries abound. Every inch of the Universe is flooded with tiny particles called neutrinos, but we still don't know how much they weigh, and thus what impact they have on how galaxies and structure formed throughout the cosmos. The Universe is far more smooth and uniform than it should be, which seems to be evidence for a brief period of anomalously rapid expansion right after the Big Bang.

What understanding we do have has been hard-won: it required innovative advances in the technology used to observe the Universe, sophisticated theoretical insights, and supercomputer calculations. Canadian astronomers have played key roles in much of this work, and have helped shape our detailed, albeit puzzling, modern picture of the Universe. As we move into a new decade, Canadian astronomers have exciting plans to address the outstanding questions in cosmology, and to develop a complete picture of our Universe's beginning, history, and ultimate fate. These activities will be based on Canada's strong twin foundations of theory and computing, combined with a set of distinct targeted experiments using a new generation of powerful facilities such as **CHORD**, **CMB-S4**, **LiteBIRD** and **MSE**. Through this approach, we will be able to study vast volumes of the Universe, and to look back to the earliest times in cosmic history.

How Have Stars and Galaxies Changed Over Cosmic Time?

The material Universe is composed of clearly identifiable basic building blocks. Stars are concentrated within galaxies, galaxies aggregate into clusters of galaxies, and galaxy clusters are found at the intersections of vast filamentary structures of dark matter and intergalactic gas. While we have mapped this overall structure in our local neighbourhood, we do not understand how this complicated picture came to be. How did matter interact with gravity and other forces to form the first stars and galaxies? How have galaxies changed over time, and how does this complex history imprint itself on the properties of galaxies we see today? How has the chemical composition of the Universe evolved as gas is converted into stars, dying stars dispersed as gas, and then the gas reconstituted back into stars again? What turns the process of star formation on and off in a galaxy, and why is the birth rate of new stars today so much lower than it was in the distant past?
As we look out into the Universe with our telescopes, we look back in time, although the situation becomes less clear the farther back we go. To understand what we see, these observations must be coupled with simulations of galaxy formation and evolution over huge virtual volumes, performed with some of the world's largest supercomputers. For decades, Canadian astronomers have provided major advances in our understanding through these measurements and calculations. We now plan to apply our technological and scientific leadership to some of the most sophisticated astronomical experiments ever conceived, which will allow us to study smaller and fainter galaxies, over larger volumes, than was ever previously possible. The goal now within reach is to unveil the entire cosmic history of stars and galaxies. This history spans more than 13 billion years, ranging from the formation of the very first luminous objects, to comprehensive studies of the ecology of stars, gas, dust and dark matter within the Milky Way and other nearby galaxies. In the coming decade, Canadian astronomers will combine detailed interlocking data sets from facilities such as **ALMA**, **CASTOR**, **SKA1** and **a cooled infrared space telescope** with state-of-the-art theory and modelling to explain what we see around us in the Universe, and how it came to be.

We now sit at an exciting frontier, in which powerful facilities and calculations will have the capability to unveil some of the Universe's most closely held secrets.

What Are the Extreme Conditions of the Universe?

The Universe offers extremes of space, time, mass, density, energy and temperature all completely beyond our everyday conceptions. The cosmos thereby allows us to push the limits of our physical understanding in ways we could never hope to approach in an Earth-based laboratory. Many exotic astronomical phenomena can now be used to test theories of fundamental physics and to study stellar evolution, and as precision probes of a huge range of astrophysical processes.

The Universe's extremes also push the limits of our techniques and our technology. The remarkable first images of a black hole's event horizon required synchronised observations from telescopes all over the planet, from Antarctica to Hawaiʻi. The data flows needed to find sudden bursts of radio waves all over the sky are equivalent to 10% of the data rate of all the world's cell phones combined. And the ongoing search for the gravitational vibrations produced by distant merging supermassive black holes requires us to measure changes in stellar distances to a precision of one part in 100 trillion. Canadians have been at the forefront of these projects and other research on the extreme Universe, and are leaders in the associated technology development and supercomputing.

We now sit at an exciting frontier, in which powerful facilities and calculations will have the capability to unveil some of the Universe's most closely held secrets. What do supermassive black holes look like, and how did they form? What extreme processes produce gravitational radiation? Is gravity completely described by Einstein's theories, or is there a better model? What violent and exotic processes cause millions of extraordinarily intense flashes, flares and explosions to occur across the sky every night? And what do all of these extreme processes tell us about the fundamental structure of matter, space and time? By using the powerful capabilities of observatories and programs like **Gemini**, **LSST**, **ngVLA** and **XRISM**, along with the calculations and computations needed to interpret this tsunami of data, Canadian astronomers will play a leading role in understanding the physical limits of the Universe.

In only
25 years
since the discovery of “exoplanets” orbiting other Sun-like stars, astronomers have now confirmed
3,000+
planetary systems
throughout the Milky Way

Why Are Planetary Systems So Diverse and Could Other Planets Host Life?

One of the most exciting frontiers in science is the study of other solar systems. It has been only 25 years since the discovery of “exoplanets” orbiting other Sun-like stars, and in that time astronomers have now confirmed more than 3,000 planetary systems throughout the Milky Way. In principle, these discoveries should cast light on the origin of our own planet, and on how life on Earth might have begun. However, most discovered exoplanets look nothing like our own solar system: there are planets orbiting double stars, worlds covered in planetary oceans hundreds of kilometres deep, “super Earths” that might be rocky and habitable but with gravity much stronger than our home planet, and huge gas giants that orbit their parent stars every few days. Canadians have developed new ways of finding these faint, distant worlds, and have made groundbreaking studies of their orbits and atmospheres.

This diversity of planets and its contrast with our own solar system was not anticipated, nor is it yet fully understood. Despite so many discoveries, this field is still in its infancy. How do planets form? Are there any other solar systems that resemble our own? How many Earth-like planets are there in the Milky Way Galaxy? And do any of these many thousands of exoplanets harbour life? These are some of the fundamental questions astronomers now aim to address over the next decade, using new knowledge, expertise and tools.

The key first step to understanding how planets form and evolve is to measure the composition of exoplanets and their atmospheres: this will be a core focus for Canadian astronomy over the next decade. These studies must be accompanied by observations of the “protoplanetary” disks of gas and dust that surround newly-formed stars. Such disks will become future planetary systems, and their different evolutionary paths are what lead directly to the huge diversity in exoplanet properties observed around older stars. Accompanying theoretical modelling and computational simulations of protoplanetary disks, planet formation and exoplanet atmospheres will be essential to interpret new observations and advance our understanding.

The coming decade will also see the first attempts at establishing whether or not life exists elsewhere in the Universe. Travel to or even creating pictures of exoplanets is beyond our technological capabilities for the foreseeable future, due to the great distances of exoplanets from Earth and their relatively small sizes. The most likely evidence for life will therefore be specific signatures of biological activity in the chemical composition of exoplanet atmospheres. Canadians are positioned to lead the effort to find the rocky Earth-like planets thought most suitable for hosting life, and then to make the precision atmospheric studies needed to answer one of the most important questions ever asked: Are we alone?

All these experiments will be exceedingly difficult, and will require a new generation of groundbreaking instruments, largely built by Canadians, deployed on facilities such as **CFHT**, **JWST**, **POEP** and **a very large optical telescope**. Driven by sophisticated computational predictions and coordinated with advanced theoretical interpretation, the foundations are now in place for Canadians to play a central role in the burgeoning exploration of exoplanetary systems, and in the accompanying search for life in the Universe.

Chapter 5

In the 21st century, answers to fundamental questions in astronomy and cosmology require not just traditional observations or calculations, but also enormous data sets and large-scale computational simulations.

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Thor's Helmet Nebula (NGC 2359)

Image credit: Canada-France-Hawaii Telescope / Coelum

Recommendations on Facilities, Projects and Resources

In this Chapter, we present priorities and recommendations for Canadian astronomy over the next decade. These include key overarching recommendations for the entire field, as well as specific recommendations in the areas of theoretical astrophysics, digital research infrastructure, instrumentation development, and observational facilities;[12] a summary of the corresponding funding requirements is provided in Table 5.1. These combined initiatives represent a vision for a flourishing and successful astronomical community that will have access to dramatic new capabilities across theory, experiment and observation, and which will sit at the forefront of knowledge and discovery.

The priorities we recommend in this report will deliver:

- **Powerful new observational facilities on the ground and in space;**
- **High-capacity computation facilities for both theory and data processing;**
- **The human capital and technological capacity needed to exploit these facilities and to thereby make fundamental advances across astronomy as summarized in Chapter 4;**
- **Multiple international leadership positions for Canadian astronomers; and**
- **Inclusive and respectful relationships within our professional community and within local, national and international communities impacted by our work.**

Implementation of these recommendations will be overseen by the long range plan implementation committee (LRPIC) of the Canadian Astronomical Society (CASCA). The status of these recommendations plus proposed updates or changes will be considered in a Mid-Term Review (MTR) to take place around 2025.

12 Further detailed discussion on theoretical, computational and observational priorities is provided in Chapter 6, while a wider set of recommendations on funding, governance, and the role of astronomy in Canadian society are discussed in Chapter 7.

Table 5.1: Recommended Canadian investments in theoretical astrophysics, digital research infrastructure, instrumentation development, and observational facilities over the period 2021–2030. Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change. For further details, see the full discussion around each recommendation in Chapter 6 or Chapter 7.

Recommended Investments In Theoretical Astrophysics

Program	Anticipated Cost to Canada	Relevant Timescale
CITA: Support of fully funded postdoctoral fellowships in theoretical astrophysics based outside the University of Toronto	~40% of CITA NSERC grant	2020: Analysis by CITA 2021: Enact for 2021 competition
CITA: Salaries for all CITA Fellows, CITA National Fellows and Canada Fellows at national/international standard for prize fellowships	~$0.2M per year	2020: Dialogue with NSERC 2021: Submission of CITA renewal proposal 2022–: New funding

Recommended Investments In Digital Research Infrastructure

Program	Anticipated Cost to Canada	Relevant Timescale
NDRIO support for general astronomy supercomputing	Across all disciplines: $375M initial investment plus $50M/year	2021–2030
SKA1 processing, storage and data transport	See "SKA1 Regional centre" below	

Recommended Investments In NRC-University Partnerships

Program	Anticipated Cost to Canada	Relevant Timescale
NRC in-kind support for CFI initiatives	Current levels or above	Commencing in 2021
Scientific and operational personnel support for mid-scale facilities	$1M per year	
Support for instrumentation laboratories	TBA	

Recommended Ground-Based Facilities: Large (>$30M) Investments In Near-Term Projects

Priority	Project	Anticipated Cost to Canada (New Construction/Operations)	Estimated Operational Date
1	**VLOT (TMT)**[13]	TBD[14] / US$7M[15] per year	2033 or later
2	**SKA1**	Observatory: $80M[16] / $8M[17] per year SKA1 Regional centre: $65M[18] (construction plus ops)	2026 (science verification)

13 At the time of writing, Canadian access to a very large optical telescope is best implemented by continued participation in TMT, sited either at Maunakea in Hawai'i or Observatorio del Roque de los Muchachos in the Canary Islands.

14 In 2015, the Canadian government committed $243.5M for specific TMT activities, including NFIRAOS and enclosure construction. Any additional construction costs are not yet determined.

15 The annual operations cost for TMT constructed on Maunakea vs TMT constructed on Observatorio del Roque de los Muchachos are similar to within a few percent.

16 In 2017-dollars.

17 Average annual cost in 2017-dollars for 2021-2030 during the SKA1 construction phase, with costs ramping up towards the end of the decade.

18 Cost for a Canadian SKA1 Regional Centre over 2021-2030 in 2017-dollars, including processing, storage, networking, and staffing costs.

Table 5.1 (Continued)

Recommended Ground-Based Facilities: Large (>$30M) Investments In Future Projects (Unranked)			
Project (alphabetical)		**Anticipated Cost to Canada (New Construction/Operations)**	**Estimated Operational Date**
MSE		$110M[19] / $7M[19] per year	2031
ngVLA		US$130M[19] / US$6M[19] per year	2028 (early science)
Recommended Ground-Based Facilities: Continued Mid-Scale ($5M-$30M) Investments In Current Facilities			
Priority	**Project**	**Anticipated Cost to Canada (Ongoing Operations)**	**Operational Since**
1	ALMA	US$1.8M[20] per year	2011
2	Gemini	US$6.0M[20] per year	1999-2000
3	CFHT	US$4.0M[20] per year	1979
Recommended Ground-Based Facilities: New Mid-Scale ($5M-$30M) Investments In Future Facilities			
Priority	**Project**	**Anticipated Cost to Canada (New Construction/Operations)**	**Estimated Operational Date**
1	CHORD	$23M / $0.6M per year	2023
2	CMB-S4 or comparable facility	$4M-$7M / $0.5M per year	2026
3	LSST	- / $3M per year (in kind)[21]	2023

19 In 2018-dollars.

20 Canadian contribution in calendar year 2020.

21 LSST is not accepting cash funds from its partners to cover operations. The amount listed is the cost of in-kind Canadian contributions to LSST operations.

Table 5.1 (Continued)

Recommended Space Astronomy Missions: Very Large (>$100M) Investments

Priority	Mission	Anticipated Cost to Canada[22]	Estimated Launch Time Scale[23]
1	CASTOR	$250M-$400M	Late-2020s
2	NASA Flagships[24] (Hardware, Science, Technical)	~$100M	Mid-2030s

Recommended Space Astronomy Missions: Large ($25M-$100M) Investments

Priority	Mission	Anticipated Cost to Canada[22]	Estimated Launch Time Scale[23]
1	LiteBIRD	$25M-$40M	Late-2020s
2	Cooled infrared space telescope	TBD	TBD

Recommended Space Astronomy Missions: Other (<$25M) Investments

Priority	Mission	Anticipated Cost to Canada[22]	Estimated Launch Time Scale[23]
1	JWST operations	$2.4M per year[25]	Late 2021
2	POEP	$15M[26]	Mid-2020s
3	NASA Flagships (Science, Technical only)	TBD	Mid-2030s

22 Costs are estimates provided by each mission's Canadian principal investigator, and represent approximate total life-cycle costs (i.e., development, construction, launch, operations and science).

23 With the exception of JWST, these are estimates provided by each mission's Canadian principal investigator.

24 A hardware contribution to a NASA Flagship mission should be regarded overall as a lower priority than investing in LiteBIRD at the recommended levels.

25 Support for the operations phase over the nominal JWST mission lifetime of five years; does not include costs incurred so far.

26 This does not include launch, which is expected to be a small increment on the total cost.

Recommendation on Selecting the Locations of Astronomy Facilities and Infrastructure

We recommend that the Canadian astronomical community (e.g., ACURA, CASCA and NRC-HAA) work together with Indigenous representatives and other relevant communities to develop and adopt a comprehensive set of guiding principles for the locations of astronomy facilities and associated infrastructure[27] in which Canada participates. These principles should be centred on consent from the Indigenous Peoples and traditional title holders who would be affected by any astronomy project. In addition, when such consent does not exist, the principles should recognize that the use or threat of force is an unacceptable avenue for developing or accessing an astronomical site. The principles should also acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime. These principles should be developed as soon as possible, and then applied to *all* future Canadian participation in new or existing astronomical programs, projects and national and international facilities. Engagement and implementation should be consistent with the spirit of the Calls to Action of the Truth and Reconciliation Commission of Canada and of the United Nations Declaration on the Rights of Indigenous Peoples.

Recommendation on Coordination of Funding Agencies

We recommend that the leadership of agencies which fund or otherwise support astronomical research (NRC, CSA, CFI, NSERC, NDRIO, CIFAR) coordinate efforts through regular meetings. Involving ACURA and/or LRPIC in such meetings could further improve coordination efforts.

Recommendations on Theoretical Astrophysics

Theoretical astrophysics is an essential part of modern astrophysics. Canada has a long and successful history in theoretical astrophysics, and has built a critical mass of world-leading theorists who study phenomena across the Universe. Support for theory should come from a variety of sources, including as part of the operational scientific support provided by the Canadian Space Agency (CSA) and National Research Council of Canada (NRC), for Canada's space-based and ground-based astronomical facilities, respectively. The recommendations below are targeted toward the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto and its accompanying national program. As CITA now moves into its fifth decade, the CITA footprint is envisioned to grow and decentralize, so that it can play a greater role in enhancing the national theoretical astrophysics profile on the world scene.

We recommend that CITA strengthen its national role by committing ~40% of its annual NSERC funding to postdoctoral fellowships based outside the University of Toronto. These positions should be fully funded by CITA, without any host contributions allowed or required, and with a limit on the number of National/Canada Fellows per institution, in analogy with the NASA Hubble Fellowship program. The University of Toronto should remain ineligible to host CITA National Fellowships or the first half of Canada Fellowships, as is presently the case.

We recommend that CITA offer salaries and research allowances for CITA Fellows, Canada Fellows, and CITA National Fellows at identical levels and durations. We further recommend that the remuneration should be competitive with commensurate national and international prize fellowships, with the goal of attracting and retaining the world's best early-career theorists.

We recommend that CITA seek an expansion of its postdoctoral program in its next funding proposal to NSERC. Additional funding should be used to prioritize the two recommendations above before increasing the overall number of fellowship positions supported.

We recommend that CITA increase its focus on training for students and postdoctoral fellows and on organizing theory-focused meetings, in coordination with the Perimeter Institute and the broader theory community.

We recommend that CITA and CASCA work together to recognize the role of theoretical astrophysics by establishing and awarding national prizes in this field.

Recommendations on Digital Research Infrastructure

In the 21st century, answers to fundamental questions in astronomy and cosmology require not just traditional observations or calculations, but also enormous data sets and large-scale computational simulations. Many theoretical programs require enormous computing resources, both to perform simulations or calculations and then to store and analyze the output. Several of the future observational facilities and programs recommended in this chapter will produce petabyte-scale data products, which then need to be distributed electronically to the community and also archived in perpetuity. To maintain Canadian

27 Astronomy projects not only require telescopes and observatories, but also need support facilities, headquarters, project offices, instrumentation laboratories, integration and test facilities, computing and processing centres, etc.

leadership in astronomy, substantially increased access to large-scale high-performance computing is required. The shared computing resources currently available in Canada cannot meet the needs of Canadian astronomy in the next decade. Continuous investment in research computing in Canada can accommodate such requirements, but the planning and investment cycle must begin immediately.

We recommend that Canada maintain its commitment to digital research infrastructure outlined in Budget 2018, through an initial investment of $375M plus an ongoing expenditure of $50M per year over the next decade. This major investment in Canada's New Digital Research Infrastructure Organization (NDRIO) is needed to revitalize and then sustain Canada's research capabilities across all disciplines.

We recommend that CASCA and ACURA work to ensure that NDRIO meets the unique computational resource requirements of theoretical and observational astrophysics, which we estimate as 100 petaflop-years each of CPU and GPU calculations and 75 PB of online storage by 2025. CASCA's Computation and Data Committee should monitor developments within NDRIO and should vigorously represent the interests of astronomy researchers through NDRIO's Researcher Council and other governance and advisory structures.

We recommend that NRC's Canadian Astronomy Data Centre (CADC) continue to receive strong support, both as a provider of astronomy-specific service layers that use NDRIO infrastructure, and as a coordinator of long-term archiving of digital data products for astronomy.

Recommendations on NRC-University Partnerships

Access to the world's forefront observatories is essential for any healthy astronomy community. In Canada, the Herzberg Astronomy and Astrophysics Research Centre (HAA) at the National Research Council of Canada (NRC) has the mandate and responsibility to facilitate this access. However, there are several shortfalls that prevent Canada from maximizing its investments in astronomy infrastructure. These include the lack of a national process for allocating NRC funding contributions to the construction of university-led mid-scale initiatives, the need for operational support for these mid-scale facilities, and the inherent difficulty of maintaining a stable core of expertise in university-based instrumentation programs. These shortcomings can be addressed through new partnership programs between NRC and Canadian universities. ACURA should take the lead advocating for any new federal funding required, potentially through an increased funding envelope for HAA.

We recommend that HAA and the university community obtain an additional ~$1M/year for Canadian astronomy, in order to appoint early-career STEM personnel who can provide direct scientific and operational support for Canada's investments in mid-scale astronomical facilities and infrastructure.

We recommend that HAA implement a national process for committing significant[28] in-kind contributions to CFI initiatives proposed by astronomers from Canadian universities. These investments can help ensure that the Canadian astronomy community will have broad access to a coherent and effective array of capabilities.

We recommend that HAA and Canadian universities form partnerships to enhance the capabilities of university-based experimental astrophysics laboratories through additional funding, shared personnel, and coordinated infrastructure investments. These partnerships will enable high-risk, high-reward innovations, and will provide the continuity and availability of experts that are essential for successful participation in leading-edge astronomical facilities.

Recommendations on Observational Facilities

Canadian astronomy's strong record of success has come from our involvement in facilities with a broad range of project sizes, time scales, and science areas. No single telescope or program can answer the wide range of scientific questions set out in Chapter 4. To make fundamental discoveries and to provide outstanding training opportunities, Canadian astronomy will require investment and participation in telescopes and experiments both on the ground and in space, covering a range of wavelengths, technologies and science programs. We correspondingly recommend below a set of facilities that provide the full set of capabilities needed to explore the cosmos. These facilities provide Canadian leadership or substantial involvement across all wavelengths, using telescopes that have unique and distinct technical capabilities.

The recommendations below are based on a set of pre-defined criteria announced at the initiation of the Long Range Planning process. Scientific excellence is the first and most fundamental criterion: recommended initiatives must enable fundamental or transformational advances in our understanding of the Universe. An additional overall criterion is that the sum of the recommendations should provide a set of facilities and programs that reflects the strengths and breadth of Canadian astronomy, with a range

28 "Significant" should be defined in consultation with the HAA Advisory Board, in the context of HAA's resources and other obligations.

of project sizes, time scales, science areas and degrees of Canadian participation, offering strong prospects for training of Canadian highly-qualified personnel (HQP), and providing specific tangible benefits to Canadians.

Optical/infrared/ultraviolet astronomy and radio/millimetre/submillimetre astronomy are the two broad pillars that have historically underpinned much of Canadian observational astrophysics. A key component of a world-class Canadian astronomy program is strength across both these spheres. Throughout the coming decade, we also anticipate that Canadians will contribute to and participate in major programs at X-ray and gamma-ray wavelengths, and across multi-messenger astrophysics and astroparticle physics.[29]

For **optical/infrared/ultraviolet astronomy**, Canada needs capabilities in both imaging and spectroscopy, and needs telescopes whose observations are both “wide” (able to cover large areas of the sky) and “deep” (able to study very faint objects). There also needs to be a pathway from surveys, which perform large censuses and uncover entire new populations of objects, to targeted individual observations, which study specific stars, galaxies and other phenomena in detail. Our recommended set of facilities provide all these capabilities:

Broad surveys: The **CASTOR** space mission will provide a hundredfold improvement in survey speed over the Hubble Space Telescope, and will consequently allow Canadian astronomers to perform spectacular new studies of a huge range of cosmic phenomena ranging from exoplanets to cosmology. We also recommend that Canada participate in **CFHT**, **LSST** and **MSE**; the major new survey capabilities of these three facilities, covering both imaging and spectroscopy, are needed to address a variety of additional pressing science questions set out in Chapter 4.

Targeted studies: In order to be able to study the faintest and most distant objects in the Universe, it is vital that Canada obtain a substantial share of a **very large optical telescope**. Other powerful capabilities for performing detailed studies of individual objects and populations will be provided by **Gemini**, **POEP** and **a cooled infrared space telescope**, each of which offers a unique combination of observing modes, instruments and wavelength coverage aimed at filling major gaps in our understanding of the Universe.

At **radio/millimetre/submillimetre wavelengths**, facilities fall broadly into the categories of observatories (typically open to competitive proposals from the community, covering many different programs and observing modes of a variety of sizes), and experiments (facilities dedicated to obtaining one main measurement or data set, often centred on cosmology). Canada has had outstanding success at both approaches, in the last ten years most notably through ALMA (an observatory) and CHIME (an experiment). For the coming decade, we recommend that Canada maintain its strong portfolio of both observatories and experiments, and that the Canadian community also pursue hybrid opportunities that exploit the strengths of both approaches:

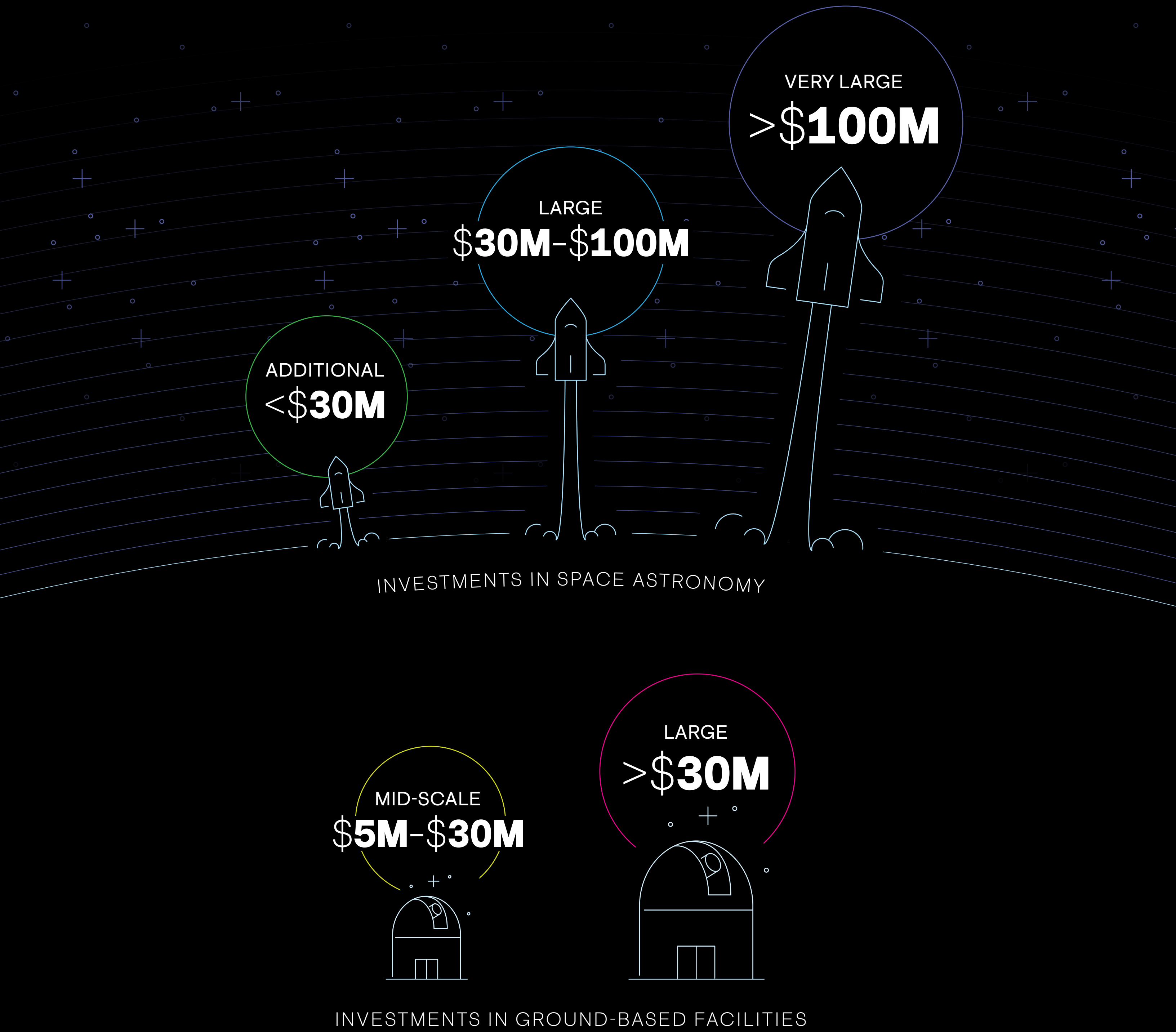
Observatories: **SKA1** will be a global radio observatory that will position Canadian astronomers to answer a range of fundamental questions about the origins, structure and evolution of the Universe by virtue of its wide field of view and powerful survey capabilities. The **ngVLA** and **ALMA** arrays will be powerful complements to SKA1, focusing on phenomena that can only be understood by observing at higher frequencies (~1–100 gigahertz for ngVLA and ~100–1,000 gigahertz for ALMA) and with higher angular resolution. On Canadian soil, **CHORD** will build on the heritage of CHIME and will similarly perform dedicated commensal experiments on cosmology and fast radio bursts, but will operate in a national facility mode that will allow a wide range of users and the development of new science programs.

Experiments: Canada is positioned to maintain its world leadership in studies of the cosmic microwave background through substantial participation in both **CMB-S4** or a comparable facility on the ground and the **LiteBIRD** mission in space. These two experiments target the cosmic microwave background in distinct ways (deep observations for CMB-S4 and all-sky coverage for LiteBIRD), allowing us to fully exploit this relic radiation for understanding the origins, history and current contents of the Universe.

Virtually all the programs envisaged for these facilities will have intensive needs for theoretical analysis and computational processing, as recommended earlier in this Chapter. Furthermore, while many measurements will rely on the unique capabilities of one particular facility, there are also many questions that can only be answered by the combination of data from two or more different telescopes. Finally, we emphasize the very large breadth of astrophysics research in Canada: in addition to the core facilities prioritized below, Canadian astronomers will continue to have access to and make use of many other current and upcoming telescopes, as described in Chapters 3 and 6, respectively.

29 In the prioritizations below, we note NASA’s Lynx X-ray Observatory as a possibility for significant Canadian investment. Other opportunities for X-ray astronomy are discussed in Chapter 6, while LRP2020 white papers W024, W031, W034, W036, W041 and W042 provide further details on Canadian ambitions in high-energy and multi-messenger astrophysics.

Recommendation funding categories for observational facilities:



We separate our recommendations on observational facilities into distinct categories:

- **Large (>$30M) investments in ground-based facilities**
- **Mid-scale ($5M–$30M) investments in ground-based facilities**
- **Very large (>$100M) investments in space astronomy**
- **Large ($30M–$100M) investments in space astronomy**
- **Additional (<$30M) investments in space astronomy**

This division does not reflect any preferences or scientific distinctions. In particular, the ambitious science program that Canadian astronomers envisage will require many different types of astronomy infrastructure. In particular, the astronomy portfolio for the next decade cannot consist solely of the very largest telescopes, but requires substantive investments in facilities across a range of sizes and budgets.

The above categorization also recognizes that the processes for obtaining funding for ground-based and space-based projects are distinct, and that investments at different levels tend to be requested and allocated in different ways. Specifically:

- Large ground-based facilities are typically funded by direct requests to the Government of Canada and then are subsequently managed by the National Research Council (which has a parliamentary mandate to operate and administer any astronomical observatories established or maintained by the Government of Canada);
- Mid-scale ground-based facilities are usually funded by some combination of the Canada Foundation for Innovation (which is the main source of funding for university-led infrastructure projects in Canadian astronomy, along with associated matching funds from provincial agencies and other sources) and the National Research Council;
- Space astronomy missions and associated activities are normally funded by the Canadian Space Agency, with possible additional contributions from the Canada Foundation for Innovation. As with large ground-based facilities, large and very large space astronomy missions must currently be funded by direct requests to the Government of Canada and then are subsequently managed by the CSA.

Finally, it is important to recognize that there is a wide variation in the time scales for different astronomy projects: a long-term vision for Canadian astronomy must incorporate the fact that some telescopes will not begin taking data until the 2030s, but require imminent Canadian commitments in order to secure future access and leadership.

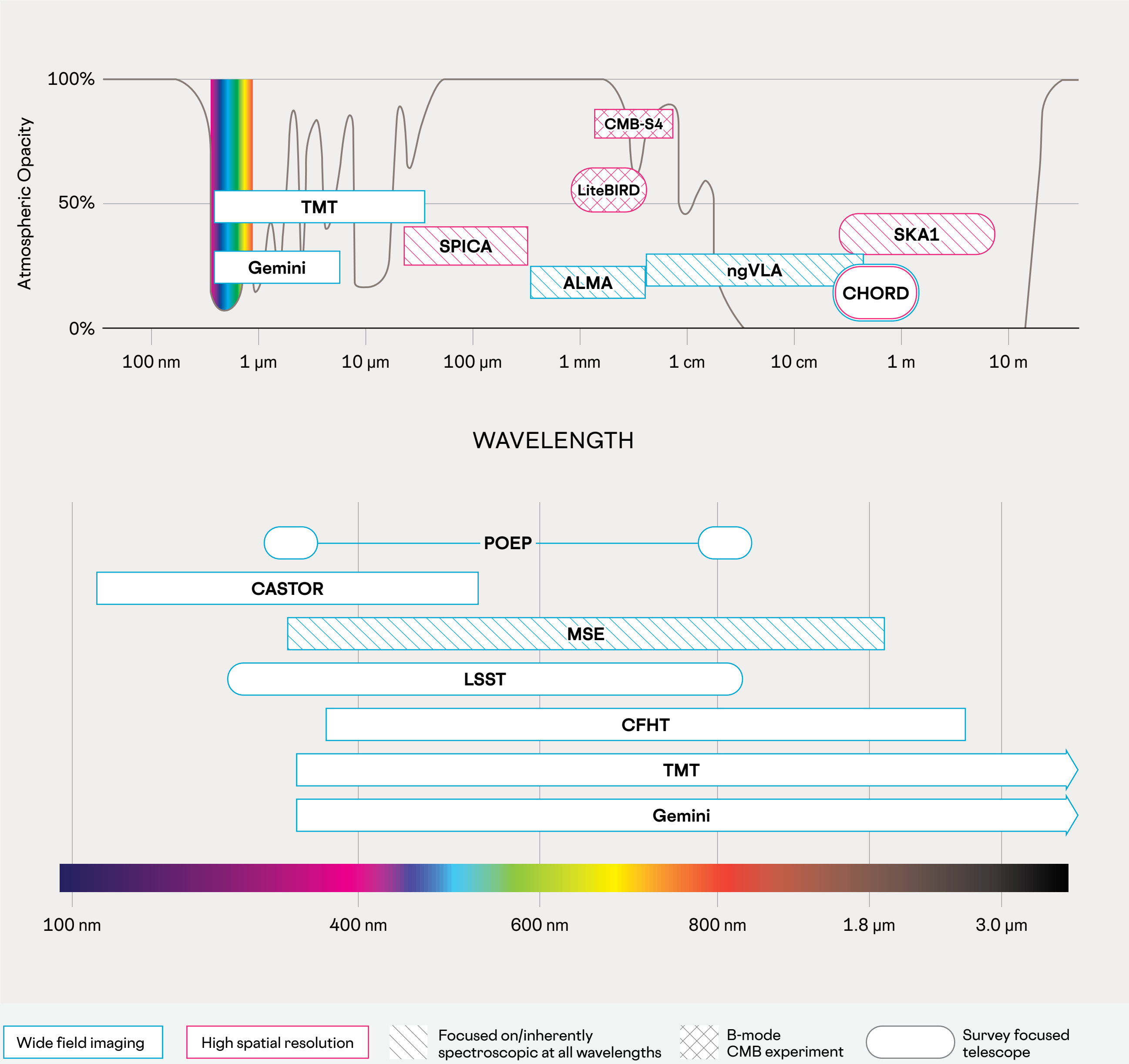
Modern astronomy projects involve complex interactions with government, industry, local land-owners and international partners, and so it is possible that not every recommendation below will be realized. Recognizing this, we have proposed a diverse and broad portfolio whose science and leadership capabilities will remain robust and compelling should there be any individual shortfalls. Forecasting the various landscapes in which contingency strategies might be needed is outside the scope of this report; CASCA's Long Range Plan Implementation Committee (LRPIC) will have a vital role in recommending alternatives and revised priorities if such situations occur.

Recommended Large (>$30M) Investments in Ground-Based Facilities

Success and leadership for Canadian astronomy require that our community be able to access the world's largest observatories and facilities. We recommend large Canadian investments in four ground-based telescopes. These facilities are all global projects: access will be shared between many countries and consortia, and it is critical that Canadian involvement in these facilities be at a level sufficient to influence scientific and technical decisions. Each of these facilities will excel in multiple science areas highlighted in Chapter 4, and will have a large user base comprising a significant fraction of the Canadian astronomy community.

Our top recommendations are for two well-developed projects that were also the highest priorities in LRP2010, and are now expected to move forward in the next 2–3 years: a **very large optical telescope** (ranked first), and **SKA1** (ranked second). We make additional unranked recommendations for **MSE** and the **ngVLA**: these two projects represent compelling future opportunities for Canada, which should be explicitly ranked once they have been fully developed.

Wavelength coverage and other capabilities of recommended facilities:



Ranked recommendations for near-term large projects:

1. VLOT: We recommend that Canada participate in a very large optical telescope (VLOT)[30], and that this participation be at a level that provides compelling opportunities for Canadian leadership in science, technology and instrumentation. Canadian access to and participation in a VLOT remains the community's highest ground-based priority; NRC, CASCA and ACURA must ensure that Canada's share in a VLOT remains at the level needed to fulfil the community's ambitions and requirements for scientific discovery, and to maintain a leadership role in facility governance and overall science and technology development. Canada has been a significant partner in the Thirty Meter Telescope (TMT) project since 2003 and has a clear scientific and technical leadership role enabled by funding and support from the federal government and NRC. Noting that the situation is complex and rapidly evolving, at the time of writing Canadian VLOT access is best implemented by continued participation in TMT, either at the currently proposed Maunakea site or at the scientifically acceptable alternative of Observatorio del Roque de los Muchachos. Canadian participation in TMT or in any other VLOT should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed site from Indigenous Peoples and traditional title holders.

We recommend that the Canadian community maintain its leadership and expertise in VLOT instrumentation development, which will ensure access to instruments that meet the needs of the community.

We recommend that NRC address any lack of access to a VLOT due to delays in TMT construction through arrangements that give Canadians access to other VLOT facilities.

2. SKA1: We recommend that Canada participate in the construction and operation of Phase 1 of the Square Kilometre Array (SKA1), in its network of regional centres, and in the project's governance. This will allow Canada to play a world-leading role in a number of transformational projects to be carried out with SKA1. The scientific goals of SKA1 align well with the strengths of Canadian researchers, and scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the past twenty years. Canada's highest priority for radio astronomy should be to fund and participate in SKA1 Design Baseline construction, operations, the accompanying network of regional centres and a staged technology development program at an overall 6% level, commensurate with Canadian scientific ambitions. We emphasize that developing the relevant infrastructure, incorporating the capabilities of a Canadian SKA1 regional centre or equivalent, is necessary for successful Canadian participation in SKA1, and will ensure community access to the processing, storage and user support required to scientifically exploit SKA1. Canada should identify a membership model for Canadian participation in the SKA Intergovernmental Organisation that can provide leadership rights for Canadian researchers and industry, with full scientific access and maximal opportunities for technological tender and procurement. Canadian participation in SKA1 should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of SKA1 sites from Indigenous Peoples and traditional title holders.

Unranked recommendations for future large projects:

MSE: We recommend that Canada play a leading and substantive role in a next-generation widefield spectroscopic survey facility. Meaningful Canadian participation should be at a level of at least 20%, which will also ensure a prominent Canadian role in driving and participating in the VLOT science that will be enabled by such a facility. The best option at present is to pursue the development, design and construction of the Maunakea Spectroscopic Explorer (MSE) at the current CFHT site on Maunakea; this offers a compelling and timely science case with significant history of and potential for Canadian leadership. Should it not prove possible to transition CFHT into MSE, we recommend that Canada play a substantive leadership role in developing the MSE concept at a different site.

We recommend that the MSE project build on its mature science case and well-developed design, and now undertake essential future steps on the path toward construction. These include obtaining consent from Indigenous Peoples and traditional title holders for the use of any sites needed for the MSE project, and establishing the governance structure and funding model needed to effectively advance this exciting project.

30 A VLOT is an optical/infrared telescope with a mirror of effective diameter ~30 metres.

ngVLA: We recommend that Canada pursue technical contributions to and scientific leadership in the proposed Next Generation Very Large Array (ngVLA), pending a positive recommendation on this project from the US Astro2020 Decadal Survey. The capabilities provided by the ngVLA will enable transformational science across many areas of astrophysics. Canada should correspondingly seek engagement with ngVLA that would result in a ~6% share of observing time, comparable with the access sought for SKA1. Canadian participation in ngVLA should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any ngVLA sites from Indigenous Peoples and traditional title holders.

We recommend that Canada focus its technical contributions to ngVLA on areas that leverage existing or ongoing Canadian work on SKA1 and other facilities. We also encourage exploration of the proposed scientific alliance between SKA1 and ngVLA, which would allow an exchange of observing time between the two facilities.

Recommended Mid-Scale ($5M–$30M) Investments in Ground-Based Facilities

We consider two types of mid-scale investment. First, Canada needs to continue reaping the benefit of **current facilities** in which we have made large previous investments. Continuing commitment is needed to retain access to these facilities, to upgrade these telescopes with new instruments and technologies, and to sustain our international competitiveness. Below we recommend that Canada continue to invest in **ALMA**, **Gemini** and **CFHT.**

Second, Canada should make new mid-scale investments in **future facilities**, both by constructing our own mid-scale telescopes, and by participating in new large international projects. The former provide targeted opportunities for novel science and serve as pathfinders for future large programs, while the latter allow us to make key focused contributions to some of the world's most powerful new observatories. Below we recommend that Canada construct the **CHORD** facility as a next-generation "made in Canada" successor to CHIME, and that we contribute to and participate in the upcoming **CMB-S4** (or comparable facility) and **LSST** projects.

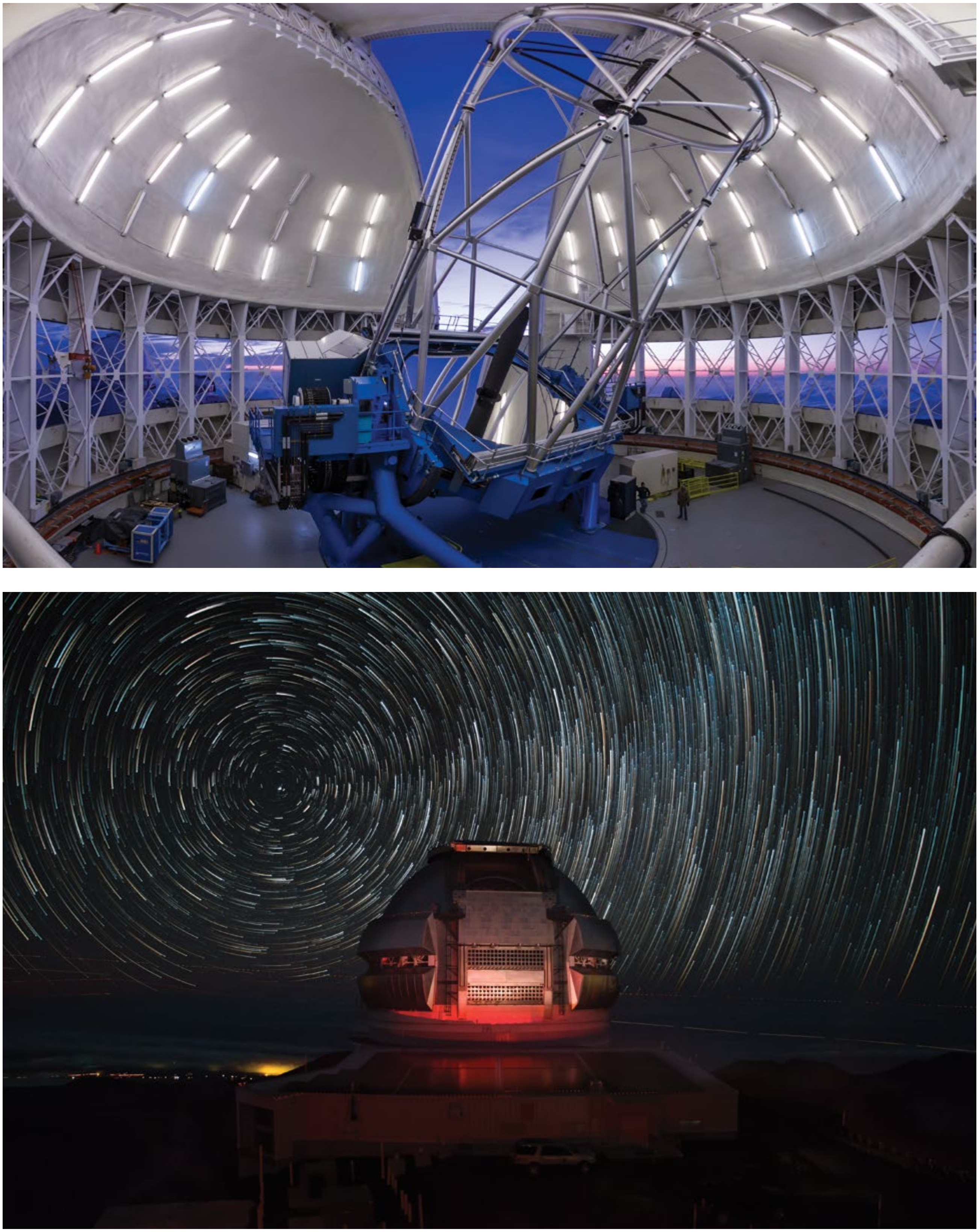
We recommend the following current and future facilities, separately ranked by priority in each category. All six projects substantially advance Canadian astronomy's needs and opportunities.

Recommendations for continued mid-scale investments in current facilities:

1. ALMA: We recommend that Canada continue to fund the Atacama Large Millimeter/submillimeter Array (ALMA) at the amount needed to maintain our current level of access, that the Canadian community identify components of future ALMA development in which we can play a role, that Canadians continue to seek leadership of ALMA large programs, and that we keep Canadians fully trained and engaged in ALMA as new capabilities become available. ALMA is an unquestioned success story, and has become a world-leading scientific facility that has had significant Canadian uptake, benefit, and output. ALMA remains the key facility for answering many frontier scientific questions. In the 2030s and beyond, there will be many exciting options for ALMA upgrades and expansions, which are likely to be considerations for future mid-term reviews and long-range plans. Canadian participation in ALMA should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

2. Gemini: We recommend that Canada remain an active participant in the Gemini Observatory over the next decade. Gemini continues to be a foundational component of Canadian observational capabilities, plays a key role in training and instrumentation development, and enables research across an incredibly wide range of science topics. Substantial recent investments and new instrumentation make it an exciting time for Canada to be a Gemini partner, and should lead to increased productivity, impact and oversubscription rates. The Gemini Observatory will be a key part of Canada's observational capabilities in the era of 30-metre telescopes. Gemini will be an important testbed for future instrumentation and will offer capabilities not offered by 30 metre-class telescopes until well into the 2030s.

We encourage broad community consultation leading up to the next Gemini assessment point in 2024 on what specific share of Gemini is appropriate for Canada in the next Gemini International Agreement, and on how the negotiation of the Maunakea master lease will affect the status of Gemini North. Canadian participation in Gemini should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.



Gemini Observatory: Gemini North sunset mirror panorama (top); Maunakea star trails over Gemini North's photo voltaic panels (bottom).

Image credits: Gemini Observatory/AURA/Joy Pollard

3. CFHT: We recommend continued Canadian participation in the Canada-France-Hawaii Telescope (CFHT) at least until the ongoing Large Programs are complete. During this period, Canada should work with the other CFHT partners to maximize unique high-impact science while reducing costs, for example by reducing the instrument complement or by further prioritizing Large Programs. Once the ongoing Large Programs are complete, Canadian involvement in CFHT will depend on whether CFHT transitions into MSE. Should MSE go ahead at the CFHT site, we recommend that Canada, its CFHT partners, and other relevant stakeholders plan for a future that involves moving SPIRou to another telescope, as this new instrument has the capability to provide high-impact science for at least a decade. Should CFHT not transition into MSE, we recommend that the Canadian astronomy community decide what approach will provide optimal access to northern wide-field capabilities in the optical, ultraviolet and near-infrared, which may mean leaving the CFHT partnership in order to pursue other opportunities (participation in Subaru is one possibility; see the section on Subaru in Chapter 6). Canadian participation in CFHT should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

Recommendations for new mid-scale investments in future facilities:

1. CHORD: We recommend funding and implementation of the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD). CHORD is a unique facility that leverages existing Canadian world scientific leadership, designed from the outset as a national facility. The expansion of capabilities and community access from CHIME will enable exciting and timely science on fast radio bursts, line intensity mapping, pulsars, and many other science areas. The very large data flows anticipated from CHORD will require an expansion of Canada's digital research infrastructure capabilities in radio astronomy, and will help the community prepare for the data challenges of SKA1. Construction and operation of CHORD should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders.

2. CMB-S4: We recommend participation in the Cosmic Microwave Background Stage 4 (CMB-S4) experiment, or other comparable facility. Involvement now will let us take leadership roles in defining the overall project. Canadians are world-leaders in all areas of cosmic microwave background research, including detector readout systems, systems integration, pipeline, mapmaking, theory, and interpretation. For continued leadership in this field, it is essential that Canada be involved in CMB-S4 or another comparable facility. Such participation is also highly complementary to LiteBIRD, which we recommend as a space-based priority below. Canadian participation in CMB-S4 or a comparable facility should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders.

3. LSST: We recommend that Canada pursue a route for national membership in the Legacy Survey of Space and Time (LSST). The science enabled by the LSST dataset is unprecedented and will provide foundational data for projects on facilities such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1. At this time, LSST and its funding agencies are still in the process of defining the parameters and requirements for a Canadian partnership in this project. Successful and meaningful Canadian participation in LSST will require development of the relevant digital infrastructure, which will also contribute significantly to the overall international success of the facility. Canadian participation in LSST should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

Because some mid-scale projects are conceived and executed on relatively short time scales, the future facilities that appear above cannot constitute a comprehensive list of all the opportunities that may arise over the next decade. We anticipate that there will be newly emerging mid-scale investment opportunities to consider at the time of the next mid-term review in 2025.

Recommended Very Large (>$100M) Investments in Space Astronomy

Canada has a rich heritage of success in space-based astronomy. Participation in multiple new space astronomy missions is needed to maintain our expertise and skill base, and to address the broad scientific needs of the Canadian astronomy community. Most notably, there are specific opportunities for significant Canadian leadership in space astronomy in the coming decade, as well as opportunities to lay the foundations for participation and leadership in missions to be launched in the 2030s and beyond. To capitalize on all these prospects, Canada should seek to be a leader or significant partner in one major space astronomy mission over the next decade. We assert that Canada can lead one very large space astronomy mission with a budget greater than $100M each decade, recognizing that this would require additional funding beyond the CSA A-base budget and thus a separate request to the Government of Canada. In order to successfully compete for funding against other possible expenditures of the CSA's finite budget, investments at this scale will need to offer outstanding prospects for Canadian science, HQP training, and technical/industry leadership. Canada's priorities for space astronomy will be incorporated into CSA's forthcoming "Space Science Vision 2020" document, which will put these missions within the context of CSA's other programs.

Our highest recommendation at the very large investment scale is for **CASTOR**, an exciting mission with a broad and compelling science case, and which would be Canada's first marquee space astronomy mission. Our second ranking in this category is for significant Canadian participation in a **NASA flagship mission** (HabEx, LUVOIR, Lynx, or Origins).

CASTOR: We recommend that the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) be approved for development toward launch. The CASTOR mission is a mature concept that has a world-leading and transformational science case, strong and long-standing community support, substantial interest and involvement from Canadian industry, and enthusiastic international partners who are looking to Canadian leadership to develop and fly a wide-field optical-ultraviolet space telescope. CASTOR will also provide a superb complement to JWST and other forthcoming optical and infrared facilities. A top priority in LRP2010 and MTR2015, CASTOR continues to be an outstanding prospect for Canada's first marquee space astronomy mission. It will be vital to engage with the federal government to fund this very large mission, and to work closely with international partners like JPL/NASA and IIA/ISRO.

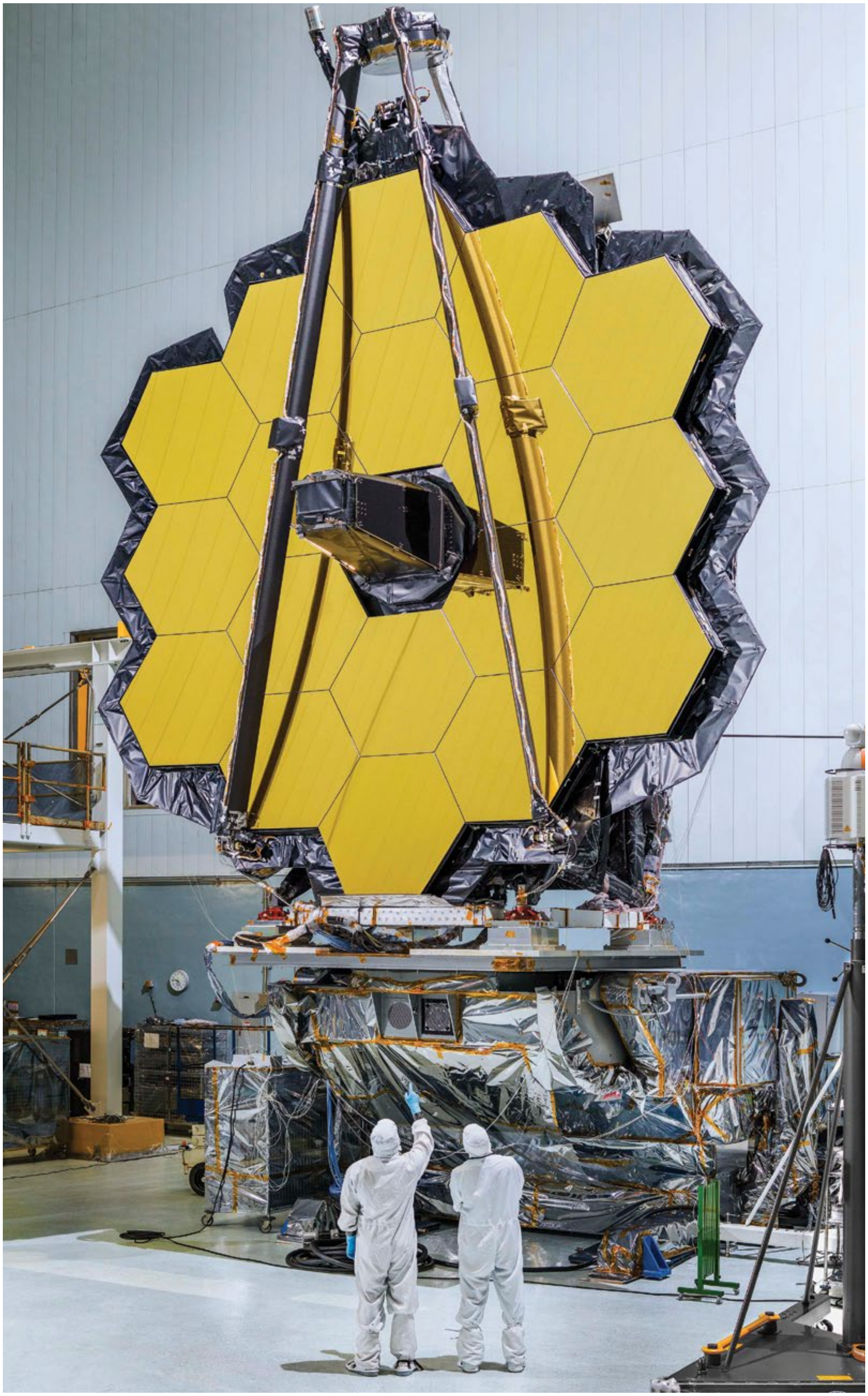
Hardware, Scientific and Technical Contributions to NASA Flagships: We recommend that Canada contribute ~$100M in hardware to a flagship astrophysics mission selected by NASA, and also contribute scientifically and technically to such a mission as recommended under Additional Investments below. However, such a hardware contribution should be regarded overall as a lower priority than investing in CASTOR and LiteBIRD at the recommended levels. A significant hardware contribution to a NASA flagship astrophysics mission would strengthen Canada's standing as a strong international partner in space astronomy. Ahead of the 2025 midterm review, Canadian astronomers should work with the CSA and industrial partners to identify potential hardware contributions to the selected NASA flagship(s) and, where appropriate, the CSA should support technology development studies. CASCA's LRP midterm review in 2025 would then be in a good position to provide guidance on an eventual contribution to a flagship mission.

Recommended Large ($25M–$100M) Investments in Space Astronomy

We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support missions and mission contributions up to $100M.

Our highest recommendation at the large investment scale is for **LiteBIRD**, a JAXA-led mission to study the cosmic microwave background. Our second ranking is for a highly-sensitive **cooled mid-and-far-infrared space telescope**. Both LiteBIRD and a cooled infrared space telescope offer a strong portfolio of ancillary science activities, provide a pathway to major Canadian technical and scientific leadership, and will result in excellent opportunities for HQP training and engagement with industry. The expected return on investment is high in both guaranteed observing time and industry opportunities.

LiteBIRD: We recommend Canadian participation in the Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD). This participation should correspond to the complete life cycle of LiteBIRD, including hardware, mission operations, and science analysis. By focusing on the polarization of the cosmic microwave background at large angular scales, LiteBIRD will be an excellent complement to the ground-based CMB-S4 facility, and will provide an outstanding opportunity for Canadian cosmologists to make unique discoveries.



Testing the James Webb Space Telescope's primary mirror.
Image credit: NASA/Chris Gunn

Cooled Infrared Space Telescope: We recommend that Canada explore opportunities for substantive participation in a large, cooled, infrared international space observatory mission. Such a mission can leverage Canada's substantial scientific and technological leadership in infrared space astronomy derived from work on Herschel and SPICA, and can revolutionize our understanding of cold gas and dust throughout the Universe through unique access to far-infrared wavelengths.

Recommended Additional (<$25M) Investments in Space Astronomy

To allow Canadian space astronomy to focus on a marquee mission and one or two other large programs, participation in other missions by the traditional route of small hardware or other contributions (up to $25M) should be limited. Mission participation should be competitively selected and should fulfill the criteria of offering outstanding prospects for Canadian science, HQP training, and technical/industry leadership.

We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support the preparatory activities (through phase A) for missions and mission contributions of all sizes, and scientific activities for missions to which Canadian astronomers contribute, regardless of whether the CSA has made a formal contribution.

In the immediate future, the CSA's highest priority in space astronomy should be **JWST**. As longer-term priorities, we recommend that CSA approve the development of **POEP** and seek opportunities for scientific and technical participation in the next **NASA flagship mission** (HabEx, LUVOIR, Lynx, or Origins).

JWST: We recommend that the CSA maintain financial support to the James Webb Space Telescope (JWST) mission and associated Canadian science for the entirety of the observatory's lifetime. Canada has already made a very large investment in this project, and continued support will leverage this investment for the highest possible science yield.

POEP: We recommend development of the Photometric Observations of Extrasolar Planets (POEP) mission. The goal should be to enable a launch in the 2025 timeframe, to allow follow-up of exoplanet discoveries made with TESS and CHEOPS, and to provide significant overlap with complementary future space astronomy missions such as JWST, ARIEL, PLATO and CASTOR. POEP has the potential to provide high science impact on exoplanets and the outer solar system for a relatively small investment, and will allow Canada to maintain leadership in small-satellite astronomy.

Scientific and Technical Participation in NASA Flagships: We recommend that the CSA provide funding that enables Canadian scientific and technical participation in preparatory activities for the NASA flagship mission(s), through design reference missions, analysis software, instrument design, science teams, working groups, etc. Any such opportunities should be disseminated widely, and appointments made by CSA should take place through an open and competitive process. These scientific and technical contributions should be pursued as soon as circumstances allow.

Chapter 6

Existing and future observational facilities require dedicated computing in order to operate, reflecting a deep integration of software and hardware that underpins most modern telescopes.

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CHIME is mapping the distribution of matter on cosmic scales to reveal the detailed evolution of structure in the Universe.
Image credit: Andre Renard/The CHIME Collaboration

Future Landscape

In this Chapter, we review the resources considered by LRP2020 for the next decade of theoretical astrophysics, digital research infrastructure, ground-based facilities, and space astronomy missions. Some of these were indicated in Chapter 5 as key priorities for Canadian astronomy over the next decade; we here provide further details on these topics, and repeat the recommendations from Chapter 5. We also summarize and comment on other facilities and programs that have been considered by the LRP2020 panel. The community input upon which these summaries and recommendations have been based can be found in the corresponding white papers and reports. Additional recommendations on funding, governance, personnel, and the role of astronomy in Canadian society are provided in Chapter 7.

Theoretical Astrophysics

Table 6.1: Recommended targets for theoretical astrophysics funding in Canada. Future costs are estimates only and are subject to change.

Program	Funder	Resource	Cost	Timeline
CITA	NSERC	Support of fully funded postdoctoral fellowships in theoretical astrophysics based outside the University of Toronto	~40% of CITA NSERC grant	2020: Analysis by CITA 2021: Enact for 2021 competition
CITA	NSERC	Salaries for all CITA Fellows, CITA National Fellows and Canada Fellows at national/ international standard for prize fellowships	~$0.2M/year	2020: Dialogue with NSERC 2021: Submission of CITA renewal proposal 2022–: New funding

Canada has a critical mass of world-leading theoretical astrophysicists, who study phenomena across the Universe and covering all main areas of astrophysics. Their activities, and the resources needed to carry them out, will be absolutely crucial to realize the science program envisioned for the coming decade and to answer the questions highlighted in Chapter 4. Specific examples of areas in which Canadian theorists plan to make significant contributions include:

- Understanding the observed striking diversity of exoplanet solar systems, which will require exquisite computer simulations of the complex physical processes that take place in the circumstellar disks of gas and dust as planets are being formed;
- Explaining the most extreme and energetic events in the Universe, which will depend on precise calculations of gravitational waves emission from the merger of compact objects;
- Gaining insight into the assembly and evolution of galaxies over cosmic times, which will require computer simulations representing huge, unprecedented virtual volumes of space;
- Understanding the enigmatic outcomes of stellar interactions and mergers, which will need high performance computer simulations and extensive studies of the evolution of stellar populations;
- Elucidating the nature of the so-called dark energy that appears to dominate our Universe and cause an acceleration of its expansion, which will need exploration of new ideas about the nature of space itself;
- Figuring out what populations of sources produce the mysterious fast bursts of radio emission seen all across the sky, which will need theorists to model and interpret these complex frequency-dependent signals;
- Probing exoplanets for life, which will rely on detailed atmosphere models to tell us whether or not a given combination of molecules is a robust indication of biological activity.

Research in theoretical astrophysics is carried out at universities across Canada, unified by the Canadian Institute for Theoretical Astrophysics (CITA), based at the University of Toronto. Leadership and oversight within CITA is provided both by University of Toronto faculty members directly appointed to CITA, and by a national group of other designated Canadian theory faculty, known as "CITA Inc." The local roots and international stature of CITA's national program have resulted in a sense of community ownership and collective pride in its accomplishments.

As CITA now moves into its fifth decade, the CITA footprint is envisioned to grow and decentralize, so that it can play a greater role in enhancing the national theoretical astrophysics profile on the world scene, and contribute to a healthy and diverse environment for trainees in astrophysics theory throughout Canada. The upcoming renewal of CITA's NSERC grant presents the opportunity to expand the CITA membership beyond the areas of traditional expertise, to strengthen the CITA fellowship program by increasing the support provided for theoretical research taking place outside the University of Toronto, and to improve regional diversity in the fellowship program to match the distribution of theory-focused astrophysics researchers across Canada.

Government funding for the bulk of theoretical astrophysics research not tied to a specific experiment or individual researcher comes both from NSERC[31] through the institutional grant awarded to CITA, and also from direct federal and provincial support to the Perimeter Institute for Theoretical Physics. Given its position as Canada's primary national astrophysics theory institute and the only

31 In Chapter 7, we recommend that the CSA support theoretical investigations and that NRC fund early-career STEM personnel, including theorists, to engage in technical and scientific support activities needed to conduct astronomy research programs on Canada's mid-scale facilities.

one with institutional support from NSERC, CITA's role in the Canadian community is distinct from any individual observatory or other national facility; as for any observatory that balances distribution of observing time among its partners, so too should CITA seek a renewed commitment to its role as a national coordinator for theoretical astrophysics, guided by the CITA Council and by CITA Inc.[32] The goal should be that CITA's NSERC funding be equitably accessible to theorists all across the country, in proportion to the faculty-level membership of CITA and CITA Inc, both within and beyond the University of Toronto. One of CITA's great successes is the large number of former fellows who now hold astrophysics theory faculty positions across Canada. CITA's National Fellowship and Canada Fellowship programs correspondingly now need additional funding relative to the total CITA budget, to ensure that Canadian researchers have full access to the national research program that CITA provides. A distribution of approximately 40% of the NSERC commitment to CITA is sufficient to fully fund two new postdoctoral fellows outside the University of Toronto per year. CITA should fund all its postdoctoral positions at the same salary and duration (without any co-funding or host contributions), at internationally competitive salaries, and with a limit on the number of National/Canada Fellows per institution. In its NSERC renewal, CITA should also seek to expand the number of postdoctoral researchers it can support, provided it can first meet the need to fully fund a national postdoctoral program as proposed above.

CITA can additionally boost the national capacity for theoretical astrophysics by seeking to become a hub for training courses, meetings and public outreach (possibly in partnership with Perimeter, which already has substantial experience in this area), and by working in partnership with CASCA to develop one or more Canadian astrophysics theory prizes.

At the national level, a crucial capacity for leadership in theoretical astrophysics will be hardware, software, and personnel resources for large-scale calculations and computational simulations. The pending transition from Compute Canada to Canada's New Digital Research Infrastructure Organization (NDRIO) provides a significant opportunity to improve the future of astronomical research computing for the next decade. Recommendations on digital research infrastructure (DRI) for both astronomical theory and observations follow in the next section.

Recommendation
We recommend that CITA strengthen its national role by committing ~40% of its annual NSERC funding to postdoctoral fellowships based outside the University of Toronto. These positions should be fully funded by CITA, without any host contributions allowed or required, and with a limit on the number of National/Canada Fellows per institution, in analogy with the NASA Hubble Fellowship program. The University of Toronto should remain ineligible to host CITA National Fellowships or the first half of Canada Fellowships, as is presently the case.

Recommendation
We recommend that CITA offer salaries and research allowances for CITA Fellows, Canada Fellows, and CITA National Fellows at identical levels and durations. We further recommend that the remuneration should be competitive with commensurate national and international prize fellowships, with the goal of attracting and retaining the world's best early-career theorists.[33,34]

Recommendation
We recommend that CITA seek an expansion of its postdoctoral program in its next funding proposal to NSERC. Additional funding should be used to prioritize the two recommendations above before increasing the overall number of fellowship positions supported.

Recommendation
We recommend that CITA increase its focus on training for students and postdoctoral fellows and on organizing theory-focused meetings and public outreach, in coordination with the Perimeter Institute and the broader theory community.

Recommendation
We recommend that CITA and CASCA work together to recognize the importance of theoretical astrophysics by establishing and awarding national prizes in this field.

32 One possible model is the Centre de recherches mathématiques, which supports and coordinates thirteen research laboratories across Québec and Ontario.

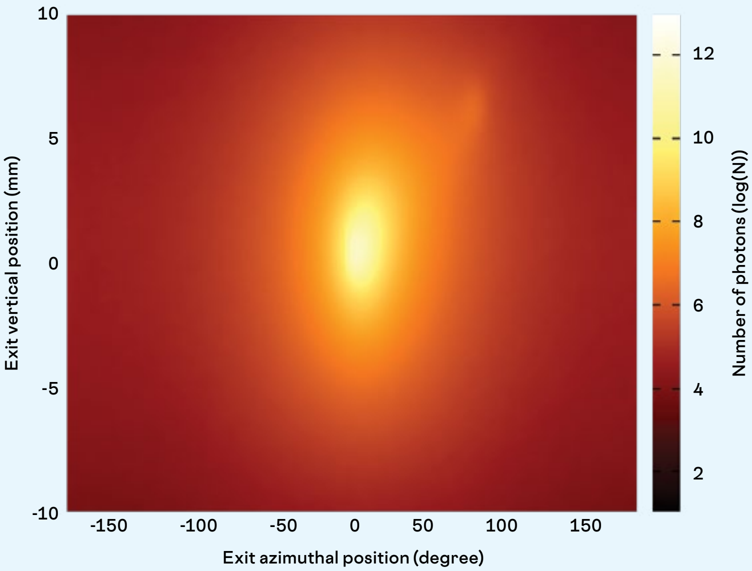
33 A similar recommendation for NSERC Postdoctoral Fellowships is made in Chapter 7.

34 Comparably prestigious prize fellowships and their starting salaries or stipends for 2020 include: Banting Fellowships (CA$70,000), Dunlap Fellowships (CA$71,000), NRC Plaskett/Covington Fellowships (CA$72,000), NASA Hubble Fellowships (US$69,500), NSF Astronomy and Astrophysics Fellowships (US$69,000), ESO Fellowships (€36,000, tax free), Australian DECRA Fellowships (AU$81,600), Berkeley Miller Fellowships (US$68,000), Harvard ITC Fellowships (US$69,500) and Flatiron Fellowships (US$87,000).

CASE STUDY

Shining the Light on Clean Water

Applying theoretical astrophysics to real-world water treatment systems



← **This color map shows a visual representation of the number of photons escaping along the surface of a cylindrical low-pressure mercury lamp when photons are coming into the lamp from an outside source, obtained using a Monte Carlo radiative transfer routine. The dull glow in the upper right represents the photons that go right through the lamp without interacting with the mercury gas inside the lamp.**

Credit: Isabelle Cyr

Carol Jones is a Professor of Physics & Astronomy and Associate Dean of the Faculty of Science at **Western University**. She studies the mysterious disks of gas around hot, young stars to find out where they come from and how they change over time. Jones grew up in the London area and received her PhD from Western in 2,000. **Isabelle Cyr** is a postdoctoral researcher at Western University. She uses complex computer models to study the interactions between light and matter in the disks around massive stars. Cyr grew up in Edmonston, New Brunswick and received her PhD from Western in 2016.

Trojan Technologies, based in London, provides products and services that make water treatment processes more effective, efficient and sustainable. Trojan UV systems use ultraviolet light to disinfect drinking water and wastewater in cities and towns across Canada and around the world, and the company is continually advancing ultraviolet disinfection technology. Cyr and Jones applied their experience in computer models of the passage of light through the gas around massive stars. With support from Mitacs, NSERC, and Trojan Technologies, they worked with **Jim Robinson**, Trojan, who also obtained his PhD in the Department of Physics and Astronomy at Western, to understand the path of light through the ultraviolet lamps in Trojan's reactors. Their computer models, tested with experiments, will result in more efficient water treatment systems.

The world's supply of clean water is under substantial stress due to industrialization, increasing demand, rising biological and chemical contamination amongst other factors. This stress represents a significant threat to world health, our environment, and current and future generations around the globe. The unique partnership between astronomers and a leading Canadian company will advance water treatment for all. ◆

Digital Research Infrastructure

Table 6.2: Recommendations for digital research infrastructure funding. Future costs are estimates only and are subject to change.

Program	Funder	Resources	Cost	Timeline
General astronomy supercomputing	NDRIO	Will evolve over the decade. Estimate of astronomy needs in 2025 (excluding SKA1): • 100 petaflop years CPU • 100 petaflop years GPU • 75 PB online storage	Across all disciplines: $375M initial investment plus $50M/year	2021-2030
SKA1 Regional Centre: processing, storage and data transport	Funded through the SKA project	Processing: 9.7 cumulative petaflop years Online storage: 238 cumulative PB years Nearline storage: 654 cumulative PB years Data transport: 100 Gb/s	$65M[35]	2021-2030

Answers to the fundamental questions in astronomy and cosmology set out in Chapter 4 will require not just traditional observations or calculations, but will also need enormous data sets and large-scale computational simulations. Many theoretical programs require formidable computing resources, both to perform simulations or calculations and then to store and analyze the output. Several of the future observational facilities and programs recommended in Chapter 5 will produce exabyte-scale data products, components of which need to be distributed electronically to the community and also archived in perpetuity. Furthermore, fundamental analysis tasks such as stellar classification, redshift determination, and cross-correlating multi-wavelength sky surveys have become so complex that they now rely heavily on approaches involving astroinformatics, machine learning, and artificial intelligence. The computational facilities available to Canadian astronomers process petabytes of data per year from current experiments, while Canada provides a leadership role in the development of data standards within the International Virtual Observatory Alliance, and are bringing astronomy research computing into a cloud-based environment that crosses boundaries across wavelength and research domains.

However, the stark context in which all this takes place is that the shared plus dedicated computing resources currently available in Canada *cannot meet the needs of Canadian astronomy in the next decade*. To maintain Canadian leadership in astronomy, substantially increased access to large-scale high-performance computing is required. Scaling from the current level and growth of astronomy-related resource requests to Compute Canada, we estimate that by 2025, annual Canadian needs for large-scale astronomical simulations and observational analyses will be approximately 100 petaflop-years each of both CPU and GPU calculations. These requirements are 10 and 25 times, respectively, the current Compute Canada capacity across all disciplines. This disparity results from the lack of national supercomputing capacity in Canada discussed in Chapter 3. Although this shortfall seems extreme, astronomers' needs are neither unrealistic nor unfeasible: Canadian astronomy's projected needs for 2025 are similar to the resources that astronomers in many other countries already have access to in 2020.

Astronomy also has significant storage needs: data sets are generally large, complex, multi-dimensional and not easily compressible. Data also need to be retained for years or even decades, both because an overall experiment or survey can take a long time to complete, and because a significant fraction of astronomical discovery now relies on reprocessing archival or publicly released data in new ways. Finally, many astronomical observations focus on tracking changes in celestial objects over time: the full time baseline needs to be retained for subsequent analysis, and re-observing an object later can never recapture its prior behaviour. It is thus not surprising that the storage needs of Canadian astronomy will in the near future exceed available capacity: for example, the proposed Canadian LSST platform and archive (see below) will initially require 8 petabytes of storage, plus a subsequent 1.5 petabytes per year as the survey data accumulate. Scaling from recent Compute Canada requests for general-purpose storage for astronomy, we estimate that 75 PB of fast online storage will be needed by 2025. Bandwidth will be another key requirement—the proposed Canadian SKA1 Regional Centre (see below) will require a network capacity of 100

35 This cost is repeated in Table 6.4 (page 89) on recommendations for ground-based radio facilities.

gigabytes per second. Again, continuous investment in research computing in Canada can accommodate such requirements, but the planning and investment cycle must begin immediately to ensure international competitiveness.

One of the great risks facing 21st century astronomy, and Canadian astronomy in particular, is that we will not have the software systems needed to fully exploit the digital data sets that will be created. Astronomical computing requires software, databases, and the expertise to create and maintain these vital tools. In particular, managing large datasets requires increasingly specialized expertise and software solutions, often called middleware or cyberinfrastructure. The Canadian expertise in these fields is largely concentrated at HAA's CADC, which provides the service offerings (e.g., customized virtual machines, managed storage, batch processing using virtual machines, group access rights) needed by astronomers through the CANFAR service layer on Compute Canada infrastructure. Supporting CADC in the development and long-term retention of expertise in software and middleware is critical for the success of Canadian participation in current and future data-intensive astronomy projects.

The above discussion focuses on a pressing need for general purpose computational resources to be shared across the community. In addition to this, existing and future observational facilities require dedicated computing in order to operate, reflecting a deep integration of software and hardware that underpins most modern telescopes. In particular, modern radio telescopes such as CHIME, CHORD and SKA1 derive much of their extreme sensitivity from dedicated supercomputing capabilities. This level of software integration also extends beyond observations and into the data extraction and analysis needed to convert measurements into scientific discoveries. Most notably, full Canadian participation in SKA1 (see discussion below) will require a Canadian SKA1 Regional Centre commencing in 2022, with an initial storage capacity of 6 petabytes and computing power of 0.3 petaflops, growing by 2030 to ~240 petabytes and 1.7 petaflops to keep up with the intake of SKA1 data. The CPU needs for SKA1 alone at the end of the decade are comparable to the entire current capacity of Canada-wide research computing. However, with continued investment in research computing in Canada to keep up with Moore's Law, the computing needs for SKA1 could be served with a small fraction of Canada's future computational capacity by 2028.

Canada's entire research community shares similar digital infrastructure challenges over the next decade to those faced by Canada's astronomers. Without a sustained commitment to computational infrastructure over the next decade and beyond, Canada's scientists will fall ever farther behind their competitors. Furthermore, because computational research is playing an ever larger role globally, Canada's scientists require such a commitment simply to be able to contribute meaningfully to computationally dominated fields. We therefore call for Canada to maintain its commitment to digital research infrastructure set out in Budget 2018 through the next decade, in particular an initial investment of $375M to fund the immediate revitalization and continuing improvement of Canadian digital research infrastructure. This needs to be followed by ongoing expenditure on DRI at the level of $50M per year throughout the coming decade. This investment in DRI will ensure the competitiveness and global leadership of Canadian astronomy over the next decade.

Recommendation

We recommend that Canada maintain its commitment to digital research infrastructure outlined in Budget 2018, through an initial investment of $375M plus an ongoing expenditure of $50M per year over the next decade. This major investment in NDRIO is needed to revitalize and then sustain Canada's research capabilities across all disciplines.

Recommendation

We recommend that CASCA and ACURA work to ensure that NDRIO meets the computational resource requirements of theoretical and observational astrophysics, which we estimate as 100 petaflop-years each of CPU and GPU calculations and 75 PB of online storage by 2025. CASCA's Computation and Data Committee should monitor developments within NDRIO and should vigorously represent the interests of astronomy researchers through NDRIO's Researcher Council and other governance and advisory structures.

Recommendation

We recommend that NRC's Canadian Astronomy Data Centre (CADC) continue to receive strong support, both as a provider of astronomy-specific service layers that use NDRIO infrastructure, and as a coordinator of long-term archiving of digital data products for astronomy.

Ground-Based Facilities: Optical and Infrared

Optical telescopes are among the earliest astronomical instruments. The history of large ground-based telescopes in Canada dates back more than a century. Modern ground-based optical and infrared (OIR) telescopes cover the wavelength range 0.3–10 micrometres; the specialized capabilities of individual facilities allow for discovery across different domains (such as time-variability or high-resolution imaging). In this section we review all optical and infrared facilities that have been considered for LRP2020, and provide specific recommendations for those programs considered as key priorities for the next decade of discovery. Facilities are listed in alphabetical order, with recommendations from Chapter 5 repeated where appropriate.

Table 6.3: Costs and schedules of recommended ground-based optical and infrared facilities (in alphabetical order; see Chapter 5 for prioritizations and categorizations). Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change.

Project	Anticipated Cost to Canada		Canadian Share of Observing Time[36]	Construction Start	Operations Start
	New Construction Costs	Operations			
CFHT	N/A	US$4.0M/year (Canadian contribution in calendar year 2020)	42.5%	1974	1979
Gemini	N/A	US$6.0M/year (Canadian contribution in calendar year 2020)	18.15%	1994	1999-2000
LSST	N/A	$3M[37]/year in 2020-dollars (in-kind)	Full access to survey data	2015	2023
MSE	$110M in 2018-dollars	$7M/year in 2018-dollars	20%	2026	2031
VLOT (TMT)[38]	TBD[39]	US$7M[40]/year in 2020-dollars	15%	TBD	2033 or later

36 For facilities that are not yet operational, the share listed is provisional or proposed. Note that the share of Canadian observing time is not necessarily derived from or related to the Canadian share of construction or operations costs.

37 LSST is not accepting cash funds from its partners to cover operations. The amount listed is the cost of in-kind Canadian contributions to LSST operations.

38 At the time of writing Canadian access to a very large optical telescope is best implemented by continued participation in TMT, sited either at Maunakea, Hawai'i or Observatorio del Roque de los Muchachos in the Canary Islands.

39 In 2015, the Canadian government committed $243.5M for specific TMT activities, including NFIRAOS and enclosure construction. Any additional construction costs are not yet determined.

40 The annual operations cost for TMT constructed on Maunakea vs TMT constructed on Observatorio del Roque de los Muchachos are similar to within a few percent.

Arctic Astronomy

Antarctica is known to offer superb conditions for optical and infrared astronomy, including long unbroken periods of darkness, cold and dry conditions that minimize atmospheric contamination, excellent image quality, and a sky mostly free of the trails from satellite constellations. Similar conditions may be obtainable in the high arctic regions of Inuit Nunangat, with the added advantages that such sites are easier to reach than Antarctica and are accessible year round. In the past 10–15 years, Canadian astronomers have conducted site testing at the Polar Environment Atmospheric Research Laboratory (PEARL) (latitude 80° N) on Ellesmere Island / Umingmak Nuna in Nunavut, with comparison to three remote high coastal mountains elsewhere on Ellesmere. These campaigns have shown the potential for superb image quality, comparable to Maunakea in Hawaiʻi and Cerro Tololo in Chile and far better than anywhere else in Canada. Should these imaging prospects be realized, even a small to moderate size telescope at such a site could be a world-class observatory and could make significant research contributions. However, the existing site studies are still only preliminary: a conclusive study will require data taken over multiple winters, employing a tower away from the deleterious effects of the PEARL facility.

The LRP2010 report recommended: (1) that image quality in the High Arctic be fully characterized at multiple sites; (2) that confirmation of a high-quality site should be followed by design, science and technical studies for a 1–4 metre telescope; and (3) that if such studies demonstrated a strong and feasible case, construction of such a telescope should proceed. A distributed network of small telescopes has since been proposed for the PEARL site, with a collective aperture of about a metre. However, this has not advanced beyond a concept study, and there has been no site-testing or other data taking at PEARL since 2013, owing to a lack of funding and the challenging logistics.

Optical and infrared astronomy from the Arctic remains an exciting future option for Canada, but the site conditions, feasibility and cost are yet to be established. Consent from Indigenous Peoples and traditional title holders for astronomical activity at any proposed site, backing from the Canadian astronomy community and associated funding will all be needed before this possibility can be advanced further. Potential funds might be on offer from the Department of National Defence for orbital debris studies, and also from government agencies interested in attracting international investment.

We separately note Arctic radio astronomy as a new focus of activity. Canadians have been testing the low-frequency radio environment at McGill Arctic Research Station (latitude 79°N) for global reionization experiments, with pathfinder elements deployed in 2018. There are also plans to use the new 12-metre Greenland Telescope to image supermassive black holes as part of the Event Horizon Telescope.

CFHT

The Canada-France-Hawaii Telescope (CFHT) is a 3.6-metre optical/infrared telescope on the summit of Maunakea. CFHT has been operating since 1979 and has made broad contributions across astronomy and cosmology, enabled by the combination of innovative instrumentation and the best image quality on the mountain. Leadership in CFHT allowed Canadians to conduct the first legacy surveys on a 4-metre-class telescope, which had lasting impact in the astronomy community by providing some of the most accurate supernova cosmology results and the first galaxy cluster redshift surveys.

CFHT is a partnership between the National Research Council (NRC) of Canada, the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii (UH). Canada has a 42.5% share of CFHT, and currently makes an annual cash contribution of US$4.0M (2020) to operations. Canadian astronomers can obtain CFHT observing time through the Canadian Time Allocation Committee (CanTAC), or through calls for CFHT Large Programs. For time awarded by CanTAC, around 60–70 observing proposals are currently submitted per year, with an oversubscription ratio of 2–4. Four CFHT Large Programs are currently being executed, all of which have substantial Canadian leadership and involvement. The Canada-France Imaging Survey (CFIS) Large Program is part of the larger UNIONS project that has enabled Canadian participation in the Euclid mission led by the European Space Agency (ESA). There have been more than 800 Canadian-led CFHT publications, which have been cited more than 40,000 times; the highest impact papers have been ground-breaking discoveries on topics such as globular clusters, galaxy evolution, and dark energy. Canadians are leading the proposed redevelopment of CFHT and its site as the Maunakea Spectroscopic Explorer (MSE; see page 84).[41]

41 Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawaii ends in 2033.

North side of CFHT. Image credit: CFHT Corporation

Recommendation
We recommend continued Canadian participation in CFHT at least until the ongoing Large Programs are complete. During this period, Canada should work with the other CFHT partners to maximize unique high-impact science while reducing costs, for example by reducing the instrument complement or by further prioritizing Large Programs. Once the ongoing Large Programs are complete, Canadian involvement in CFHT will depend on whether CFHT transitions into MSE. Should MSE go ahead at the CFHT site, we recommend that Canada, its CFHT partners, and other relevant stakeholders plan for a future that involves moving SPIRou to another telescope, as this new instrument has the capability to provide high-impact science for at least a decade. Should CFHT not transition into MSE, we recommend that the Canadian astronomy community decide what approach will provide optimal access to northern wide-field capabilities in the optical, ultraviolet and near-infrared, which may mean leaving the CFHT partnership in order to pursue other opportunities (participation in Subaru is one possibility; see the section on Subaru below). Canadian participation in CFHT should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 7).

The current instrumentation suite for CFHT consists of two imagers (MegaCam and WIRCam), two spectrographs (ESPaDOnS and SPIRou) and an imaging Fourier transform spectrometer (SITELLE). MegaCam, WIRCam and ESPaDOnS are around 15 years old. MegaCam still provides the only wide-field near-ultraviolet imaging capability on a 4-metre or larger telescope, a key capability for cosmological measurements that complements the data sets from Euclid, the Nancy Grace Roman Space Telescope (formerly WFIRST), and the Vera C. Rubin Observatory (formerly LSST). SITELLE and SPIRou have begun taking data just in the last few years and are uniquely powerful in their science areas. With one of the largest fields of view of any integral field spectrograph, SITELLE offers unprecedented capability for mapping the physical conditions in nearby galaxies and star-forming regions. SPIRou's high-precision radial velocity measurements provide the ability to search for exoplanets around low-mass stars and investigate the physical processes at play during the first million years of star-and-planet systems.

Gemini

The Gemini Observatory has been a fundamental optical/IR facility for Canada for over two decades, offering a large suite of instruments on two 8-metre telescopes: a northern facility on Maunakea in Hawai'i and a southern facility on Cerro Pachón in Chile. Gemini is currently funded by a partnership of six countries: the United States, Canada, Chile, Brazil, Argentina and Korea. Canada's share in the partnership is currently 18.15%. Canada has recently extended the agreement to partner in Gemini through 2027, with an assessment point for the next Gemini International Agreement planned for 2024.

Gemini has a strong history of scientific discovery, including the Canadian-led first image of a multi-planet system beyond the solar system, studies of high-redshift quasars, and constraints on dark energy from supernovae. Over the next five years Gemini will enjoy a renaissance, with the commissioning of a revitalized instrumentation suite that is very well-aligned with the general needs of the Canadian astronomical community into the 2020s and beyond. As examples, the capabilities of these new instruments will enable studies of the chemical make-up of the Milky Way halo, early evolution of stars and planetary systems, the contents of nearby and distant galaxies, and the rapid follow-up of newly-discovered variable and transient objects. A new Gemini-North adaptive optics system represents a significant investment from the US National Science Foundation, while the Canadian-led Gemini Infrared Multi-Object Spectrograph (GIRMOS) will revolutionize our ability to study the faintest, oldest and most distant objects in the Universe and to probe the formation of stellar and planetary systems.

Over the past decade, Gemini has introduced two new programs to increase its impact. The first is a Fast Turnaround program which offers roughly 10% of the telescope time to a monthly proposal submission and assessment, with data obtained 1–4 months after submission. The Canadian Gemini Office originally led the effort to develop the necessary software to support this program and Canadian PIs have been awarded nearly 40% of the time allocated through it. Secondly, as of 2014, Large and Long Programs (LLPs) are now allocated up to 20% of the observing time, allowing for proposals of projects that require significant time, potentially over several semesters. Although to date only a small number of Canadian PIs have been awarded time for LLPs, their programs are among the largest ever accepted on Gemini, and exceed the share of time allocated by Canada for LLP participation. Canadians are also active participants in many US-led LLPs.

Canadian oversubscription rates for Gemini have declined over the past several years, but still exceed 2:1. Some instruments and modes are even more heavily oversubscribed. Canadian astronomers are productive users of both telescopes. Canadian Gemini papers (those with a Canadian author or co-author) have a higher impact than that of the average Gemini paper. Canadian papers based on Gemini-South data have been more impactful compared to those from Gemini-North, primarily due to the very strong impact of the Gemini Planet Imager on Gemini South. Canada's share of Gemini has facilitated many student-led programs, and Gemini has thus proven to be a powerful thesis-producing machine for Canada. There are now 63 MSc and PhD theses utilizing Gemini data, with more in progress. Currently, an average of five Canadian theses are produced per year using Gemini data.

The Gemini Observatory will continue to provide access to both hemispheres of the sky,[42] performing pathfinder science that will enable programs on 30 metre-class telescopes and providing capabilities that those telescopes will not offer for some time (such as high-resolution spectroscopy in the northern hemisphere). It will also play a key scientific role in follow-up and characterization of phenomena discovered with LSST, ALMA, JWST, MSE and SKA1.

Recommendation

We recommend that Canada remain an active participant in the Gemini Observatory over the next decade. Gemini continues to be a foundational component of Canadian observational capabilities, plays a key role in training and instrumentation development, and enables research across an incredibly wide range of science topics. Substantial recent investments and new instrumentation make it an exciting time for Canada to be a Gemini partner, and should lead to increased productivity, impact and oversubscription rates. The Gemini Observatory will be a key part of Canada's observational capabilities in the era of 30-metre telescopes. Gemini will be an important testbed for future instrumentation and will offer capabilities not offered by 30 metre-class telescopes until well into the 2030s.

We encourage broad community consultation leading up to the next Gemini assessment point in 2024 on what specific share of Gemini is appropriate for Canada in the next Gemini International Agreement, and on how the negotiation of the Maunakea master lease will affect the status of Gemini North. Canadian participation in Gemini should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 7).

42 Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawaii ends in 2033.

Rubin Observatory at sunset, lit by a full moon. Image credit: Rubin Observatory/NSF/AURA

LSST

The Legacy Survey of Space and Time (LSST) is slated to begin operations in 2022 using the 8.4-metre optical telescope[43] of the Vera C. Rubin Observatory, now under construction on Cerro Pachón in Chile. The Vera C. Rubin Observatory was the highest recommended ground-based facility in the US Astro2010 decadal review of astronomy, and is the first telescope in its class designed to study the optical transient universe. The LSST will be a 10-year survey of the sky that will deliver a 500-petabyte set of images and data products, which will address some of the most pressing questions about the structure and evolution of the universe, its evolution and the nature of many discrete objects. The impact of LSST will be felt in all fields of astronomy.

The survey is designed to address four key science areas: dark matter and dark energy, hazardous asteroids and the remote solar system, the transient optical sky, and the formation and structure of the Milky Way. The scientific questions that LSST will address are profound, and yet the concept behind the design of the LSST program is remarkably simple: to conduct a deep survey over an enormous area of sky at a cadence that provides images of every part of the visible sky every few nights, and to continue in this mode for ten years to achieve astronomical catalogs thousands of times larger than have ever previously been compiled.

LSST will be a powerful new survey that will enable transformative science in the studies of transient objects and wide-field astronomy. The high volume data stream originating from this program will require specialized management in order to capitalize on the information within the data. A limited set of LSST data products will be made public world-wide. However, much of the data release will be delayed, and/or in a form impractical to access for individual astronomers without access to a platform designed to extract meaningful products of specific design from the continuous stream of data. The creation of data management platforms generating tailored data products is therefore critical to realizing LSST's scientific potential. The strongest science benefit will come from the synergy of LSST with other Canadian facilities that will follow-up the transient alerts and discoveries flagged in the survey data. Much of the key physics will come from data projects launched on other facilities, such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1, initially motivated by LSST data.

In 2016, the University of Toronto signed a memorandum of agreement with the LSST Corporation on behalf of a Canadian LSST consortium, and Canada has been correspondingly recognized by LSST as a potential international contributor. Proposed Canadian contributions include the infrastructure and personnel to develop a science platform, and an archive at the Canadian Astronomy Data Centre (CADC) to host enhanced public LSST data products. The intent is that these efforts will be formally recognized by LSST and its funding agencies as substantive in-kind contributions to the project, facilitating access to proprietary LSST data for all Canadian astronomers. The total cost of these contributions will be approximately $3M per year over the next decade.

43 The telescope itself was formerly known as the Large Synoptic Survey Telescope (LSST); the recast acronym now refers to the survey to be undertaken with this telescope.

Recommendation

We recommend that Canada pursue a route for national membership in LSST. The science enabled by the LSST dataset is unprecedented and will provide foundational data for projects on facilities such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1. At this time, LSST and its funding agencies are still in the process of defining the parameters and requirements for a Canadian partnership in this project. Successful and meaningful Canadian participation in LSST will require development of the relevant digital infrastructure, which will also contribute significantly to the overall international success of the facility. Canadian participation in LSST should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 7).

MSE

The Maunakea Spectroscopic Explorer (MSE) began as a Canadian-led concept for a next-generation Canada-France-Hawaii Telescope (ngCFHT) during LRP2010. MSE is a project to design and construct a wide-field spectroscopic telescope at a site with excellent natural seeing, and in so doing to continue the tradition of Canadian leadership in wide-field astronomy established with CFHT. MSE is an end-to-end science platform for the design, execution and scientific exploitation of transformative, high-precision spectroscopic surveys at low-, medium-, and high-resolution from 0.37 to 1.8 micrometres. MSE will unveil the composition and dynamics of the faint Universe, and will impact nearly every field of astrophysics across spatial scales from individual stars to the largest-scale structures in the Universe. Canadian astronomers were very active in the leadership that developed the strong and diverse MSE science program, which includes the following pillars: high-resolution stellar spectroscopy to understand the chemistry and motions of distant Milky Way stars, studies of galaxy formation and evolution over billions of years, a large-volume redshift survey to constrain cosmological parameters, measurements of the dark matter halos of Milky Way satellites, and the calibration of black hole mass estimates for millions of quasars.

The MSE design features an 11.25-metre aperture telescope dedicated to multi-object spectroscopy with 4,300 fibres over a 1.5-degree^2 field of view. MSE is proposed to be located at the current CFHT site on Maunakea,[44] replacing the dome with a new enclosure 10% larger than the current size, while leaving the foundation and much of the remaining infrastructure intact. It is expected that 80% of useful observing time will be dedicated to large, multi-year Legacy Surveys proposed by MSE partners and chosen in a competitive, peer-reviewed process. The remaining 20% of observing time will be allocated to the partners, based on their relative share in MSE, for smaller strategic surveys. A set of Design Reference Surveys will be created and iterated during the design and construction phases, so that the MSE science community will be ready to take full advantage of all of MSE's capabilities.

MSE has the potential to be a critical hub in the emerging international network of front-line astronomical facilities over the coming decades, naturally complementing and extending the scientific power of telescopes like SKA1, Euclid, the Vera C. Rubin Observatory, and many other facilities. MSE will have particular synergy with a VLOT, since the overlap in wavelength range and dedication to large surveys means MSE will provide consistent data sets of huge numbers of targets. TMT and other VLOTs will be able to follow up such datasets with higher resolution or deeper observations. Having both MSE and TMT in the Northern hemisphere would maximize the complementarity between the two facilities.

The MSE project passed a Conceptual Design Review in 2018, and in November 2018 the CFHT Scientific Advisory Council endorsed MSE as the scientific future of CFHT. The cost to build the MSE conceptual design on the CFHT site is US$420M including risk margins, and the cost to operate the facility is estimated at US$25M/year, all in 2018 dollars. A model with several roughly equal major partners instead of one dominant partner is anticipated, in which Canada would pursue a partnership at the level of 20% ($110M construction, $7M per year operations, 2018 dollars). The current MSE partnership consists of Canada, France, the University of Hawaii, Texas A&M University, Australia, China, and India, plus observers from the US National Optical-Infrared Astronomy Research Laboratory and a consortium of UK universities and research institutes; developing a governance structure compatible with both government and university decision-making processes will be important for the project's future. The MSE Science Team consists of approximately 400 scientists worldwide, including approximately 40 from Canada and an equal number from France, exceeded only by the number of members from the USA.

44 Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawaii ends in 2033.

Recommendation

We recommend that Canada play a leading and substantive role in a next-generation widefield spectroscopic survey facility. Meaningful Canadian participation should be at a level of at least 20%, which will also ensure a prominent Canadian role in driving and participating in the VLOT science that will be enabled by such a facility. The best option at present is to pursue the development, design and construction of the Maunakea Spectroscopic Explorer (MSE) at the current CFHT site on Maunakea; this offers a compelling and timely science case with significant history of and potential for Canadian leadership. Should it not prove possible to transition CFHT into MSE, we recommend that Canada play a substantive leadership role in developing the MSE concept at a different site.

We recommend that the MSE project build on its mature science case and well-developed design, and now undertake essential future steps on the path toward construction. These include obtaining consent from Indigenous Peoples and traditional title holders for the use of any sites needed for the MSE project (see recommendation in Chapter 7), and establishing the governance structure and funding model needed to effectively advance this exciting project.

SDSS-V

The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy, and has resulted in hundreds of publications by Canadian astronomers. SDSS consists of a series of very wide field optical surveys of the sky, including both photometry and spectroscopy. The original SDSS project, which commenced in 2000, provided a public release of uniform, well-calibrated optical photometry and spectroscopy over large parts of the sky, and it has been heavily used for scientific studies ranging from asteroids to the large-scale structure of the Universe. SDSS-II, SDSS-III and SDSS-IV followed, providing fundamental insights into exoplanets, Galactic structure, galaxy evolution, large-scale structure and cosmology.

SDSS-V commenced observations in Fall 2020. SDSS-V is a panoptic spectroscopic survey that will continue the SDSS tradition of innovative data and collaboration infrastructure, with a focus on mapping of our Galaxy, supermassive black holes, and the Local Volume. SDSS-V will be the first facility providing multi-epoch, all-sky, optical and infrared spectroscopy, as well as offering contiguous integral-field spectroscopic coverage of the Milky Way and nearby galaxies.

Institutions can join SDSS-V as full members (costing US$1150k for data access for everyone at that organization), or as associate members (at a cost of US$230k per "slot," where one slot corresponds to one faculty member or staff scientist, one postdoc, and their students). Contributions can be cash or in-kind. SDSS-V will be governed by an Advisory Council, while collaboration policies will be developed and implemented by a Collaboration Council. Full members will have representation on both these councils, as will associate members (or groups thereof) with at least three slots. At the time of writing, three Canadian institutions have committed to associate membership in SDSS-V: University of Toronto (3 slots), University of Victoria (1 slot) and York University (1 slot). With three slots, the University of Toronto has direct representation on the SDSS-V Advisory Council and Collaboration Council, while Victoria and York's single slots do not give them a vote on these councils.

SDSS-V will be a substantial astronomical survey with major and long-lasting impact. While there will be Canadian participants in SDSS-V, there are currently few identified opportunities for significant Canadian leadership, and there is thus not a strong case for membership in SDSS-V to be funded on a national level at the present time. We encourage the SDSS-V community in Canada to identify additional participants and funding, which can provide the foundations for possible discussions regarding a national presence in this project.

Subaru

Subaru is an 8.2-metre optical-infrared telescope run by the National Astronomical Observatory of Japan (NAOJ). It has operated on the summit of Maunakea since 1999, and is the only 10-metre class telescope capable of wide-field imaging. Subaru has a focused, highly successful instrumentation program built upon wide-field imaging (Hyper Suprime-Cam, HSC), wide-field spectroscopy (Prime Focus Spectrograph, PFS) and high-contrast imaging (the Subaru Coronagraphic Extreme Adaptive Optics, SCExAO). There is also ambition at NAOJ to develop a ground-layer adaptive optics system that will serve a suite of wide-field near-infrared instruments.

HSC is an ultra-wide-field camera that has had an enormous impact on our understanding of topics including high redshift galaxies and supermassive black holes, galaxy clusters and low surface brightness galaxies. Currently under construction, PFS is a wide field (1.3-degree diameter) multifibre spectrograph designed for follow-up of HSC's imaging surveys. Among other science goals, the combination of wide-field imaging and spectroscopy of galaxies enables precision measurements of cosmological parameters that will complement space-based surveys (e.g. from Euclid and the Roman Space Telescope). The PFS consortium will have an allocation of several hundred guaranteed nights in return for providing the instrument, and this will be used to conduct one or more large surveys that are now being prepared through the Subaru Strategic

Programs (SSP). Attempts by Canadians to obtain funding to join PFS and the associated SSP have not been successful to date.

SCExAO is one of the few dedicated high-contrast imaging spectrographs worldwide. Its main science goals are the imaging discovery and characterization of the thermal near-infrared light of exoplanets and disks around nearby young stars. Some Canadian astronomers have used the Gemini-Subaru time exchange program to access SCExAO, and there is Canadian interest in joining the SCExAO campaign science team for the upcoming exoplanet/disk campaign. The SCExAO team enthusiastically supports Canadian involvement in future instrument developments in science programs and in sharing expertise in data reduction. SCExAO, with its modular approach, would be one of the best instruments to validate Canadian high-contrast technologies for future deployment on 30-metre class telescopes.

Canadians have shown increasing interest in requesting Subaru time through the Gemini-Subaru Exchange Program. NAOJ has been seeking potential partners for Subaru operations, including Canada. Two types of partnership are envisaged: Partners and Associates. Partners (minimum US$2M/yr, for at least three years) require a larger cash contribution than Associates (US$400k/yr for 2 years), can apply for Intensive (5–40 nights) and Large (40+ nights) programs, and have a role in governance. Unlike Partners, Associates do not have a role in governance, and cannot participate in Large Programs.

Subaru will remain the dominant wide field imager in the northern hemisphere for at least a decade[45] and with PFS it will host the only 10-metre class, wide field optical/infrared spectrograph until MSE. Canadian astronomers have correspondingly expressed interest in gaining enhanced access to Subaru's wide field-of-view and set of powerful new instruments. The level of Canadian participation and leadership in Subaru would be at a relatively small level relative to the prospects offered by comparable expenditures on other current and future facilities. We encourage those interested in expanded Subaru access to identify pathways through which Canada could have significant influence on future decisions for the telescope and its large surveys. Increased exploitation of the Gemini-Subaru Exchange Program could be an important component of these efforts.

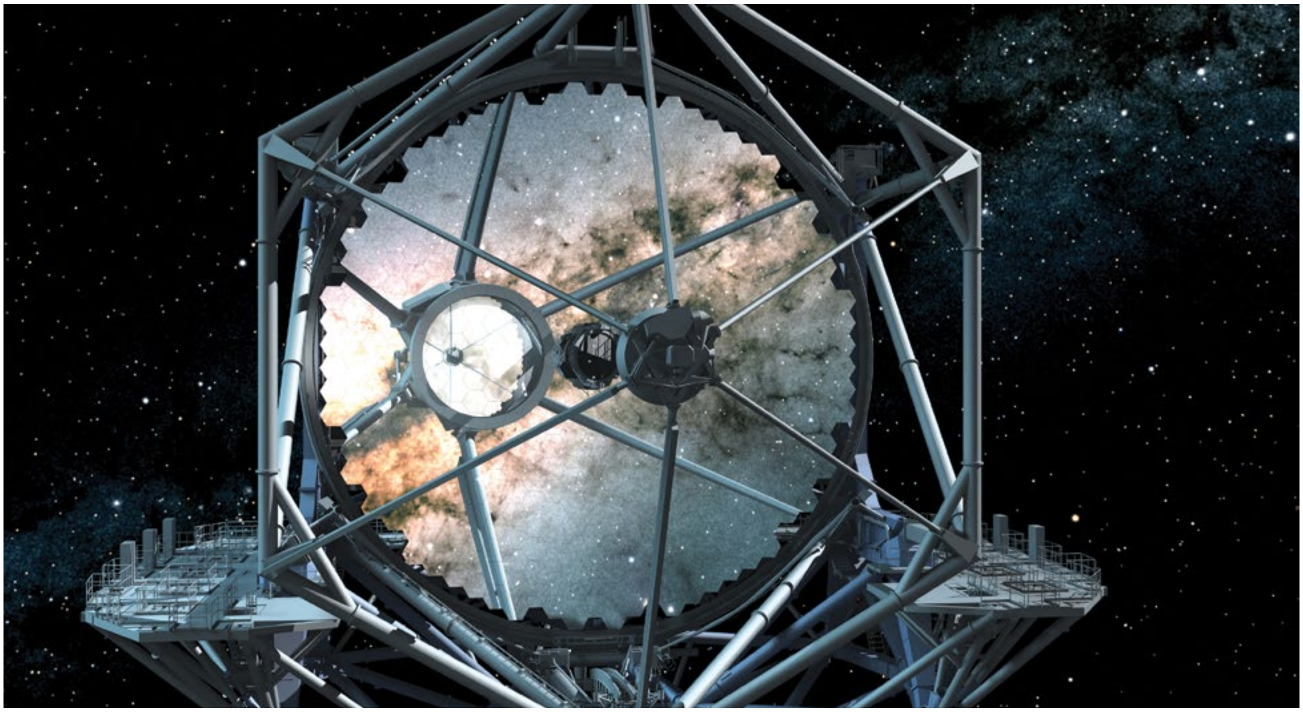
VLOT

A Very Large Optical Telescope (VLOT) is defined as an optical/infrared facility with a mirror diameter of approximately 30 metres. This is around ten times the collecting area of the world's largest current telescopes, and represents the scale of facility needed to answer frontier questions in observational astronomy, including discovery and characterization of exoplanets, the oldest Milky Way stars and the first galaxies, new tests of general relativity and cosmology, measurements of supermassive black holes in nearby galaxies, and detection and spectral characterization of distant icy bodies in the solar system. Three VLOTs are being planned or constructed: the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT), and ESO's Extremely Large Telescope (ELT).

Canadian access to and participation in a VLOT has for decades been a very high priority for the community (i.e., in both LRP2000 and LRP2010). Based on this support, Canada has been actively involved in the TMT project since the founding of the TMT Observatory Corporation in 2003. India, China, Japan, and several US-based institutions are all also current partners in the project. TMT was poised in LRP2010 to be a major success of the 2010–2020 decade. Indeed, in April 2015, Prime Minister Stephen Harper announced $243.5M to support TMT construction and an envisaged 15% Canadian share of observing time. Canadian astronomers are playing leadership roles in TMT science planning and instrumentation development. Canadian industry is also heavily engaged in the project, particularly through design and construction of the enclosure.

In 2009, the TMT Board of Directors selected Maunakea in Hawaiʻi as the preferred site for TMT. With GMT and ELT both being built in Chile, TMT is the only VLOT planned for a northern hemisphere site. The proposal to site TMT on Maunakea had formal support from some groups in Hawaiʻi, including in 2009 from the Board of Trustees of the Office of Hawaiian Affairs (OHA). A Conservation District Use Permit for Maunakea was obtained in 2013, and construction began in 2014 with a groundbreaking and blessing ceremony. However, interventions by Native Hawaiian protectors of the mountain and a 2015 revocation of the TMT construction permit led to a halt on all site work. In 2015, the OHA Board of Trustees rescinded its support for the selection of Maunakea as the site for the proposed TMT project, and no longer has any official position on this matter.

45 Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawaii ends in 2033.



Artist concept of TMT Primary Mirror. Image credit: TMT International Observatory

In October 2018, the Supreme Court of Hawaiʻi upheld the Conservation District Use Permit issued to TMT by the Hawaiian Board of Land and Natural Resources, and a "notice to proceed" with construction was issued in June 2019. Recommencement of construction was planned for July 2019, but demonstrators again intervened. No further construction activity has taken place. A series of discussions between all involved parties and across the Hawaiian community began in July 2019 and is continuing; at the time of writing, there has been no public outcome from these discussions.[46]

The importance of the TMT project to Canadian astronomy is well understood by astronomers, by NRC, and at higher levels of government. In 2016, in response to the reality that siting on Maunakea was not guaranteed, CASCA and ACURA assembled an ad hoc committee[47] to provide an analysis of several proposed alternative sites. This analysis included engagement with the national community of professional astronomers, and was provided to the TMT Board. In October 2016, the Board selected Observatorio del Roque de los Muchachos (ORM) in the Canary Islands as an alternate site for the TMT. The ORM site offers a site of sufficient quality to execute TMT core science, provides relevant existing infrastructure, and maintains TMT's standing as the only VLOT located in the northern hemisphere. The delay from the planned 2014 construction start means that the TMT timeline is now several years behind those of the ELT and GMT, both of which have begun construction. Because of this delay, there is a significant risk that Canadian astronomers will be disadvantaged against astronomers from other countries when foundational discoveries begin coming from the ELT and GMT. It is crucial that Canadians secure at least some initial access to ELT and/or GMT as the VLOT era begins.

A VLOT's key technologies and capabilities will enable transformational science. A major Canadian contribution to the TMT project is the NFIRAOS adaptive optics system, the culmination of many decades in pioneering Canadian leadership in this field. NFIRAOS will open up fundamentally new capabilities, increasing sensitivity by a factor of more than 200 over that of current 10-metre class telescopes and enabling unprecedented precision astrometry of both Galactic and extragalactic objects. These capabilities will provide transformative observations of gravitational lensing and microlensing, proper motions of Local Group galaxies, fueling and feedback mechanisms for active galaxies, exoplanets, protoplanetary disks, and much more. Despite

46 Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around TMT and because the current master lease under which astronomical use of the mountain is managed by the University of Hawaii ends in 2033.

47 This committee was succeeded by the CASCA-ACURA TMT Advisory Committee (CATAC), which continues to advise both CASCA and ACURA on TMT-related issues and also provided input to LRP2020.

the challenges of deep mid-infrared observations from the ground, the high spatial and spectral resolution that can be achieved with a VLOT enables some very exciting exoplanet science that Canadians are eager to tackle. Imaging sub-Saturn mass planets at a separation of 10 astronomical units, detecting biosignatures in transit spectroscopy of Earth-like planets, and measuring the distribution of complex, life-related molecules in protoplanetary disks will all be made possible. There will be a competitive process for designing and constructing successive generations of VLOT instruments. Canada already has ongoing involvement in the development of high-resolution spectrographs on both TMT and ELT, and has ambitions for other instrumentation concepts in future development cycles. The new large-scale integration and test facility at NRC-Herzberg, built for the construction of NFIRAOS, can also be used to enable future Canadian VLOT instrumentation.

While highly-multiplexed spectrographs on 10-metre-class telescopes will dominate wide-field spectroscopy, large samples of very faint objects require the collecting area of a VLOT. The large aperture of a 30-metre telescope provides the sensitivity needed to explore the stellar populations of faint and low surface brightness galaxies, quasar and galaxy outflows, low-mass satellite dynamics, the initial-final mass relation in stars, low-mass halo stars and white dwarfs, supernovae, and many other topics. TMT in particular is designed as an agile extremely large telescope, well-suited for rapid response, targets of opportunity, and time-variable science. Instruments that can take advantage of this are poised to have a big impact on the largely unexplored field of transient phenomena that vary on timescales of less than a day, in a way that cannot be matched by GMT or ELT. Measurement of radial velocities in objects with very short orbital periods enables, for example, the characterization of high-mass neutron stars, X-ray binaries, exoplanet transits, and close white dwarf binaries (which are the presumed progenitors of some supernova explosions and are potential gravitational wave sources).

Recommendation
We recommend that Canada participate in a VLOT, and that this participation be at a level that provides compelling opportunities for Canadian leadership in science, technology and instrumentation. Canadian access to and participation in a VLOT remains the community's highest ground-based priority; NRC, CASCA and ACURA must ensure that Canada's share in a VLOT remains at the level needed to fulfil the community's ambitions and requirements for scientific discovery, and to maintain a leadership role in facility governance and overall science and technology development. Canada has been a significant partner in TMT since 2003 and has a clear scientific and technical leadership role enabled by funding and support from the federal government and NRC. Noting that the situation is complex and rapidly evolving, at the time of writing Canadian VLOT access is best implemented by continued participation in TMT, either at the currently proposed Maunakea site or at the scientifically acceptable alternative of Observatorio del Roque de los Muchachos. Canadian participation in TMT or in any other VLOT should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed site from Indigenous Peoples and traditional title holders (see recommendation in Chapter 7).

Recommendation
We recommend that the Canadian community maintain its leadership and expertise in VLOT instrumentation development, which will ensure access to instruments that meet the needs of the community.

Recommendation
We recommend that NRC address any lack of access to a VLOT due to delays in TMT construction through arrangements that give Canadians access to other VLOT facilities.

Ground-Based Facilities: Radio, Millimetre and Submillimetre

Canada has decades of leadership in astronomical observations at radio, millimetre and submillimetre frequencies, with highlights ranging from the first ever very long baseline interferometry experiment in 1967, to the 1,000+ fast radio bursts that have now been discovered by the CHIME telescope. The future of Canadian astronomy at these frequencies is especially exciting, with opportunities covering both Canadian born-and-bred experiments and large international facilities, and with observational capabilities from 10 megahertz up to 1,000 gigahertz. In this section we review the radio, millimetre and submillimetre facilities that have been considered for LRP2020, and provide specific recommendations for those programs considered as key priorities for the next decade of discovery. Facilities are listed in alphabetical order, with recommendations from Chapter 5 repeated where appropriate.

Table 6.4: Costs and schedules for recommended ground-based radio and submillimetre facilities (in alphabetical order; see Chapter 5 for prioritizations and categorizations). Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change.

Project	Anticipated Cost to Canada		Canadian Share of Observing Time[48]	Construction Start	Operations Start
	New Construction Costs	Operations			
ALMA	N/A	US$1.8M/year (Canadian contribution in calendar year 2020)	Not fixed[49]	2003	2011
CHORD	$23M	$0.6M/year	100%	2021	2023
CMB-S4 or comparable facility	$4M-$7M	$0.5M/year	Full access to survey data	2021	2026
ngVLA	US$130M in 2018-dollars	US$6M/year in 2018-dollars	6%	2025	2028 (early science)
SKA1	Observatory: $80M in 2017-dollars	Observatory:$8M/year[50] in 2017-dollars	6%	2021	2026 (science verification)
	SKA1 Regional Centre: $65M[51] in 2017-dollars				

ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) was the top-ranked priority for a new ground-based facility in the 2000 Long Range Plan. Ten years later, at the time of LRP2010, construction of ALMA's 66 dishes on the Chajnantor plateau in northern Chile was well underway; the first science observations took place in 2011. Since then, ALMA has proven itself to be a high-impact, high-demand observatory, with record numbers of proposals submitted to the past few annual calls and large numbers of highly cited scientific papers across topics from protoplanetary disks to high-redshift galaxies and quasars. Since Cycle 4 in 2016, ALMA has also begun to carry out large programs.

ALMA's scientific impact reaches into nearly every area of astronomy. Highlights include the first image of a supermassive black hole by the Event Horizon Telescope; Canadians led the analysis that extracted the physics, such as black hole mass and spin, from that image. A Canadian-led collaboration has shown that radio galaxies located in clusters and groups can drive molecular gas flows up to tens of kiloparsecs in altitude. Canadians are also leading innovative studies of proto-stellar, proto-planetary and debris disks, including the first systematic study of their morphologies and the location of gaps that can signal unseen planets. The first Canadian-led ALMA large program, Virgo Environment Traced in CO (VERTICO), will map 51 spiral galaxies in the nearby Virgo cluster and use a multi-wavelength approach to quantify the effect of cluster environment on the star-forming molecular gas.

The LRP2010 ALMA white paper laid out eight specific metrics that could be used to judge the success of Canada's participation in ALMA. These metrics ranged from publications to collaborations to student training and leadership in ALMA operations, as well as the successful completion of the Band 3 receivers and ALMA development projects. By these eight metrics, Canada's involvement in ALMA over the past decade has been an unquestioned success. To call out one particular criterion, Canadians are making excellent use of ALMA in training graduate students and postdoctoral researchers: over half of

48 For facilities that are not yet operational, the share listed is provisional or proposed. Note that the share of Canadian observing time is not necessarily derived from or related to the Canadian share of construction or operations costs.

49 Canadian users of ALMA compete for the 37.5% of ALMA time available to North American researchers, which means Canada has no guaranteed observing time allocation, imposing no minimums and limited by only the quality of the submitted proposals.

50 Average annual cost for 2021-2030 during the SKA1 construction phase, with costs ramping up towards the end of the decade.

51 Cost for a Canadian SKA1 Regional Centre over 2021-2030, including processing, storage, networking, and staffing costs.

ALMA anntennas stand among a winter wonderland in their home on the Chajnantor Plateau.
Image credit: ALMA (ESO/NAOJ/NRAO)

Canadian first-author ALMA papers published through to June 2018 were led by graduate students or postdocs. The first ALMA Large Program led within Canada (VERTICO) is also the first led by a postdoctoral researcher. The successful delivery of these wide-ranging goals argues strongly for Canada's continuing participation in operating and developing ALMA over the next decade and beyond.

The ALMA Observatory has identified a set of short and medium-term development goals that will keep ALMA at the cutting-edge of astronomy and allow it to continue producing transformational scientific results in future decades. The science ambitions of this "Roadmap to 2030" build on the demonstrated achievements of its original science goals. The Roadmap identifies three new science goals with a theme of cosmic origins. "Origins of Galaxies" seeks to trace key elements from the early universe to the peak of cosmic star formation via detection of dust continuum emission and the cooling lines of key atoms (i.e., carbon and oxygen) and molecules, such as carbon monoxide. "Origins of Chemical Complexity" seeks to trace the evolution from simple to complex organic molecules from interstellar gas through star and planet formation to individual solar systems. Finally, "Origins of Planets" sets a goal of resolving the terrestrial planet formation zone in the nearest star-forming regions via dust continuum observations. In addition, ALMA will continue to play a pivotal role in making increasingly more detailed images of supermassive black holes as part of the Event Horizon Telescope.

ALMA's key science goals for the 2020s in turn motivate new technical developments. Over the next decade, the focus is on expanding the spectral bandwidth of ALMA by a factor of at least two, leading to a corresponding decrease in the integration time required for a variety of scientific programs. This increase in bandwidth requires upgrades to ALMA's receivers, electronics, and correlator. Improvements to the ALMA Archive are another important focus, particularly in the area of applying data mining to large spectral datasets. There are opportunities for Canadian participation and/or leadership in many of these development areas.

Recommendation

We recommend that Canada continue to fund the Atacama Large Millimeter/submillimeter Array (ALMA) at the amount needed to maintain our current level of access, that the Canadian community identify components of future ALMA development in which we can play a role, that Canadians continue to seek leadership of ALMA large programs, and that we keep Canadians fully trained and engaged in ALMA as new capabilities become available. ALMA is an unquestioned success story, and has become a world-leading scientific facility that has had significant Canadian uptake, benefit, and output. ALMA remains the key facility for answering many frontier scientific questions. In the 2030s and beyond, there will be many exciting options for ALMA upgrades and expansions, which are likely to be considerations for future mid-term reviews and long-range plans. Canadian participation in ALMA should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 7).

CHORD

The Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) is a pan-Canadian project, designed to work with and build on the success of the Canadian Hydrogen Intensity Mapping Experiment (CHIME). CHORD will be an ultra-wideband array of a large number of small-diameter dishes, providing extreme sensitivity over 300–1,500 megahertz over a large field-of-view. CHORD will consist of a central array of 512 6-metre dishes sited at the Dominion Radio Astrophysical Observatory (DRAO) near Penticton BC, supported by a pair of distant (1,000–3,000 km) outrigger stations, each equipped with CHIME-like cylinders and a 64-dish array. With breakthrough sensitivity, bandwidth, and localization capabilities, CHORD will elucidate the nature of fast radio bursts and their precise location within galactic hosts; map the distribution of matter on cosmic scales to reveal the detailed evolution of structure in the Universe; and measure fundamental physics parameters, such as probing neutrino properties and testing General Relativity.

Canadian researchers are leading every aspect of CHORD, and will be developing the critical technologies, analyzing the world-leading data set, and making the crucial discoveries. CHORD will be a national effort that deepens the relationships that have developed in Canada's radio astronomy community through previous CFI-funded collaborations. The core institutions include

McGill, the University of Toronto, UBC, the University of Calgary, the Perimeter Institute, and NRC Herzberg, with all Canadian astronomers able to participate in the science teams. CHORD will also enhance the capabilities of the DRAO site and its infrastructure, serving the broad Canadian astronomy community. Internationally, the team will continue their successful partnerships with world-leading groups and forge new links.

The CHORD team is seeking $23M for construction and operation of this facility. The design and costing are based on previous experience with the CHIME and CHIME/FRB projects, both of which were delivered on time and on budget, and are meeting or exceeding performance specifications. Costing for the dishes has been provided by NRC. Seed funding to design and prototype the outrigger stations has been secured from the Gordon and Betty Moore Foundation, part of larger in-kind and cash contributions already pledged or secured. CHORD will have very low operation costs. The outrigger stations and cylinders are under development already, and will be fully commissioned and operating in two years. Once funding is secured, it will take 1–2 years to finalize the design of the dishes for the core and outriggers, and 2–3 years for full construction.

Key technologies required for CHORD have been demonstrated in laboratory settings, and the majority are already operating on-sky in fielded prototype systems. Concerns about handling and processing the deluge of raw data have been largely retired with CHIME's success. For placement of the outriggers, the team is in discussions with existing radio observatories such as Algonquin in Ontario, and Green Bank, Owens Valley and Hat Creek in the USA.

Recommendation

We recommend funding and implementation of CHORD. CHORD is a unique facility that leverages existing Canadian world scientific leadership, designed from the outset as a national facility. The expansion of capabilities and community access from CHIME will enable exciting and timely science on fast radio bursts, line intensity mapping, pulsars, and many other science areas. The very large data flows anticipated from CHORD will require an expansion of Canada's digital research infrastructure capabilities in radio astronomy, and will help the community prepare for the data challenges of SKA1. Construction and operation of CHORD should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 7).

CMB-S4

The Cosmic Microwave Background Stage 4 Experiment (CMB-S4) is envisioned to be the ultimate ground-based cosmic microwave background experiment. Studies of the cosmic microwave background address the questions of how the universe began and the nature of its extreme conditions. The core science case for CMB-S4 includes the search for primordial gravitational waves as predicted from inflation, the imprint on the cosmic microwave background of relic particles including neutrinos, and unique insights into dark energy and tests of gravity on large scales. Facilities at the scale of CMB-S4 are the culmination of a long and strong set of Canadian contributions in this field, recognized by the 2008, 2012 and 2018 Gruber Cosmology Prizes, and by the 2020 Breakthrough Prize for New Horizons in Physics. The CMB-S4 sensitivity to primordial gravitational waves will probe physics at the highest energy scales and cross a major theoretically motivated threshold in constraints on inflation. The CMB-S4 search for new light relic particles will shed light on the early Universe ten thousand times farther back than current experiments can reach.

CMB-S4 is a collaboration between experimental efforts, bringing together previously competitive groups to begin science operations in 2026. Canadian designs for the readout electronics are one of the core proposed technologies. CMB-S4 is largely funded through partnerships between the US National Science Foundation and Department of Energy. For Canada to become a builder participant in CMB-S4 will require significant funding for the development of infrastructure and a dedicated pipeline team. The level of required Canadian contribution to construction is estimated at $4M–$7M, as could be obtained through a future CFI proposal.

As discussed below, there are recent plans for a significant extension to the Simons Observatory called "SO-Enhanced." The relationship between CMB-S4 and SO-Enhanced is still evolving, and neither project is yet fully funded. It is possible that Canadian cosmic microwave background researchers will need to choose which of these projects to participate in, and it is also possible that only one of these projects will proceed to construction. We focus on CMB-S4, but note that our recommendations apply equally to other cosmic microwave background experiments with comparable science capabilities.

Recommendation
We recommend participation in the Cosmic Microwave Background Stage 4 (CMB-S4) experiment, or other comparable facility. Involvement now will let us take leadership roles in defining the overall project. Canadians are world-leaders in all areas of cosmic microwave background research, including detector readout systems, systems integration, pipeline, mapmaking, theory, and interpretation. For continued leadership in this field, it is essential that Canada be involved in CMB-S4 or another comparable facility. Such participation is also highly complementary to LiteBIRD, which we recommend as a space-based priority below. Canadian participation in CMB-S4 or a comparable facility should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 7).

FYST

The Fred Young Submillimeter Telescope[52] will be a millimetre/submillimetre 6-metre single-dish telescope that will do important science in tracing large-scale galaxy distributions, probing dusty, obscured star formation, and measuring polarized cosmic microwave background foregrounds. Single-dish telescopes like FYST fill a crucial role in surveying large areas of sky; interesting sources found in such surveys can then be studied in further detail with interferometers like ALMA. FYST is also an important technological precursor to CMB-S4 and the Simons Observatory.

An international consortium led by Cornell University is building FYST on Cerro Chajnantor in northern Chile, for completion by 2023 at a total cost of $90M including five years of operations. The very low precipitable water vapour at FYST's high-altitude site offers an unparalleled mapping speed at its highest observing frequency (860 gigahertz). Canadian astronomers contribute broadly to the FYST collaboration and propose to build Prime-Cam (PCam), the powerful, first-light camera for FYST. The wavelength coverage, sensitivity, spatial resolution and large field-of-view of PCam on FYST will allow it to perform an impressive set of wide-area surveys.

Canadian involvement in FYST is led by a consortium of universities that have secured funding through institutional and individual grants. The Canadian FYST team seeks to fund shipping, assembly, and commissioning of the telescope in Chile and the PCam module construction. We encourage Canadian participation in FYST, as a complement to participation in ALMA, CMB-S4, and other far-infrared and submillimetre facilities.

JCMT and Future Large Submillimetre Single-Dish Telescopes

The James Clerk Maxwell Telescope (JCMT) is a 15-metre single-dish located at the summit of Maunakea on Hawaiʻi, and currently observes at 350 and 660 gigahertz. The JCMT has had two core instruments over the past decade, SCUBA-2 and HARP. SCUBA-2 is a revolutionary large-format bolometric camera with substantial Canadian contributions, accompanied by two Canadian ancillary instruments, a Fourier transform spectrometer and a polarimeter. HARP is a 4x4 focal-plane array of heterodyne receivers, built by the UK with Canada contributing the correlator.

JCMT has had a broad science impact spanning more than thirty years. Notable Canadian work over the last decade includes leadership of large surveys on deep cosmological fields, nearby galaxies, the Galactic Plane, star-forming molecular clouds in the Gould Belt, debris disks, magnetic fields in star-forming regions, and time-variability of protostellar sources. Canada was a 25% partner in JCMT from first light in 1987 through 2014, when national participation in this facility formally ended as recommended in LRP2010 and preceding reviews. MTR2015 supported efforts to maintain Canadian access to JCMT through various university coalitions, and the Canadian submillimetre community successfully obtained such support from 2015 through to 2019. JCMT is currently operated by the East Asian Observatory, while the CADC continues to host the JCMT Science Archive as an in-kind contribution. Canadian astronomers were eligible to lead large JCMT observing program proposals in 2019 and to join accepted new large programs in 2020; there is no guarantee that this access will continue in the future.

A consortium of Canadian universities led by McMaster University hopes to contribute toward construction of a new submillimetre continuum camera, which is envisaged to be JCMT's marquee instrument for the next decade.[53] This camera will be able to map star formation and galaxy formation twenty times faster than SCUBA-2. The wide-field mapping capabilities of this new camera

52 Formerly known as CCAT-prime, FYST is a smaller and descoped version of the CCAT concept that was discussed in MTR2015.

53 Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section above) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawaii ends in 2033.

will make it a powerful discovery instrument for at least ten years: it will serve as a valuable complement to the high-resolution capabilities of ALMA, enhancing the Canadian community's ability to obtain large amounts of ALMA observing time. We encourage continued participation in JCMT through individual funding efforts.

There is also significant Canadian interest in more ambitious proposals for large (25+ metre diameter) single-dish submillimetre telescopes such as CCAT-25 and AtLAST. A broad and compelling science program will be one key component of a national path toward participation in such a facility. We support continued development of such concepts, and anticipate discussion of a science and business case for such telescopes in MTR2025.

ngVLA

The Next Generation Very Large Array (ngVLA) is a transformational radio observatory being designed by the US National Radio Astronomy Observatory (NRAO). The ngVLA will consist of a central cluster of 19 (6-metre) dishes in New Mexico, a further 214 larger (18-metre) dishes distributed throughout the US Southwest, plus another 30 (18-metre) dishes spread across North America (including the DRAO site near Penticton, BC), Hawai'i[54] and the Caribbean out to baselines of nearly 9,000 km. The ngVLA will provide order-of-magnitude improvements in sensitivity and angular resolution over the current Karl G. Jansky Very Large Array (VLA), and provide continuous frequency coverage from 1.2 to 116 gigahertz.

Observations with the ngVLA will address many aspects of the science questions articulated in Chapter 4. Key science goals for ngVLA include unveiling the formation of solar-system analogues on terrestrial scales, probing the initial conditions for planetary systems and life, charting the assembly, structure, and evolution of galaxies from the first billion years to the present, using Galactic Centre pulsars to make fundamental tests of General Relativity, and understanding the formation and evolution of stellar and supermassive black holes and compact objects in the era of multi-messenger astronomy.

The ngVLA project is awaiting a recommendation from the US Astro2020 decadal survey. The construction cost of ngVLA is estimated at US$2.25B, plus operations costs of US$93M/year. NRAO is seeking international partnerships that will provide 25% of construction and operation costs; the LRP2020 white paper on the ngVLA proposes Canadian participation in the ngVLA at the 7% level. As with other ground-based facilities, radio-frequency interference from satellite constellations (e.g., Starlink) has recently emerged as a possible technical risk to the ngVLA. The effects of this interference are currently unknown, and have not been considered as a basis for the recommendation provided here.

Canadians have been vigorous users of the current VLA. For example, 15% of all VLA papers have had at least one Canadian co-author, with 5% of VLA papers having a Canadian lead. Canadians have been involved in scientific leadership of ngVLA from the very start, are active members on the Executives of the ngVLA's Science Advisory Council and Technical Advisory Council, are leading the organization of science-use case studies and ngVLA-related science meetings, and envisage substantial potential for technical leadership on ngVLA development (e.g., in NRC's composite dish technology also planned for use in CHORD). It is important to note that the science capabilities of ngVLA, SKA1 and ALMA all complement rather than duplicate or compete with each other, and that there is commonality between proposed Canadian technical contributions to ngVLA and SKA1. The ngVLA and SKA1 have evolved with this synergy in mind: the original SKA concept included high-frequency capability similar to that of ngVLA, and the SKA1 and ngVLA projects are investigating a process to establish a scientific alliance. The combination of ngVLA, SKA1 and ALMA can provide Canadians access to next-generation radio observing capabilities over an almost continuous frequency range from 50 megahertz to 950 gigahertz, positioning Canada to be a major player in global radio astronomy in the 2030s and beyond.

Recommendation

We recommend that Canada pursue technical contributions to and scientific leadership in the proposed Next Generation Very Large Array (ngVLA), pending a positive recommendation on this project from the US Astro2020 Decadal Survey. The capabilities provided by the ngVLA will enable transformational science across many areas of astrophysics. Canada should correspondingly seek engagement with ngVLA that would result in a ~6% share of observing time, comparable with the access sought for SKA1. Canadian participation in ngVLA should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any ngVLA sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 7).

We recommend that Canada focus its technical contributions to ngVLA on areas that leverage existing or ongoing Canadian work on SKA1 and other facilities. We also encourage exploration of the proposed scientific alliance between SKA1 and ngVLA, which would allow an exchange of observing time between the two facilities.

54 NRAO is considering various ngVLA sites in Hawai'i, but there are no plans to place any ngVLA dishes on Maunakea.

Simons Observatory (SO)

The Simons Observatory (SO) is a cosmic microwave background experiment currently under construction in the Chajnantor Science Preserve in the Atacama Desert in Chile. The originally defined concept, "SO-Nominal," will be sensitive to both temperature and polarization anisotropies in the cosmic microwave background, and will operate in six bands covering 27 to 280 gigahertz in two separate telescope configurations: three 0.5-metre telescopes to map the sky on large angular scales, and one large-aperture 6-metre telescope for high-resolution science. SO-Nominal will have a total of 60,000 cryogenic bolometers, with first light anticipated for 2023. An upgrade pathway to double the mapping speed by 2025 has also been proposed: this "SO-Enhanced" program adds more dishes and detectors, and adds five years of operations. This would require substantial additional funding, and is awaiting a recommendation by the US Astro2020 decadal survey process.

SO-Nominal is a logical step toward the next-generation cosmic microwave background science goals discussed for CMB-S4 above. An iterative approach has been very successful over the past thirty years of cosmic microwave background research, and the SO collaboration has developed technology and pipelines that are directly applicable to CMB-S4 and LiteBIRD.

SO-Nominal has been funded by a combined US$40M grant from the Simons Foundation, Heising-Simons Foundation and participating US institutions, including Princeton University, the University of California at San Diego, the University of California at Berkeley, the University of Pennsylvania and Lawrence Berkeley National Laboratory. Various Canadian institutions and individuals have been contributing to SO-Nominal through in-kind analysis and computing, but future participation will require cash funding to be applied toward instrumentation and development of the analysis pipeline. We encourage the cosmic microwave background community to pursue the funding required for meaningful participation in SO-Nominal, which is estimated to be at the level of $1M–$2M, and which would give Canadian researchers standing within the SO governance structure. Canadian participation in the more ambitious SO-Enhanced project would require additional funding and would likely require a choice between involvement in SO-Enhanced and CMB-S4, as discussed in our recommendation on CMB-S4 above.

SKA1

The Square Kilometre Array (SKA) is an exciting global observatory that will enable transformational research on the history, contents, extreme conditions, and prospects for life in the Universe. The SKA will be built in two phases, with the first phase (SKA1) representing about 10% of the full facility (SKA2).[55] SKA1 will consist of two sites: an array of ~200 mid-frequency dishes (SKA1-Mid, covering the frequency range 0.35–15.3 gigahertz) in the Karoo region of South Africa, and an array of ~130,000 low-frequency antennas (SKA1-Low, covering 0.05–0.35 gigahertz) in outback Western Australia, with headquarters at Jodrell Bank Observatory in the UK. SKA1 will be the largest and most powerful wide-field radio telescope for the foreseeable future.

The technical specifications, science requirements and anticipated scientific performance of the SKA1 Design Baseline are well established, and almost all elements of that design have passed critical design review (CDR). The System CDR pass in December 2019 confirmed that the Baseline Design is also complete at the system level, and therefore that the project is ready to transition from the design phase to the construction phase; construction is set to commence in 2021.

Scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the last two decades. SKA1 is poised to make fundamental advances across a broad range of fields by virtue of its combination of sensitivity, angular resolution, imaging quality, survey speed and frequency coverage. The scientific goals for SKA1 align well with the strengths of Canadian researchers. Canada is a world leader in studies of pulsars, cosmic magnetism and transients, as well as in low-frequency cosmology. Our multi-wavelength expertise in galaxy evolution, multi-messenger astronomy and planetary system formation—in which radio observations play a critical part—is also a key strength. The Canadian community therefore has the potential to play world-leading roles in a number of the transformational projects to be carried out with SKA1. A proposed 6% participation in the SKA1 Design Baseline is well-matched to Canadian scientific capacity and ambitions. This commitment is estimated to cost $160M in construction and operations contributions over the period 2021–2030.

55 SKA2 is not yet defined or costed, nor is it related to SKA1 commitments. Once this information exists, future MTRs or LRPs should consider the prospects for Canadian participation in SKA2.

Artist rendition of the SKA1-Mid dishes in Africa. Image credit: SKA Organisation

Canada is a leader in technological development for SKA1 through effective partnerships between universities, NRC Herzberg and industry. Canada's key SKA1 technological capabilities include the design and fabrication of correlators and beamformers, digitizers, low-noise amplifiers, signal processing, and monitor and control. These technologies provide a suite of possible in-kind contributions to offset construction costs, yielding an excellent return on the capital investment required to participate in SKA1 at a level commensurate with our scientific ambitions.

A network of SKA1 Regional Centres (SRCs) will be needed to handle the global science processing, archive and user support needs for SKA1. Canada has the computing platform and archive development expertise to make important contributions to the SRC network that will deliver global SKA1 scientific computing capability. A Canadian SRC would leverage our national computing strength and would provide processing, storage and user support tailored to Canadian SKA1 needs, thereby allowing Canadian astronomers to fully exploit the scientific capabilities of SKA1. The cost of a Canadian SRC (covering both construction and operations) is estimated to be $65M (in 2017-dollars) for the period 2021–2030, over and above the construction and operations funding indicated above for the telescope itself; this cost would be part of the total request for SKA1. Because Canada's involvement in SKA1 may be at the intergovernmental treaty level, this computing infrastructure would likely require a separate funding stream from that for general computing resources discussed in the "Digital Research Infrastructure" section above. The infrastructure could be operated by NDRIO, NRC-CADC, universities, or some partnership of these organizations.

Canadian contributions to SKA1 now span twenty years, marked by scientific and technological leadership that persists today within a vibrant metre- and centimetre-wave radio community. Canada at last has the opportunity to reap the scientific benefits of our contributions; an early commitment to construction would maximize our impact on this phase and our technological benefits.

The SKA project is planning to soon become an Intergovernmental Organisation (IGO), governed by a treaty ratified by all participating countries. Canada currently holds Observer status on the Council Preparatory Task Force of the SKA IGO, which is an important step towards participating in SKA1 construction and operations. However, Canada risks forfeiting the opportunity to provide scientific and technical leadership in SKA1 if a path to participation in the IGO is not identified and defined. Lack of IGO participation would also mean we risk missing out on construction tender and procurement, which would significantly worsen the cost-benefit ratio of SKA1 participation.

Recommendation

We recommend that Canada participate in the construction and operation of Phase 1 of the Square Kilometre Array, in its network of regional centres, and in the project's governance. This will allow Canada to play a world-leading role in a number of transformational projects to be carried out with SKA1. The scientific goals of SKA1 align well with the strengths of Canadian researchers, and scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the past twenty years. Canada's highest priority for radio astronomy should be to fund and participate in SKA1 Design Baseline construction, operations, the accompanying network of regional centres and a staged technology development program at an overall 6% level, commensurate with Canadian scientific ambitions. We emphasize that developing the relevant infrastructure, incorporating the capabilities of a Canadian SKA1 regional centre or equivalent, is necessary for successful Canadian participation in SKA1, and will ensure community access to the processing, storage and user support required to scientifically exploit SKA1. Canada should identify a membership model for Canadian participation in the SKA Intergovernmental Organisation that can provide leadership rights for Canadian researchers and industry, with full scientific access and maximal opportunities for technological tender and procurement. Canadian participation in SKA1 should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of SKA1 sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 7).

CASE STUDY

Ultra-sharp Vision from a Balloon-Borne Telescope

Student-built technology produces the ultimate steadicam

SuperBIT will next fly in 2022 for around

100 days

and will collect thousands of dramatic new images of the cosmos

← SuperBIT launch in Timmins, Ontario, Sep 2019.

Image credit: SuperBIT team

Canadian astronomers don't just build telescopes on the ground or in space, but also on balloons. The latest such experiment is the **Super-pressure Balloon-borne Imaging Telescope**, or **SuperBIT**, which is producing images as good as those from the mighty Hubble Space Telescope, but at one-thousandth the cost.

By flying at an altitude of around 35 km, SuperBIT gets above 99% of the atmosphere, allowing spectacularly sharp images like those obtained by Hubble. However, to avoid a blurry image, the camera has to remain rock steady while taking the photo. On a balloon this can be extremely challenging, especially for the 30-minute exposures needed to study very faint stars and galaxies.

The SuperBIT team, based at the **University of Toronto**, has solved this problem using advanced cameras, precision gyroscopes and rapid computing. These re-adjust the pointing of SuperBIT's camera hundreds of times per second to compensate for the swaying of the balloon's motion.

The resulting precision is extraordinary: the camera's steadiness in test flights has been equivalent to aiming a laser through the eye of a needle five kilometres away, without wavering, for 30 minutes straight! SuperBIT will next fly in 2022 for around 100 days, and will collect thousands of dramatic new images of the cosmos.

SuperBIT will provide unique information on the nature of Dark Energy, while offering a superb training environment for the next generation of scientists and engineers. The team is comprised almost entirely of students, who get the opportunity to design and build the camera, fly the balloon and then analyze the data, all within the timespan of a 5-year PhD.

Experiments like SuperBIT let scientists test technology that might only be months old, in contrast to the decades of development that go into a space mission. Indeed, many of the ideas developed on Canadian balloons have later found their way into much bigger space missions.

SuperBIT is just the beginning. Next will come GigaBIT, which will be so powerful that one balloon flight of a few months will surpass the 30 years of data collected by Hubble.

The future is bright for Canadian ballooning, which continues to be a uniquely powerful way of studying the sky. ◆

Space Astronomy Missions

Observations from space are a key aspect of astronomy because of freedom from atmospheric weather, absorption and distortion, and because some wavelengths are not observable from the ground. Access to and participation in space observatories are an essential element of Canadian astronomy across the entire range of research interests. Canada has played a significant role in past and ongoing space observatories, and has earned a deserved reputation for hardware, data handling, and scientific exploitation. In this Section we discuss the space-based facilities that have been considered for LRP2020. Although Chapter 5 lists the recommended missions in priority order, in this section we comment on all considered missions[56] in alphabetical order,[57] with recommendations from Chapter 5 repeated where appropriate. Additional recommendations to the Canadian Space Agency (CSA) and to the Joint Committee on Space Astronomy (JCSA) are provided in Chapter 7.

Table 6.5: Costs and schedules of recommended space astronomy missions (in alphabetical order; see Chapter 5 for prioritizations and categorizations). Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change.

Mission	Anticipated Cost to Canada[58]	Participating Agencies (lead listed first)	Anticipated Launch Time Scale[59]
CASTOR	\$250M-\$400M	CSA, ISRO, JPL? UKSA?	Late-2020s
JWST Operations	\$2.4M per year[60]	NASA, ESA, CSA	Late 2021
LiteBIRD	\$25M-\$40M	JAXA, ESA, NASA?, CSA	Late-2020s
NASA Flagships	Hardware: ~\$100M Science, Technical: TBD	NASA, ESA?, CSA	Mid-2030s
Cooled Infrared Space Telescope	TBD	CSA + TBD	TBD
POEP	\$15M[61]	CSA	Mid-2020s

ARIEL

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) is an approved medium-class space astronomy mission led by the European Space Agency (ESA). ARIEL will be a 1-metre telescope designed to obtain precise transmission spectroscopy over 0.5–7.8 micrometres for a large number of transiting exoplanets with hydrogen-rich atmospheres, from hot Jupiters to warm sub-Neptunes. It is scheduled for launch in 2028 and will be stationed at the Earth-Sun system's second Lagrange point ("L2"). During its 4-year mission, ARIEL will study the composition of exoplanet atmospheres and characterize their chemical gradients, structure, diurnal and seasonal variations, clouds, and albedo. ARIEL will observe about one thousand diverse exoplanets, and is highly complementary to JWST, which will realistically characterize only dozens of planets in its lifetime. A large sample is essential to understand the huge diversity of exoplanet atmospheres, how exoplanets form, and how they evolve. ARIEL is the

56 We do not address in this Chapter the opportunities provided by commercial satellites, since no specific proposals relating to such opportunities were made to the LRP2020 process. A broader recommendation on future involvement in commercial satellite programs is made in Chapter 7.

57 Except for NASA Flagships, which are discussed together.

58 Costs are estimates provided by each mission's Canadian principal investigator, and represent approximate total life-cycle costs (i.e., development, construction, launch, operations and science).

59 With the exception of JWST, these are estimates provided by each mission's Canadian principal investigator.

60 Support for the operations phase over the nominal JWST mission lifetime of five years; does not include costs incurred so far.

61 This does not include the launch costs, which are expected to be a small increment on the total cost.

BLAST-TNG launch from Antarctica, February 2020. Image credit: Federico Nati

only mission designed for and dedicated to performing a spectroscopic survey of a large, well defined sample of exoplanets. The ARIEL mission is of great interest to the Canadian exoplanet community, supplementing and supporting many of their ongoing and future projects. The mission is complementary to the POEP program (see below), which is planned to launch on a similar timescale.

The ARIEL consortium recently approached Canadians to convey their interest for Canada to join and contribute to the mission. A hardware contribution for one of two subsystems well matched to Canadian industry was proposed (the cryoharness or the AIRS detectors), as well as a contribution of the software pipeline. The cost of the hardware contributions is on the order of $5M and $15M, respectively. The Canadian industrial expertise to contribute these hardware components was developed and proven in building the NIRISS instrument for JWST. The cost for a software pipeline contribution is estimated to be about $3.5M.

Currently there are three Canadian faculty-level members in the ARIEL consortium. Going forward, community participation can be expanded through an open process should Canada join and contribute financially to the mission. We encourage participation in ARIEL as a complement to JWST, as part of a community roadmap on exoplanets, and as a science pathfinder for future missions.

ATHENA

The Advanced Telescope for High-ENergy Astrophysics (ATHENA) was selected by ESA in 2014 as a large-class mission, for launch in 2031. ATHENA is an X-ray telescope with an effective collecting area of ~1.4 m² at an X-ray energy of 1,000 electronvolts. Its two instruments include an X-ray integral field unit spectrograph (X-IFU), and the Wide-field Imager (WFI) for imaging and moderate-resolution spectroscopy over a large field of view. The primary science objectives for ATHENA are to map hot gas structures and determine their physical properties, and to search for and characterize supermassive black holes. Although Canadian involvement in Athena was prioritized in MTR2015, little progress has been made in determining any potential contribution. Thus while we encourage interested Canadian researchers to participate in this mission, there is not a case for a national contribution.

Ballooning

Stratospheric balloons offer near-space observing conditions for around 1% of the cost of an equivalent satellite, while also providing a platform to advance the technology readiness level of key systems for future space astronomy missions. Furthermore, balloon astronomy offers outstanding training opportunities: typical experiment timeframes allow graduate students to play a key role in instrument design, field campaigns, and scientific data analysis over the course of their degree.

The CSA's Stratospheric Balloon program (STRATOS) has provided launch opportunities to over 24 Canadian scientific balloon payloads since its beginning in 2012. Balloon launch support is provided by the Centre national d'études spatiales (CNES) of France, through a cooperation agreement with the CSA. Most of the launches that CNES has provided took off from Timmins, Ontario. However there have also been STRATOS launches from Kiruna, Sweden

(2016) and Alice Springs, Australia (2017). The time in the stratosphere for these flights has ranged from 10 hours to several days. For projects with US collaborators funded by the National Aeronautics and Space Administration (NASA), flights are also available through NASA's Columbia Scientific Balloon Facility (CSBF) from a variety of locations, including long duration (weeks long) flights from Antarctica.

Since 2011, funding for stratospheric balloon borne payloads has been provided by the CSA's Flights and Fieldwork for the Advancement of Science and Technology (FAST) program. There have been six completed calls for proposals. For balloon payloads involving a launch within the period covered by the award, the maximum total funding available over the course of a three-year award has ranged from $100k to $500k. Of this funding, a significant fraction of the award is meant to be devoted to training highly-qualified personnel, including undergraduate and graduate students, postdoctoral researchers, and other trainees. Multiple Canadian institutions may apply to FAST for the same project as long as the individual roles are clearly defined. Even so, this level of funding is adequate for a Canadian contribution to a multinational collaboration, but is insufficient to support an entire Canadian-led balloon project.

Within this context, there have been several highly successful balloon experiments with substantial Canadian involvement over the last decade, including the Balloon-Borne Large Aperture Sub-mm Telescope for Polarimetry (BLASTPol), the E and B Experiment (EBEX), the High Contrast Imaging Balloon System (HiCIBaS) and the SPIDER cosmic microwave background experiment. Current and upcoming projects supported by FAST include the Super pressure Balloon-borne Imaging Telescope (SuperBIT) plus its planned successor GigaBIT, the next-generation BLAST Polarimeter (BLAST-TNG), the Primordial Inflation Polarization Explorer (PIPER), and the High Energy Light Isotope eXperiment (HELIX).

To maintain leadership in astrophysical ballooning over the next decade, the Canadian astrophysical ballooning community has identified the following priorities:

- Continued support for HQP training and technology development;
- Gaining access to flights of several month durations using NASA's super-pressure balloon technology;
- Competitions to fund Canadian university groups to lead large experiments;
- Support for development of balloon gondolas and flight infrastructure systems that can be used by multiple experiments.

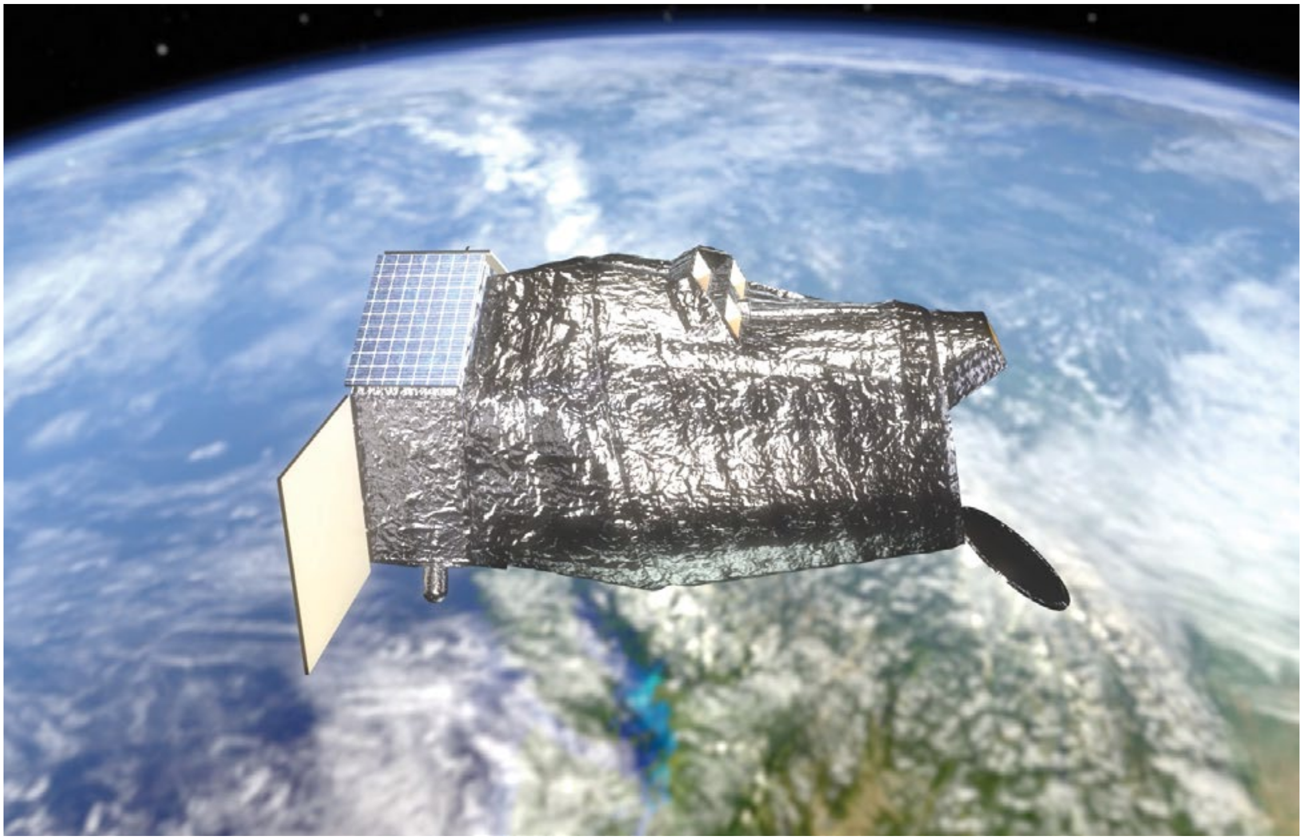
The LRP2020 panel notes the crucial technological, strategic and training benefits of balloon-borne astrophysics, and encourages the CSA to work with the ballooning community to achieve the above goals.

CASTOR

The Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) is a proposed Canadian-led 1-metre space telescope designed to provide both imaging and spectroscopy in the ultraviolet/optical spectral range (0.15–0.55 micrometres). Imaging with ~0.15-arsecond resolution will be obtained simultaneously in three passbands: UV (0.15–0.30 micrometres), u' (0.30–0.40 micrometres) and g (0.40–0.55 micrometres) over a 0.25-deg^2 field of view. The corresponding survey speed of CASTOR in ultraviolet/optical imaging will exceed that of the Hubble Space Telescope by roughly two orders of magnitude. In addition, the proposed spectroscopic capabilities for CASTOR include a multi-object digital micro-mirror spectrograph, providing moderate to high-resolution ultraviolet spectroscopy, and a grism mechanism yielding full-field, low-resolution spectroscopy in the UV and u' channels. Finally, a single detector placed in each of CASTOR's focal planes will allow precision photometric monitoring of bright exoplanet hosts. CASTOR has the potential to make transformational advances across a wide range of fields, probing the physics of star formation from our galaxy to the distant Universe through spatially-resolved ultraviolet/optical imaging, exploring the atmospheres of exoplanets through transit spectroscopy and photometry, improving constraints on dark energy through weak lensing measurements, studying the properties of the outer solar system through the discovery and study of small bodies, and localizing and following up electromagnetic counterparts to sources detected by gravitational-wave observatories.

CASTOR has been conceived as a CSA-led project. At the same time, international contributions are highly valued as they strengthen Canada's international ties, bring additional scientific and technical expertise to the project, and reduce the cost to Canada, making it possible to consider a mission of greater scope. Likely international partners include India (through the Indian Space Research Organization, ISRO), as well as JPL/Caltech/NASA. Other international partners potentially include the UK Astronomy Technology Centre and Laboratoire d'Astrophysique de Marseille (LAM) in France. The total mission cost for CASTOR with only imaging capabilities is estimated at around $400M; this includes launch and contingencies but excludes science support (~$20M). Adding the two spectroscopic modes mentioned above would add approximately $30M.

The highest recommendation from LRP2010 for Canadian Space Astronomy was for significant Canadian involvement in either Euclid or WFIRST (now renamed the Roman



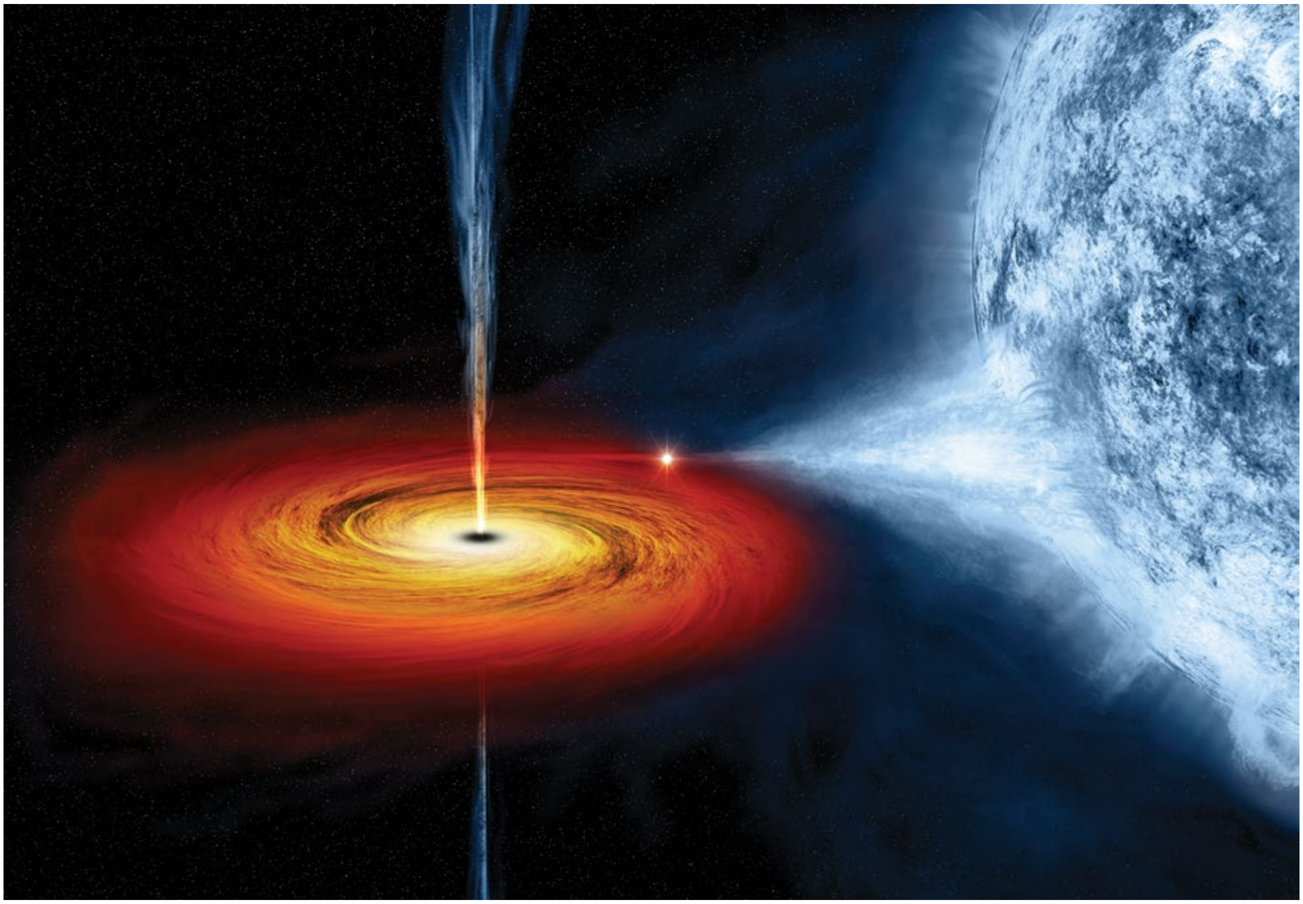
Artist's impression of CASTOR space telescope. Image credit: The Canadian Space Agency and CASTOR team

Space Telescope), or the development of a Canadian Space Telescope. The former has not come to pass. CASTOR would represent the long-awaited fulfillment of the latter, and a chance to revitalize Canada's space astronomy sector. The proposed timeline for CASTOR is as follows: a 12-month Phase A study (establishing system requirements) could begin as early as mid-2021. Phase B and C studies (i.e., preliminary and critical design reviews, respectively) would require 30 months. Fabrication, integration and testing (Phase D) would require approximately two years. Launch followed by the 60-month Phase E (operations) would thus occur in the late 2020s. This operational period would overlap with both LSST and the Roman Space Telescope, and possibly the final years of the Euclid and JWST missions. The baseline mission lifetime for CASTOR is a minimum of 5 years, and it would operate in a low-earth, sun-synchronous, dawn-dusk orbit, at an altitude of 800 km.

To maximize CASTOR's prospects of success, a development path for such large projects will need to be established within Canada, as part of a predictable and well-defined process for selecting, funding and maintaining a portfolio of major CSA science missions. In order to play the leadership role envisaged, the CSA must also secure the backing of international partners, whose interest in this project is high but who will soon need a clear commitment from Canada.

Recommendation

We recommend that the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) be approved for development toward launch. The CASTOR mission is a mature concept that has a world-leading and transformational science case, strong and long-standing community support, substantial interest and involvement from Canadian industry, and enthusiastic international partners who are looking to Canadian leadership to develop and fly a wide-field ultraviolet space telescope. CASTOR will also provide a superb complement to JWST and other forthcoming optical and infrared facilities. A top priority in MTR2015, CASTOR continues to be an outstanding prospect for Canada's first marquee space astronomy mission. It will be vital to engage with the federal government to fund this very large mission, and to work closely with international partners like JPL/NASA and IIA/ISRO.



Colibrì will study the accretion flows around black holes like Cygnus X-1, shown here in an artist's impression.
Image credit: NASA/CXC/M Weiss

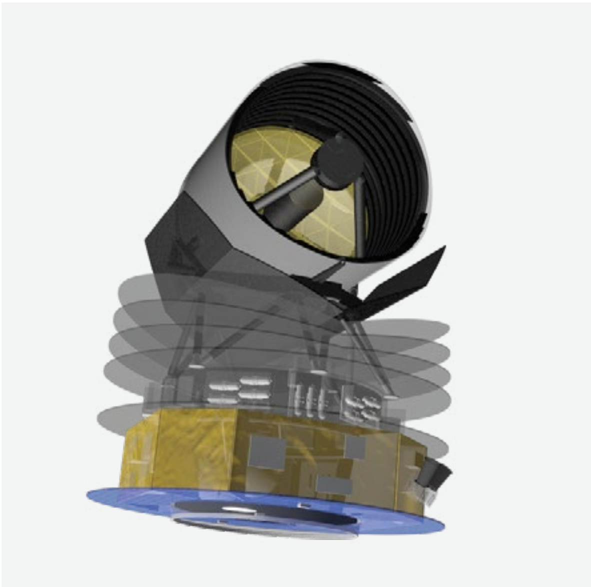
Colibrì

Colibrì is an X-ray telescope currently in the concept study phase. Colibrì will boast high spectral resolution, high throughput, and large effective area over the energy range 200–20,000 electronvolts (2,000 cm^2 at 6,400 electronvolts). Colibrì offers a similar energy resolution to the gratings on Chandra and XMM-Newton and to the bolometers on Hitomi, but with ten times the effective area of these missions. It is also envisioned to provide high time resolution, better than 1 microsecond, matching the innermost orbital period for a 10 solar-mass black hole. Key science goals for Colibrì include studying the structure of accretion flows in the vicinity of black holes and neutron stars, and the study of emission from the surfaces of neutron stars. It will also investigate the nature of spacetime around black holes, the physics of jet launching, and the properties of ultra-dense matter.

Colibrì is a Canadian-led mission concept, drawing on most of the Canadian high-energy astrophysics community. Potential additional partners include NASA for mirrors and transition-edge sensor (TES) detectors, the US National Institute of Standards and Technology (NIST) for TES detectors, the Canadian Light Source for testing and calibration, and NASA/ESA for launch. In early 2020, Colibrì completed an 18-month concept study funded by CSA, with Honeywell and MDA as industrial partners. The recommendations the team presented to the CSA as the path forward for continued development of the mission included a science maturation study and a number of technology studies that would increase the capacity of the Canadian aerospace industry, as well as further mission goals. The total estimated cost of Colibrì is $1.34B, including launch, with an estimated launch date of December 2032.

We encourage further study of Colibrì through the CSA's development time lines and funding schemes, accompanied by relevant science and technology development studies and the continued development of the required international partnerships.

Cooled Infrared Space Telescope



Notional design for a cooled infrared space telescope.
Image credit: SPICA team

The mid- through far-infrared spectral region is an important indicator of how, where, and when the galaxies in the Universe emit energy. This wavelength regime is also abundant in spectroscopic diagnostics, including those from light molecules such as H_2 and HD, important for direct determinations of gas mass. This is also the most important part of the electromagnetic spectrum for observations of water, in both gas and ice form, and thus a key probe into the pathway to life around stars. Furthermore, a wealth of fine-structure lines probes the ionized regions around hot stars and active galactic nuclei—providing essential diagnostics of temperature, metallicity, and hardness of the radiation field. Similarly, dust features manifest strongly in this window, including emission from polycyclic aromatic hydrocarbons (PAHs), silicates, minerals, and both crystalline and amorphous ices. When combined with the fine-structure lines, PAH and dust emission provide important diagnostics for the energy budget of galaxies. In this context, a space telescope with a cooled mirror, optimized for mid- through far-infrared imaging and spectroscopy, would open up a vast and unique discovery space and enable transformational discoveries in the study of galaxy evolution across cosmic time, the baryonic cycle in nearby galaxies, star formation in galactic molecular clouds, the evolution of protoplanetary disks, and exoplanet atmospheres. Such a mission would revolutionize our understanding of how the Universe, our Galaxy, our Sun, our solar system, and the Earth began and have evolved up to this point in time.

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA), led by ESA and JAXA, was a mission concept aimed to address these goals. Thanks to sustained investment by CSA over the past decade, Canada established substantial scientific, technical and strategic leadership in the SPICA mission, and was positioned to provide the high-resolution spectrometer, a contribution expected to be at a level of \$50M–\$60M. However, in October 2020 ESA and JAXA announced their decision to no longer consider SPICA as a candidate for ESA's Cosmic Vision Programme.

The SPICA community is still adapting to this disappointing development. Nevertheless, there remain many compelling reasons for Canada to continue to pursue participation in a future cooled infrared space mission. A combination of low telescope background and instruments employing state-of-the-art detectors can bridge the gap in capabilities between near-infrared and submillimetre observatories, and can offer a major advance in capability over previous highly successful far-infrared missions such as Herschel. Canada invested over \$6M in development activities for the high-resolution spectrometer on SPICA, and given the generic nature of the cryogenic technology development, it is estimated that over 80% of this investment could be repurposed for a future far-infrared opportunity. Canada should therefore continue investing in the technology developed for the SPICA mission, so as to be positioned for a significant instrument development role in other upcoming cooled infrared missions (of which NASA's Origins Space Telescope is one possibility as discussed below).

Recommendation
We recommend that Canada explore opportunities for substantive participation in a large, cooled, infrared international space observatory mission. Such a mission can leverage Canada's substantial scientific and technological leadership in infrared space astronomy derived from work on Herschel and SPICA, and can revolutionize our understanding of cold gas and dust throughout the Universe through unique access to far-infrared wavelengths.

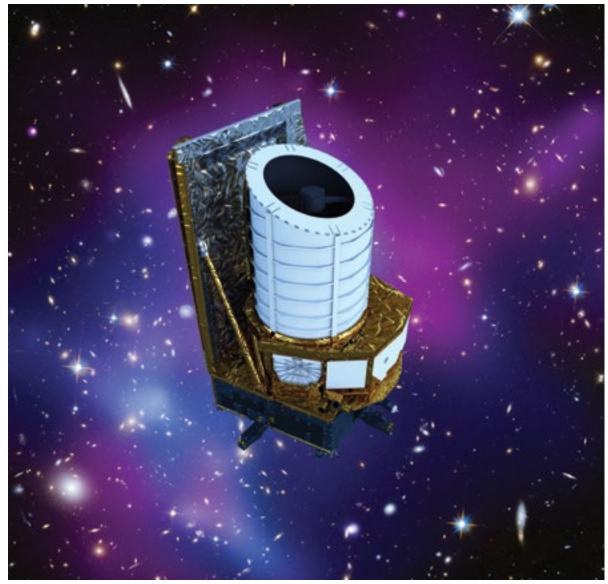
ÉPPÉ

The Extrasolar Planet Polarimetry Explorer (ÉPPÉ) is a proposed concept for a microsatellite mission that would use time-resolved differential polarimetry to characterize known exoplanets (hot Jupiters, Neptunes, super-Earths) and serve as a pathfinder for spectropolarimetric exoplanet biomarker detection. In contrast to current follow-up methods, polarimetry is well-suited to studying non-transiting exoplanets, preferentially around brighter stars. The differential polarimetry capabilities of ÉPPÉ would be uniquely sensitive to polarized scattered light from dust, clouds, and haze, enabling characterization of planetary surfaces and atmosphere content. To date, ground-based polarimeters have struggled to reach the 1 part-per-million level of precision required to detect scattered light from an exoplanet. The notional ÉPPÉ concept consists of a polarimetry instrumentation payload with a 30-cm aperture telescope operating in the 300–800 nanometre band from a 180-kg class spacecraft, somewhat larger than a typical microsatellite. ÉPPÉ would use Magellan Aerospace's new MAC-300 satellite bus design. A Sun-synchronous low-Earth orbit would enable on-target stares for up to two months. The CSA-funded concept study for ÉPPÉ was completed in late 2019. The projected cost of the mission, estimated at $40M–$45M without launch, is moderately high for a microsatellite, and technical and scientific risks remain significant. Given these risks, the current level of maturation, the moderately high cost, and the short-term preference for POEP (see below) in these science and mission size categories, it is too early to recommend ÉPPÉ as a community-wide priority; however, we encourage further development of the ÉPPÉ mission concept.

Euclid

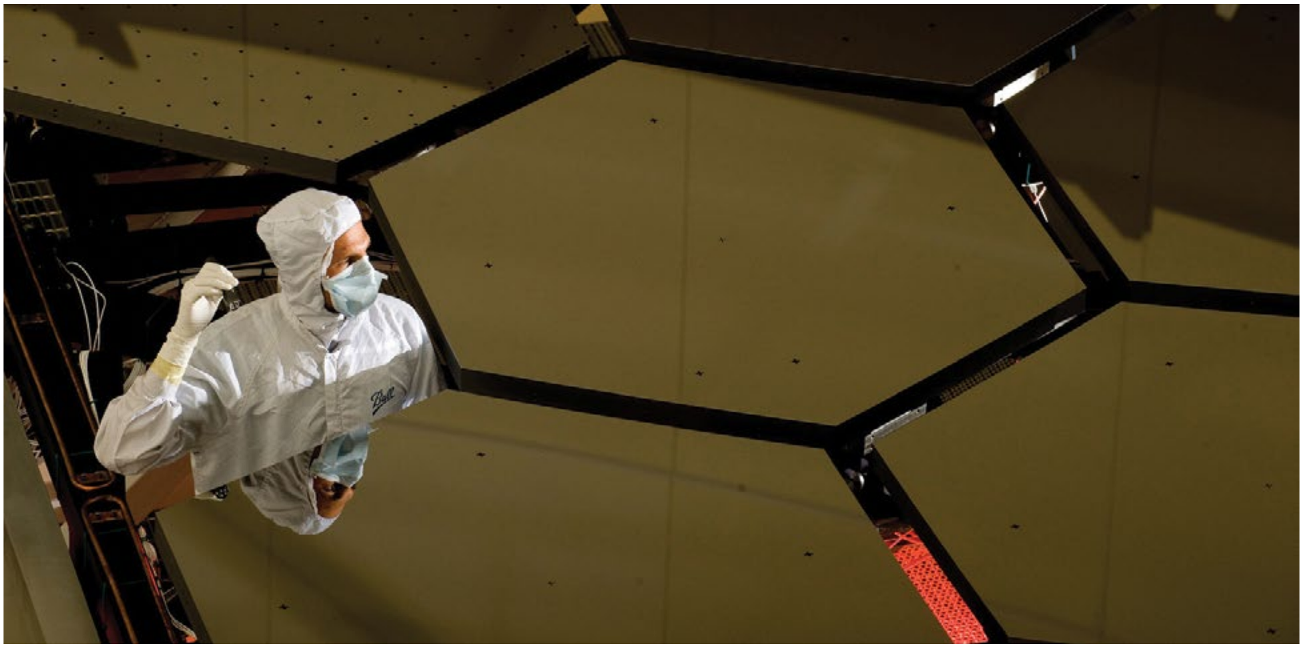
Euclid is an ESA-led 1.2-metre diameter space telescope selected in October 2011, with launch planned for 2022. The Euclid Mission aims to survey over 15,000 deg^2 of the extragalactic sky with imaging in a wide visible (riz) band at 0.1-arcsecond resolution, near-infrared photometry (Y, J, and H) and near-infrared spectroscopy.

The goals of the Euclid mission include understanding why the expansion of the Universe is accelerating and the nature of the dark energy seemingly responsible for this acceleration. The imprints of dark energy and gravity will be tracked by Euclid using two complementary cosmological probes to capture signatures of the expansion rate of the Universe and the growth of cosmic structures: weak gravitational lensing and galaxy clustering. Although low-redshift cosmology is the primary driver of the mission, a wide range of science, from the formation and evolution of galaxies down to the detection of brown dwarfs, will be possible with the Euclid near-infrared imaging data set, which includes broadband visible images and near-infrared photometry of roughly 1.5 billion galaxies and near-infrared spectroscopy of roughly 25 million galaxies.



Artist's impression of the Euclid spacecraft.
Image credit: ESA/ATG medialab

Canada joined the Euclid Consortium in 2016, when CFHT approved CFIS as a Large Program. CFIS, along with other ground-based surveys, will be used by Euclid to measure photometric redshifts in the northern sky. Twenty-seven faculty-level astronomers in Canada are members of the Euclid Consortium. Such participation requires research support for science team members. We encourage inter-agency discussions (CSA, NSERC, NRC) on co-funding such opportunities.



Six of the 18 JWST mirrors are readied for shipment. Image credit: NASA/MSFC/David Higginbotham/Emmett Given

JWST

The James Webb Space Telescope (JWST) is a 6.5-metre infrared-optimized space telescope, currently scheduled to launch to L2 in October 2021. JWST's four unique science instruments promise unprecedented sensitivity and transformative impacts for a broad range of astrophysical questions: JWST will trace the expansion history of the Universe, probe cosmic conditions at the epoch of reionization, reveal the formation and assembly of galaxies, identify the progenitor stars of supernova explosions, study proto-planetary systems and the ancient history of our own solar system, characterize the atmospheres of exoplanets, and establish the potential habitability of Earth-like temperate worlds. Capabilities include imaging plus slit, slitless, and integral-field unit (IFU) spectroscopy, and cover the wavelength range 0.6 to 28 micrometres. The mission is designed to last at least 5 years with a maximum of 11 years, limited by the propellant needed to keep the telescope in orbit. JWST is currently in its final phases of integration, with at least a 6-month launch delay resulting from the COVID-19 pandemic.

JWST represents an international partnership led by NASA, in collaboration with the European Space Agency and the CSA. Canada's substantial hardware contribution to the JWST project comprises the Fine Guidance Sensor (FGS) and the Near-Infrared Imaging and Slitless Spectrograph (NIRISS), included in the same instrument module. Canada will also play a leading role in early JWST science, with its leadership of both the CAnadian NIRISS Unbiased Cluster Survey (CANUCS) and NIRISS Exploration of the Atmospheric diversity of Transiting exoplanets (NEAT) 200-hour guaranteed-time observation (GTO) programs for the NIRISS instrument team; and a 30-hour Early Release Science (ERS) program to observe prototypical photo-dissociation regions with imaging and IFU spectroscopy using the NIRCAM, NIRSpec, and MIRI instruments. In addition, Canada is guaranteed at least 5% of the General Observer time (averaged over the long term).

Canada's involvement in JWST has been enabled by a significant (~$180M) investment from the CSA. This large commitment is consistent with the fact that the Canadian astronomical community ranked JWST first among space astronomy missions in the previous two LRPs, and recognizes the importance of this mission to the future of broad areas of astronomy.

Recommendation
We recommend that the CSA maintain financial support to the JWST mission and associated Canadian science for the entirety of the observatory's lifetime. Canada has already made a very large investment in this project, and continued support will leverage this investment for the highest possible science yield.

LiteBIRD satellite.

Image credit: Canadian Space Agency

LiteBIRD

The Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) is a planned millimetre-wavelength space telescope scheduled for launch to L2 in the 2020s for three years of observations. LiteBIRD covers 15 bands between 34 and 448 gigahertz, and its focal plane detector consists of a multichroic superconducting detector TES array with ~3,000 bolometers. LiteBIRD detects polarization using half-wave plates. It will provide all-sky polarization measurements of the cosmic microwave background on large angular scales, which complement the higher-resolution, deeper yet partial maps of the cosmic microwave background from future ground-based experiments such as CMB-S4.

The key scientific goal of LiteBIRD is to search for the signals of inflation, specifically through the detection of B-mode patterns in the map of cosmic microwave background polarization. Such B-mode patterns are understood to be sourced by primordial gravitational waves that arise during the cosmic inflationary epoch (10^{-38} sec after the beginning of the Universe). LiteBIRD will test representative theories of inflation (e.g., single-field slow-role models with large field variation).

LiteBIRD is a Japanese-led project with collaboration between Japanese, US, European and Canadian groups, and was selected by JAXA's Institute of Space and Astronautical Science in June 2019 for launch in the mid-2020s, and a planned mission lifetime of three years. LiteBIRD was also identified as the top priority for Canadian cosmic microwave background science in MTR2015. LiteBIRD is enabled by key technology breakthroughs, including a novel Canadian TES multiplexed readout system that has been demonstrated in many of the world's ground-based cosmic microwave background observatories, and which is planned for deployment in CMB-S4. This Canadian technological contribution is already baselined for the mission, enabling Canadian access to LiteBIRD data. Canadian contributions are being studied through Science Maturation Studies and Mission Contribution Studies from the CSA. This project has entered Phase 0, and in order to ensure Canadian participation in this collaboration it requires a funding commitment from the CSA. The estimated cost for CSA is $25M–$45M. The project carries potential risks in that deploying millimetre-wave TES detectors in space is unprecedented. However, the potential science returns considerably outweigh such risks.

Recommendation

We recommend Canadian participation in the Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD). This participation should correspond to the complete life cycle of LiteBIRD, including hardware, mission operations, and science analysis. By focusing on the polarization of the cosmic microwave background at large angular scales, LiteBIRD will be an excellent complement to the ground-based CMB-S4 facility, and will provide an outstanding opportunity for Canadian cosmologists to make unique discoveries.

NASA Flagships

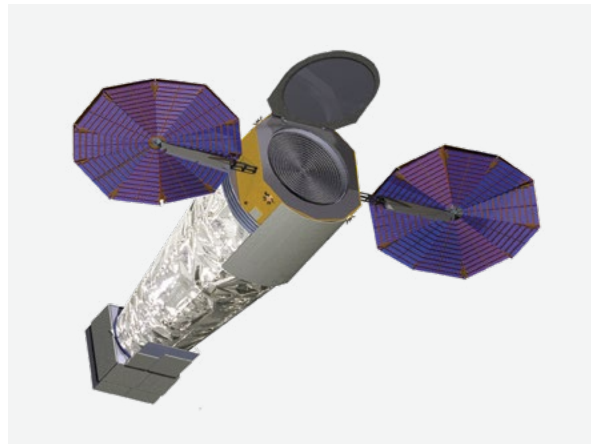
NASA develops space astronomy missions at a range of scales. The very largest missions, with budgets typically in excess of US$1 billion, are the large strategic space science missions usually referred to as “flagships.” Current and upcoming flagships include the Hubble Space Telescope, Chandra X-ray Observatory, James Webb Space Telescope and Nancy Grace Roman Space Telescope.

Four new proposed flagship astrophysics missions, HabEx, LUVOIR, Lynx, and Origins, have been proposed to the US Astro2020 decadal survey. The report from Astro2020 will recommend which of these flagship mission(s) to pursue, and Canadian preferences will not influence those decisions. Canadian astronomers have expressed interest in participating in all of these missions.

Specific comments on each proposed flagship are as follows:

HabEx: The Habitable Exoplanet Observatory (HabEx) is a mission concept for a 4-metre off-axis space telescope with coronagraphic and spectroscopic capabilities, whose main objective will be to directly image habitable Earth-like planets around sun-like stars, to characterize their atmospheres, and to look for signs of life. The science uniquely enabled by HabEx is exciting to both astronomers and the general public, representing a critical step in humanity’s quest to understand the origins of life and its prevalence elsewhere in the Universe. In addition to its main objective, HabEx will enable a broad portfolio of studies in various other areas of astrophysics, and will be of high interest to many Canadian astronomers. Canadians have a strong heritage in high-contrast imaging observations and instrumentation, and have developed expertise valuable for a space astronomy mission like HabEx through contributions and technology development for JWST. We encourage Canadian astronomers to contribute scientific and technical expertise to HabEx should it be selected.

LUVOIR: The Large UV/Optical/IR Surveyor (LUVOIR) is designed as a 15-metre diameter ultraviolet/optical/infrared space telescope**.** As a general-purpose large multi-wavelength space observatory, LUVOIR would enable transformational science across many areas of astronomy, from characterizing the icy geysers on large moons of our solar system to determining the nature of circumstellar disks and habitable exoplanets; from constraining the nature of dark matter on galactic scales to measuring the multi-phase structure of gas flows into and out of galaxies. The substantial Canadian contributions to JWST pave the way for a significant contribution to LUVOIR. If LUVOIR is selected for development by NASA, we encourage Canadian contributions to this mission, identifying the same areas of Canadian strength as for HabEx and JWST and potentially leveraging experience with CASTOR.



Design rendering for Lynx X-ray Observatory.
Image credit: Lynx team

Lynx: The Lynx X-ray Observatory will continue the revolution in X-ray astronomy started by the Chandra X-ray Observatory and XMM-Newton Observatory, by offering significant gains in imaging and spectroscopic sensitivity over the 100–10,000 electronvolt energy range. Major scientific programs planned for Lynx will include tracking the formation and growth of supermassive black holes over cosmic time, revealing the hot gas ejected by stars and galaxies into their surroundings, studying the many different ways in which stars violently end their lives, and probing the extreme physics of exotic compact objects such as neutron stars and X-ray binaries. Canadians have published more than 400 scientific papers using data from Chandra and XMM-Newton. Furthermore, the Canadian high-energy astrophysics and quantum materials communities have developed the mission concept for Colibrì (see above), which shares scientific goals and capabilities as well as key technologies with Lynx. Canadian technology and scientific studies for Colibrì, Hitomi and XRISM set the stage for a substantive Canadian contribution to Lynx.

Origins: The Origins Space Telescope is conceived as a mid- and far-infrared cooled 5.9-metre diameter telescope, providing imaging, spectroscopic and polarimetric observations. Owing to its wavelength coverage and unprecedented sensitivity, Origins would enable transformative studies on most areas of astronomy, including the birth and evolution of galaxies, the growth of supermassive black holes, the production of heavy elements, the formation of star and planets, and the cycle of water and other life ingredients and their implications for habitable worlds. Origins would offer a spectacular improvement over the Herschel Space Observatory in both sensitivity and angular resolution, and has science goals and instrumentation requirements very similar to SPICA (for which Canada was planning to contribute the high-resolution spectrometer before this mission was removed from ESA's M5 competition). Above we recommend Canadian participation in a large cooled infrared space telescope. Should the Origins mission be selected to proceed, it should be of prime consideration for Canadian participation.

There are two potential routes for Canadian participation in any selected NASA flagships. In one route, Canada participates in the scientific and technical aspects of such a mission, but without making a hardware contribution. A second, more ambitious route, involves Canada contributing significant hardware (on the order of $100M, similar to our participation in JWST), in addition to scientific and technical contributions. The former route would be achievable through existing CSA programs and budgets; the latter route would require significant additional funding.

Recommendation
We recommend that the CSA provide funding that enables Canadian scientific and technical participation in preparatory activities for the NASA flagship mission(s), through design reference missions, analysis software, instrument design, science teams, working groups, etc. Any such opportunities should be disseminated widely, and appointments made by CSA should take place through an open and competitive process. These scientific and technical contributions should be pursued as soon as circumstances allow.

Recommendation
We recommend that Canada contribute ~$100M in hardware to a flagship astrophysics mission selected by NASA. However, such a hardware contribution should be regarded overall as a lower priority than investing in CASTOR and LiteBIRD at the recommended levels. A significant hardware contribution to a NASA flagship astrophysics mission would strengthen Canada's standing as a strong international partner in space astronomy. Ahead of CASCA's midterm review in 2025, Canadian astronomers should work with the CSA and industrial partners to identify potential hardware contributions to the selected NASA flagship(s) and, where appropriate, the CSA should support technology development studies. The 2025 midterm review would then be in a good position to provide guidance on an eventual contribution to a flagship mission.

NEOSSat

The Near Earth Object Surveillance Satellite (NEOSSat), launched in 2013, has played an important role in maintaining Canadian technical capabilities in small-satellite space science. NEOSSat's imaging can be used to conduct photometric studies with precision sufficient for asteroseismology studies and other variability analyses of stars and exoplanet systems; it has already demonstrated imaging and photometry of exoplanet transits. NEOSSat is well-suited for the study of near-Earth asteroids or comets as it provides near-Sun observing capabilities and can provide direct parallax measurements of nearby objects due to its orbit around Earth. NEOSSat's first science guest observer program in 2019 was heavily oversubscribed, and recent NEOSSat imagery has demonstrated high-precision photometry on bright stars with exposure times of a few seconds. We encourage the CSA to monitor the demand for and outcomes of this program, and to adapt their support accordingly.

POEP

Photometric Observations of Extrasolar Planets (POEP) is a fully Canadian small-satellite mission whose main science objectives are characterizing known transiting extrasolar planets and discovering new ones. The baseline mission concept is a 15-centimetre space telescope on the well-tested MSCI multi-mission satellite bus with legacy from MOST and NEOSSat. The telescope would feed two frame-transfer charge-coupled devices (CCDs), in u-band and i-band, to obtain high duty cycle imaging and precise photometry. The spacecraft would be placed in an 800-kilometre Sun-synchronous orbit. The payload will have a continuous viewing zone between approximately –20° and +30° in declination, and will be capable of staring at a single field for up to two months. In Fall 2019, the mission concept completed a science maturation study funded by the CSA. The estimated total cost is $15M, including operations but excluding launch. A launch is possible as soon as 2025, with a minimum mission lifetime of two years.

POEP's transit depth measurements of known transiting exoplanets in both u and i bands will reveal the extent of their atmospheres and probe the presence of clouds and aerosols, improving our knowledge of exoplanet fundamental parameters and establishing a legacy of long-term precision timing of transit events useful for spectroscopic follow-ups. The POEP mission will uniquely complement a number of current, confirmed or proposed space-based facilities including TESS, CHEOPS, JWST, CASTOR, PLATO and ARIEL. For example, JWST and ARIEL will provide spectroscopic observations in the infrared to study molecules in exoplanet atmospheres. As clouds limit the depth to which an atmosphere can be probed using techniques such as near-infrared transit spectroscopy, the interpretation of these observations will require the understanding of the potential presence of clouds provided by POEP.

Precision i-band photometry with POEP will allow the detection of small, potentially rocky and habitable transiting exoplanets around ultra-cool dwarf stars. These faint, very red low-mass stars and brown dwarfs remain beyond the photometric grasp of TESS. However, because of favourable planet-to-star flux ratios, any planets orbiting them would offer some of the best opportunities for atmospheric characterization and biosignature detection with JWST or with a ground-based VLOT.

Beyond the field of exoplanets, the dual-band capability of POEP will also allow studies of the size-distribution of small bodies in the solar system through occultation measurements, hot white dwarfs in close or interacting binaries, the flaring properties of M dwarfs, and stellar pulsations, interiors and evolution.

Small-satellites present an effective and low-cost platform for rapid technology and methodology innovation that complements larger missions. As experience has shown with MOST and BRITE, the science impact of such missions per dollar invested compares very favorably to many major ground—and spaced-based facilities. Small-satellite missions also present an excellent opportunity to train and sustain a robust, experienced workforce within the space sector, which will provide a platform for larger Canadian-led space astronomy missions in the future. Given the strong heritage on which POEP builds, its technical risks are relatively low.

Recommendation

We recommend development of the Photometric Observations of Extrasolar Planets (POEP) mission. The goal should be to enable a launch in the 2025 timeframe, to allow follow-up of exoplanet discoveries made with TESS and CHEOPS, and to provide significant overlap with complementary future space astronomy missions such as JWST, ARIEL, PLATO and CASTOR. POEP has the potential to provide high science impact on exoplanets and the outer solar system for a relatively small investment, and will allow Canada to maintain leadership in small-satellite astronomy.

XRISM

The X-ray Imaging and Spectroscopy Mission (XRISM) is an upcoming Japanese-led space astronomy mission centred on high-resolution X-ray spectroscopy, and aims to replace the capabilities lost through the failure of the Hitomi satellite in 2016. XRISM will host two X-ray instruments: Resolve (a microcalorimeter covering the energy range 300–12,000 electronvolts) and Xtend (a CCD imager covering 400–13,000 electronvolts). XRISM is scheduled for launch in 2022, with science programs centred on studying the chemical composition of the Universe, the motions of hot gas in galaxies and galaxy clusters, and the properties of white dwarfs, neutron stars and black holes.

With support from the CSA, Resolve and Xtend are being tested and calibrated using the Canadian Light Source in Saskatoon, SK. Canadian scientists will be able to compete for XRISM observing time in return for this contribution. A Canadian scientist is a member of XRISM's International Science Team, and another is a member of the US Resolve Instrument Team. Building upon our success in contributing to the Hitomi mission, we encourage continued Canadian participation in XRISM, continued CSA support for this mission, and further technological development for high-energy astrophysics.

Chapter 7

The Canadian astronomical community must work together with Indigenous representatives and other relevant communities to develop and adopt a set of comprehensive guiding principles for the locations of astronomy facilities and associated infrastructure in which Canada participates.

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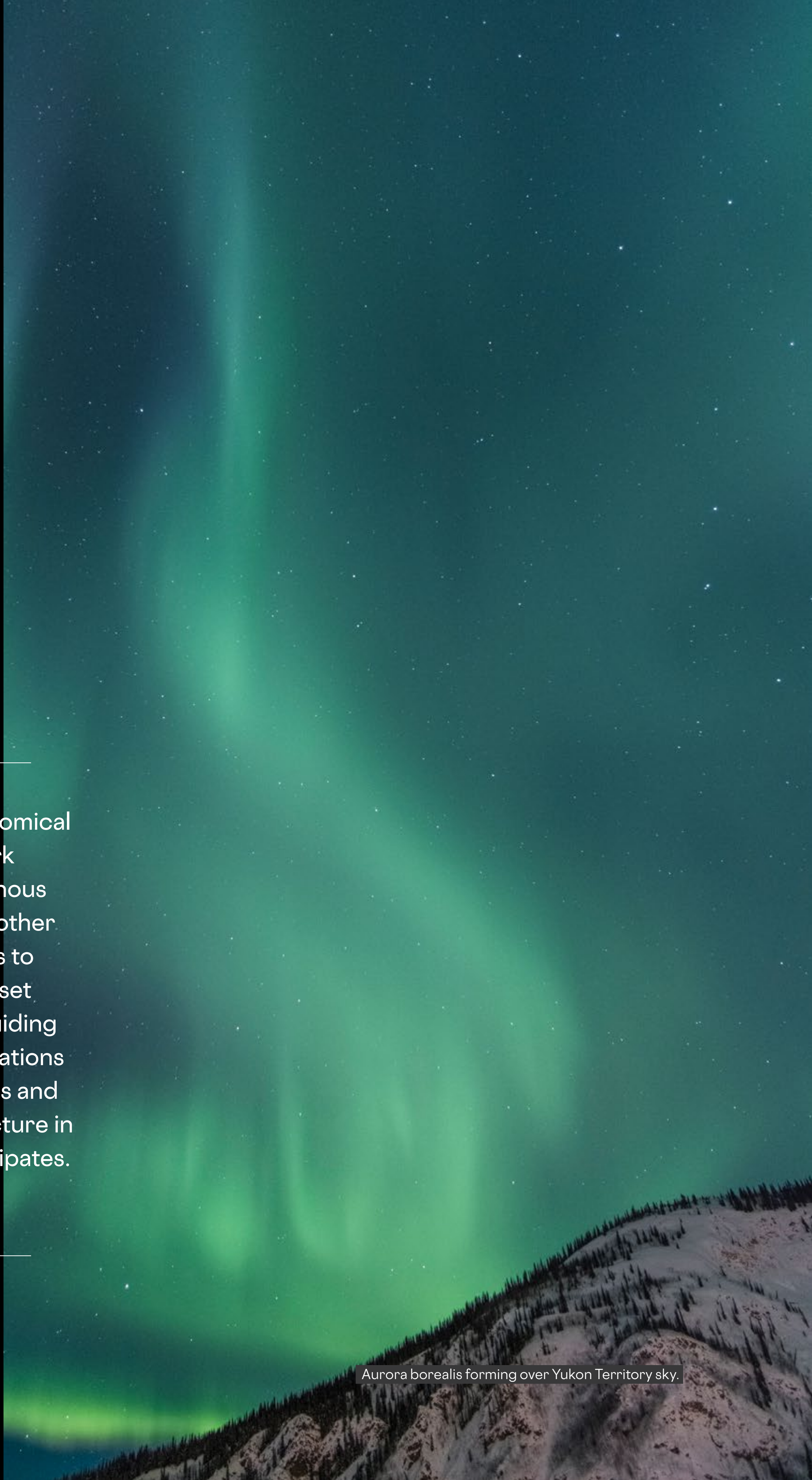


Aurora borealis forming over Yukon Territory sky.

Astronomy and Society

Astronomy's subject matter may seem far removed from everyday life. Indeed, the grand scales of space and time are part of its appeal. Astronomy enriches our culture, providing a cosmic perspective on the origins of life, planets, and the Universe.

Why do astronomy? From a beginning in timekeeping and navigation through development as the world's first international data science to a modern role that includes driving technological development, astronomy has had a wealth of impacts on society. Spinoffs from astronomy have revolutionized medical imaging, security, wireless networking, and global positioning. Training in astronomy produces experts in computational modelling, leading-edge instrumentation, quantitative problem-solving, and technical communication who can, and do, apply their skills well beyond astrophysics in areas from finance to healthcare and defence. In a time of global challenges and uncertainties, astronomical research is a long-term effort that serves to answer enduring questions and uncover new ones. It means discovering new wonders and inspiring the next generation.

Canadian astronomers affect and are affected by Canadian society, including governments and their research funding agencies, universities, industry, and the general public. In this Chapter, we make recommendations on interactions of Canadian astronomers with these stakeholders and within our professional community of colleagues, including highly-qualified personnel (HQP) such as research associates, technicians and trainees.

Professional Culture and Responsibilities

As part of Canadian society, Canadian astronomy and Canadian astronomers have responsibilities to each other and to the broader community. These include making the field more equitable and inclusive so that all who wish to participate may to do so without discrimination or harassment; behaving ethically both within and outside the research community; contributing to reconciliation through support of and engagement with Indigenous Peoples; engaging Canadians in science and discovery through education and public outreach; and mitigating climate change through carefully considering the impacts of our activities and facilities. In this section we make recommendations to both organizations and individuals on improving astronomers' professional culture and on fulfilling our responsibilities to society.

Equity and Inclusion

Based on the census of many professional astronomical societies, including Canada's, astronomy is currently not an inclusive discipline. There are many ways in which astronomy falls short, the most notable of which is the extremely low number of Black and Indigenous professional astronomers in North America, which is in turn embedded in a broader landscape of under-representation and marginalization across the research community. Furthermore, astronomers who are from marginalized backgrounds experience higher levels of harassment and discrimination than the rest of the astronomical community, which can severely hinder productivity, mental health, career advancement, and longevity in the field. Linguistic identity is an additional equity issue in Canada: English is the international language of astronomy, and francophones must therefore work in a language that is not their native tongue.

There are numerous compelling reasons why professional astronomy needs to become more equitable and inclusive. Most importantly, providing opportunities to participate for everyone who seeks to work in astronomy, and then supporting them once they are working in this field, are part of a fundamental commitment to respect the dignity and potential of all human beings. Second, astronomy is a highly collaborative field, and it has been repeatedly demonstrated that teams with diverse backgrounds and perspectives produce stronger and more impactful research outcomes. Third, as part of a commitment to fostering the next generation of scientists, astronomers must recognize that different people will be motivated and inspired in different ways, and a diverse body of astronomers thus maximizes our capacity for mentoring students and early-career researchers. Finally, from a purely transactional perspective, there is an increasing emphasis on equity, diversity and inclusion (EDI) as criteria for grant and funding applications. For all these reasons, a meaningful and sustained commitment to equity and inclusion must be a key part of astronomers' ongoing plans to make discoveries about the Universe, and should be explicitly included in values and ethics statements of professional societies.

Extensive analyses now provide unequivocal evidence for gender, racial and other biases in recruitment, peer review, career progression, and remuneration across science, research and higher education. As a result, there is a much greater awareness of and commitment to EDI amongst the scientific community than there was a decade ago, as demonstrated by the growing number of policy changes and new programs from institutions and governments, along with the creation of ethics statements and codes of conduct from professional societies. The Government of Canada has launched the Dimensions Charter,[62] and has now placed requirements on the minimum fraction of Canadian Research Chairs that universities must award to people from designated underrepresented groups. Such efforts all attempt to produce structural change. However, these broad efforts must be accompanied by actions and efforts from individuals and their institutions: a racist and sexist system that actively favours some and excludes others is deeply established in Canada, and dismantling these barriers must be a priority for all members of the Canadian astronomical community.

Demographic data are essential for understanding our community and its needs, for identifying and eliminating axes of marginalization and barriers to access, and for determining whether EDI initiatives are having an impact. Past demographic surveys of the Canadian astronomy community have had limited scope or poor uptake. The consequence is an incomplete picture of our community, especially if members of marginalized groups have been uncomfortable responding to a survey or declaring their identities. A demographic survey relies on individuals participating and then self-identifying, and thus can only be successful when the process and cultural environment allows each person to securely and confidentially respond. The resumption of equity surveys via the CASCA Equity and Inclusivity Committee (established in 2015) was a

62 Dimensions is one of several international programs promoting EDI in higher education, along with Athena SWAN in the United Kingdom and Ireland, SAGE in Australia, and SEA Change in the United States. The Dimensions program is the result of cross-country consultations to make it uniquely adapted to the Canadian context.

recommendation of MTR2015. CASCA's first attempt at a self-reporting survey in 2018 had less than 50% uptake and did not capture even the limited diversity that already exists: specific demographic groups known to have representation within the society were not represented in the survey data. CASCA must set a goal to confidently understand its own community by 2030.

A census of the Canadian astronomical community is now important for another reason. The Canadian government has adopted the Gender-Based Analysis Plus (GBA+) initiative, which highlights the fact that our experiences are a product of the intersection of our gender with other identities such as race, ethnicity, education, sexual orientation, income, disability, age, culture, geography and religion. Requests for major new funding in the form of Memoranda to Cabinet must now include information about the diversity of the community with respect to (at minimum) language, gender, Indigeneity and disability status. It is therefore vitally important that CASCA collect demographic information[63] in a way that allows the community to anonymously self-report with high uptake. There is an urgent need for the creation of a modern, efficient database that is useful to and which is trusted by the Canadian astronomical community.

In addition to building awareness of EDI issues and obtaining reliable demographic data, the most direct and meaningful way for Canadian astronomy to improve its levels of diversity and inclusion is to recruit and appoint astronomers from underrepresented groups. While it is not straightforward for the Canadian astronomy community to act monolithically on recruitment of researchers, educators and graduate students, all astronomers should actively seek ways to recruit more inclusively within their individual organizations.

The community should recognize that Canadian undergraduate physics and astronomy students are, in most cases, the beginning of the professional pipeline that leads to future CASCA members. CASCA should therefore collaborate with the Canadian Association of Physicists (CAP) and draw on the results of the National Survey of Student Engagement (NSSE) to analyze the relevant undergraduate demographic data on Canadian undergraduate students, and should identify ways to expand astronomy research opportunities for undergraduate students from minoritized groups. Imbalance of exposure to scientists as mentors and role models for Canadian youth is a strong consequence of the current monolithic ethnic composition of professional science culture in Canada, exacerbated by the expansive geography of the country. This is then compounded, for many communities, by socio-economic barriers to pursuing higher education that preclude many people from seeing themselves in the roles of scientists, instrumentalists or skilled technicians. The astronomy community has an important role to play in the mitigation of several of these barriers. Astronomy is a high-profile field, and has the potential to provide diverse role models who can inspire young people of all backgrounds into a broad range of careers across science and technology. The COVID-19 crisis has forced astronomy colloquia and conferences online, and many series are being archived and recorded, meaning that those interested in astronomy, within or outside academia, now have more equitable access to research presented by active researchers around the world (e.g., the CANadian Virtual Astronomy Seminar Series [CANVAS] hosted by HAA in Canada). Enhanced coordination and advertisement of these learning opportunities should be encouraged. In addition, better coordination of education and public outreach efforts with new interactive technologies could provide significant improvement to recruitment and retention of underrepresented groups into STEM. We discuss recommendations specific to education and public outreach below.

Recommendation

We recommend that all Canadian astronomers make a personal commitment to equity and inclusion, focused on making significant structural changes to their workplaces, classrooms, professional communities and collaborations. Every astronomer in Canada needs to be aware of the evidence for systemic racism and discrimination in astronomy (and in science more generally), must listen to the experiences and concerns of the marginalized members of our community, and must take specific actions that remove barriers and increase support for those from underrepresented groups.

Recommendation

We recommend that CASCA make equity, diversity and inclusion in Canadian astronomy an explicit part of its ethics and values, as described in its Mission Statement, Values statement, and Code of Ethics (see following section).

63 The Canadian Association of Physicists commenced its first annual Diversity in Physics survey in November 2020, which can serve as a useful guide.

Solar eclipse of August 2017. Image credit: H. Leparskas

Recommendation
We recommend that CASCA publicly commit to the principles of the Dimensions Charter to foster increased research excellence, innovation and creativity through greater equity, diversity and inclusion, and that CASCA encourage its members and their institutions to do the same. CASCA should encourage its members at the chosen Dimensions pilot project institutions to participate in the pilot over the next two years, and CASCA should then assess the outcome with respect to its own mission and values as they pertain to equity and inclusion.

Recommendation
We recommend that CASCA update its code of conduct (see following section) to explicitly include equity, diversity and inclusion, and to meaningfully address and prevent racism, discrimination and harassment perpetrated by CASCA members or occurring at CASCA events. This should be accompanied by a formalized complaints and investigation process, such as that offered by the American Astronomical Society.

Recommendation
We recommend that CASCA adopt an explicit goal to have its membership continuously diversify to better reflect the demographics of Canada at all levels. CASCA should set targets to increase participation at all levels of membership from marginalized groups, including, but not limited to Indigenous people, Black people and all people of colour who are underrepresented in our community; CASCA should formulate and then implement the strategies and partnerships needed to reach these targets, with particular emphasis on retention of marginalized groups in the professional astronomy pipeline. Since Canadian undergraduate students are one of the main sources of future CASCA members, this work should include an analysis of relevant undergraduate demographic data collected by Canadian universities, and should identify ways to expand astronomy research opportunities for Canadian undergraduate students from minoritized groups.

Recommendation
We recommend that CASCA create and maintain a means to securely collect self-reported demographic information from its members, compiled in such a way as to ensure anonymity for individuals. The CASCA Board should direct funding toward hiring professionals to create such a modern database that is easy for members to update and that its members can trust to be secure. By 2030, with a robust system in place, CASCA should have reliable demographic information (broad in scope and with high uptake) and the ability to track its progress in diversifying its community.

Recommendation[64]
We recommend that CASCA and ACURA require their Board members, committee members and officers to complete training on equity, inclusion and anti-racism as a condition of their nomination, service, or employment. CASCA and ACURA should advocate for similar requirements for other national and international leadership positions in Canadian astronomy. CASCA should also fund workshops, student activities and focused plenary sessions of CASCA Annual Meetings, at which relevant experts can provide training on equity, inclusion and anti-racism to the entire Canadian astronomy community.

64 A related recommendation is made below on the specific issue of Indigeneity training.

Ethics and Values

A core part of science is a commitment to ethical behaviour, both in one's ongoing duties of research, teaching, etc., and more broadly in interactions with others. A scientific community's ethics and values should be governed by a set of documents such as:

1. **A Mission Statement**, which establishes the scope of a community's activities.
2. **A Values Statement**, which articulates a community's core principles.
3. **A Code of Ethics**, which sets out the responsibilities of community members to their work, to each other, and to the public.
4. **A Code of Conduct**, which describes the specifics of acceptable and unacceptable behaviour when people meet and interact.

CASCA currently has a Mission Statement and a Code of Ethics, and CASCA annual meetings have Codes of Conduct (as is now the norm at most professional conferences). However, CASCA's current Mission Statement and Code of Ethics focus primarily on professional astronomy's organization and advancement, as well as the academic expectations and inter-relations of those doing astronomy. The statements need to be updated to better address CASCA's expanding role in all of the topics discussed in this section of the report: EDI, education, public outreach, sustainability, changing attitudes about our community's responsibilities to Indigenous communities and to others impacted by astronomical activities, and the need for a healthy and safe environment for all those who work in astronomy.

A revised CASCA Mission Statement and accompanying Values Statement can clarify the scope of activities across which the membership empowers CASCA to act, covering obligations to professional astronomers, to the public (through education and public outreach), and to our stakeholders. An enhanced Code of Ethics for CASCA needs to include responsibilities of individuals (both within their professional sphere and to society at large), a mechanism for sanctioning violations of professional conduct, and responsibilities of the CASCA community as a whole. Such a Code of Ethics must also be mindful of academic freedom, and must respect a diversity in personal views about how CASCA should engage with societal issues.

The nature of astronomy is such that sites in isolated or sparsely populated areas often best meet the scientific requirements for experiments and observatories. As a consequence, astronomy has long benefited from building telescopes and other facilities on carefully chosen locations in Canada and throughout the world (e.g., Hawaiʻi, South Africa, Australia, Chile). However, these same sites often either belong to or have substantial cultural, environmental or economic significance to Indigenous Peoples, traditional title holders or other long standing local communities. For example, in Canada, the Dominion Radio Astrophysical Observatory (DRAO) sits on the traditional territory of the *Syilx* People of the Okanagan Nation, while the Dominion Astrophysical Observatory (DAO) is sited within the traditional territory of the Lkwungen-speaking Peoples including the Songhees, Esquimalt and WSÁNEĆ Peoples. Such locations often have unique value or a significant history as astronomical sites, but this does not eclipse the deep value of and much longer history on those lands for Indigenous and other local communities.

There have been many instances when astronomy projects have gone ahead over the objections of Indigenous Peoples, or where commitments or promises made by astronomers to local communities have not been fully met. Looking to the future, Canadian astronomers must ensure that their ethics and values apply to the interactions with society that result from the creation and operation of astronomical facilities. The astronomy community must consequently engage meaningfully and sincerely with Indigenous and local communities as soon as potential projects are conceived, should seek consent from those who would be affected before proceeding with a project, and must sustain engagement and consent throughout the lifetime of projects that go forward.

Recommendation

We recommend that CASCA prioritize the updating of the CASCA Mission Statement (including education and public outreach, as also recommended in MTR2015) and Code of Ethics, and that CASCA create an associated Values Statement. These documents are essential for providing a basic framework for all CASCA's programs and initiatives. These documents, along with relevant Codes of Conduct, need to be self-consistent, enforceable, and subject to regular revision.

Recommendation
We recommend that CASCA regularly review its investment portfolio to ensure accordance with its Code of Ethics and Values Statement.

Recommendation
We recommend that the Canadian astronomical community (e.g., ACURA, CASCA and NRC-HAA) work together with Indigenous representatives and other relevant communities to develop and adopt a set of comprehensive guiding principles for the locations of astronomy facilities and associated infrastructure[65] in which Canada participates. These principles should be centred on consent from the Indigenous Peoples and traditional title holders who would be affected by any astronomy project. In addition, when such consent does not exist, the principles should recognize that the use or threat of force is an unacceptable avenue for developing or accessing an astronomical site. The principles should also acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime. These principles should be developed as soon as possible, and then applied to *all* future Canadian participation in new or existing astronomical programs, projects and national and international facilities. Engagement and implementation should be consistent with the spirit of the Calls to Action of the Truth and Reconciliation Commission of Canada and of the United Nations Declaration on the Rights of Indigenous Peoples.

Indigenous Engagement

There are very few Indigenous professional astronomers in Canada, and very limited discussion of Indigenous knowledge in astronomy textbooks (even those with a Canadian focus), despite the fact that Indigenous Peoples represent 5% of Canada's population. CASCA has a role to play in the visibility and retention of Indigenous researchers in the academic pipeline, by recognizing, meeting the needs of, and providing support to its Indigenous members. At the individual level, all Canadian astronomers need to understand the reasons for exclusion and attrition of Indigenous people from professional astronomy, and must make a personal commitment to removing these barriers. Supervisors of students and postdoctoral researchers should provide the funding needed for trainees to attend conferences of organizations that promote the inclusion of Indigenous Peoples in STEM, such as the Canadian Indigenous Science and Engineering Society.

More broadly, most professional astronomers have only a cursory understanding of Indigenous culture and are unclear what is meant by Indigenous Ways of Knowing or how to approach understanding the world outside the Western model of education and science. Developing relationships with local Indigenous communities is the best way for non-Indigenous people to understand the priorities and knowledge of those communities.

Canadian astronomy benefits from facilities located on Indigenous territories across Canada and elsewhere in the world. It is not sufficient for the astronomical community to acknowledge the cultural claims to lands on which the construction of telescopes or other facilities are considered. This acknowledgement needs to be coupled with increased education (of the astronomical community at large, and of leaders within the community in particular) on the policies of United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and on Indigenous history, and how these relate to current activities on sites of astronomical interest, including universities, telescopes and national facilities. CASCA itself does not need to create the relevant educational materials, but needs to facilitate training for its members and officers, first by creating an Indigenous learning component at CASCA meetings via external educators, and then by augmenting this foundation with courses such as Astronomy & Colonization,[66] Yukon First Nations 101 and Indigenous Canada. The expansion of online learning associated with COVID-19 will make these resources more widely available to astronomers.

Engagement between astronomers and Indigenous communities is important for many reasons, not least because it is part of righting the historical wrongs against Indigenous Peoples as elucidated in the calls to action of the Truth and Reconciliation Commission of Canada. The first step to such engagement is for Canadian astronomers to build relationships with Indigenous communities, as for example the relationship that DRAO and the *Syilx* People of the Okanagan Nation have developed. Increased engagement could be realized through a revision and

65 Astronomy projects not only require telescopes and observatories, but also need support facilities, headquarters, project offices, instrumentation laboratories, integration and test facilities, computing and processing centres, etc.

66 Developed by astronomer Hilding Neilson, and sponsored by CASCA and the Dunlap Institute for Astronomy & Astrophysics.

expansion of the CASCA-Westar lectureship (see EPO recommendation below) and/or through partnerships with related scientific societies (e.g., the Canadian Association of Physicists) and with non-profit groups (e.g., The Martin Family Initiative, Discovery Western and UBC's Geering Up) who are already engaged with Indigenous communities.

Astronomers often advocate engagement with the goal of increasing Indigneous participation in professional astronomy and other STEM careers. This is important to astronomers, but may not be a high priority for many Indigenous communities or individuals. While removing barriers to participation by minoritized groups is still critically important, concentrated efforts toward encouraging participation might or might not be appreciated. Approaching Indigenous communities with respect and openness, with the goal of learning from them rather than teaching and assimilating their members into our professional culture, is more likely to yield long-lasting and mutually beneficial relationships.

For First Nations, Inuit and Métis communities that are interested in education and public outreach from astronomers, we discuss below specifics of EPO efforts for the coming decade. We note here the transition in modern thinking regarding STEM outreach. Successful programs promoting STEM to the public are taking a more collaborative and protracted approach to interactions between STEM ambassadors and community leaders, teachers and community members. Studies show that outreach efforts that consist of single visits in which an expert delivers a packaged lecture or presentation (e.g., the current model for the CASCA-Westar Lectureship) hold significantly less impact in promotion of STEM than more sustained multi-year or multi-visit efforts.

Canada's federal research granting agencies—NSERC, CIHR and SSHRC—have together developed a strategic plan "Setting New Directions," co-developed with Indigenous Peoples (First Nations, Inuit and Métis), to provide a path forward toward an interdisciplinary research and research training model that contributes to reconciliation. NSERC is the federal granting agency under which astronomy funding is distributed to individual researchers, and NSERC has several programs aimed at promoting STEM within Indigenous communities, such as PromoScience[67] (which has a broad mandate to boost the number of students, particularly those in underrepresented groups, who pursue STEM fields), and Indigenous Student Ambassadors. In addition, there are many groups throughout Canada with whom Canadian astronomers could collaborate (e.g., the Manitoba First Nations Education Resource Centre and the Mi'kmaw Kina'matnewey in Nova Scotia) in order to forge relationships with Indigenous communities and to better understand Indigenous astronomy. CASCA should establish a new committee focused on Indigenous engagement, in order to develop and advance these proposed partnerships with Indigenous communities.

Recommendation
We recommend that CASCA, with guidance from its Equity and Inclusion Committee, support and advance the needs of Indigenous astronomers and students.

Recommendation
We recommend that Canadian universities and research institutions provide funding for astronomers and astronomy students to participate in the activities and meetings of organizations that promote the inclusion of Indigenous Peoples in STEM.

Recommendation
We recommend that CASCA establish a new committee dedicated to facilitating engagement and relationships with Indigenous communities, and that can partner with existing groups working to promote STEM programs that embrace both Western and Indigenous approaches. The goals should be to listen to Indigenous communities, to discover mutual interests, and to identify opportunities to learn from and support each other. Potentially in partnership with the CASCA Education and Public Outreach committee, this committee can forge partnerships with Indigenous organizations, support Indigenous education in astronomy and STEM, and can develop astronomical learning material in Indigenous languages in collaboration with relevant teachers and programs.

67 LRP2010 advocated for increased funding to PromoScience, and NSERC has indeed increased funding to this program (e.g., from $6.1M in 2017 to $11.9M in 2019).

Recommendation[68]
We recommend that CASCA and ACURA require their Board members, committee members and officers to complete training on Indigenous issues as a condition of their nomination, service, or employment. CASCA and ACURA should advocate for similar requirements for other national and international leadership positions in Canadian astronomy. Relevant Canadian-made training programs are readily available and their uptake would be an important first step. CASCA should also fund workshops, student activities and plenary sessions of CASCA Annual Meetings, in which relevant experts can provide training on Indigenous issues to the entire Canadian astronomy community.

Recommendation
We recommend that CASCA and ACURA engage external experts on issues outside of astronomy (e.g., those holding local or cultural knowledge) to provide balance and insight to decision-making. Where relevant, members of Indigenous groups should be represented.

Education and Public Outreach

Astronomy is universally inspiring, and can connect with people in ways few other scientific topics can. Appreciating the beauty and mysteries of the cosmos, seeing thousands of stars in the night sky, and realizing our place in the Universe are all ways astronomy can reach people and make them experience something different from their everyday life. Astronomy has proven itself time and again to be a fantastic "gateway science" that invites otherwise disinterested individuals, especially youth, to learn more about science through the wonders of space. Through innovative and coordinated education and outreach (EPO) practices, our community is uniquely positioned to better engage Canadians with science. Many existing online outreach initiatives were already in place before the COVID-19 pandemic, most notably "Discover the Universe," and the acceleration of online education during this period could result in a wider audience than ever. As professional researchers, every time we engage Canadians, we build societal trust in science, increase scientific literacy and critical thinking, dispel misconceptions and misinformation, and break stereotypes, all of which are important contributions to society.

Professional astronomical research is enabled primarily by public funding agencies. As such, astronomers have a responsibility to communicate their discoveries effectively to Canadian taxpayers, and to convey how the public benefits from this research. At the same time, astronomers must also be effective science advocates to voters, government officials, entrepreneurs, and key decision-makers and stakeholders. The Canadian astronomy community must highlight to the widest audience possible not just the intrinsic wonder and innate curiosity associated with the field, but also all the societal and economic benefits that result (see Chapter 3). Showcasing the impacts of astronomy in the daily lives of Canadians is one of the best ways to get people interested in astronomy, to make them appreciate the importance of the innovation it brings and to convince them that astronomy is worth investing in.

A recent survey of Canadian astronomers by CASCA's EPO committee revealed that there are healthy and successful grassroots EPO activities being run by astronomers across the country (see Chapter 3). The community believes that astronomical EPO is important and volunteers time for it. On the other hand, individual astronomers scattered across the country cannot coordinate national EPO efforts, plan large-scale events (even virtual ones), or interface with international partners as part of worldwide activities. CASCA's dedicated EPO committee can address these issues, and also coordinate partnerships with astronomy programs run from outside the professional astronomy community (e.g., science centres and astronomy clubs). To be most effective and achieve the highest impact, the CASCA EPO committee recently proposed four National Pillars for astronomy EPO across Canada:

- Digital CASCA, which incorporates all current and future web-based and social media tools that CASCA could utilize to connect and engage with Canadians.
- Discover the Universe, a national and bilingual astronomical training program that each year reaches thousands of educators (K-12 teachers, science centres and museums) and helps them by providing accessible information and resources through online and onsite workshops.
- The CASCA-Westar Lectureship, which aims to provide outreach to under-served (often remote) communities such as those without access to nearby postsecondary institutions with astronomy programs and facilities.
- Participation in and support of EPO activities spearheaded by the International Astronomical Union.

68 A related recommendation is made above on the broader issue of equity, inclusion and anti-racism training.

We additionally argue that a fifth National Pillar be considered: a coordinated EPO focus over the next few years on the series of solar and lunar eclipses that will be visible across Canada, culminating in the solar eclipse of April 8th, 2024. Cities including Hamilton, Kingston, Montréal and Fredericton will be in the path of totality, while many other locations will experience substantial partial eclipses (e.g., Toronto 99.9% totality, Ottawa 98.9%, Quebec City 98.6%, Halifax 94.4%).

These proposed National Pillars can be pursued without a core dependence on face-to-face interactions, which is particularly important in the context of the COVID-19 pandemic. Furthermore, if tools are created to maintain and expand these and other outreach activities, they can be widely disseminated online. However, developing content and delivering results to Canadians needs dedicated, clearly defined, long-term funding. The current model, in which CASCA EPO efforts rely solely on volunteer work, will not be enough to reach maximum effectiveness and impact. Hiring a dedicated national EPO coordinator to focus on executing these National Pillars is necessary.

One important task for the EPO coordinator and the EPO Committee will be to revise and expand the current model of the CASCA-Westar Lectureship. The new format (or a new program) could provide multi-year plans for repeated engagements, along with facilitated access to training material for the communities reached. The goal should be to reach more communities, e.g., through digital learning platforms to augment in-person interactions.

Canadian discoveries highlighted in the media help develop a sense of pride in Canadian science. Given that there is only a small number of dedicated science journalists in Canada, who each must cover a huge number of topics, it is imperative that astronomers do their part to communicate their discoveries to the media in an effective way. A salaried CASCA Press Officer could assist CASCA members in disseminating their scientific results to the public and the media, and help connect them to journalists, benefitting the entire astronomy community. This position could be a part-time task folded into the national EPO coordinator position recommended above, potentially with funding from ACURA as part of its efforts to promote the priorities and successes of the community.

Funding of EPO activities is a long-standing problem in Canada. Major funding programs such as NSERC CREATE and CFI Innovation put little to no importance on applicants' EPO activities in their evaluation metrics, and do not allow EPO activities as eligible expenses (see our recommendation to CFI on this below). Yet the dissemination of results from projects funded by these agencies is extremely valuable in the quest to enrich Canada's science culture.

Recommendation
We recommend that CASCA adopt and pursue the four National Pillars proposed by CASCA's Education and Public Outreach Committee (Digital CASCA, Discover the Universe, the CASCA-Westar Lectureship, and national activities initiated by the International Astronomical Union), along with a fifth pillar centred on upcoming solar and lunar eclipses.

Recommendation
We recommend that CASCA hire a paid EPO coordinator, whose primary responsibility would be to oversee implementation and progression of the National EPO Pillars. This person would also serve as the CASCA Press Officer and social media manager, assisting CASCA members and their institutions in disseminating new scientific results to the media and to the public.

Recommendation
We recommend that CASCA and its EPO committee revise and expand the CASCA-Westar Lectureship. The mandate of the CASCA-Westar Lectureship to support remote and under-served communities should be made explicit, and participants in the program should have training and support available to build connections with these communities.

Recommendation
We recommend that CASCA develop deliberate collaborations with science centres and astronomy clubs. This would include sending CASCA members to the Canadian Association of Science Centres' annual conference, and inviting science centre professionals and members of astronomy clubs to the EPO session of CASCA's annual meeting.

Recommendation
We recommend that CASCA and ACURA advocate to funding agencies such as NSERC and CFI that a portion of funding awarded for large grants (e.g., Innovation Funds, CREATE) be usable for EPO and communication activities.

Sustainability

The consequences of climate change are developing into a vast and unparalleled crisis, which is planetary in scale and yet very human in its causes and impacts. The link between human activity and climate change has been established scientifically, and there is an urgent need for a strong response to the climate crisis. Faced with this truth, we anticipate as a society that inaction and delay are neither ethical nor wise; every field of human activity, astronomy included, must take urgent steps to mitigate the crisis and avoid the worst potential outcomes, while adapting to those consequences that are now inevitable. As one of the most public-facing of the sciences, astronomy must be especially clear and deliberate; our individual and collective actions must be consistent with our ethics and values statements (see above) and with our understanding of climate science and its implications. Astronomers' contributions can strengthen science education, increase science literacy and build capacity in science at all levels, all of which are important for enabling Canadian society's collective response to the climate crisis and other challenges of sustainable development.

In light of the crisis, greenhouse gas (GHG) emissions from our various professional activities must be understood as significant research costs, to be ethically justified, budgeted, and rationed. This can only be done with support and engagement on all levels, by individuals, research institutions, universities, and funding agencies. The climate impact of new astronomy infrastructure, for both construction and operations, must be considered when facilities are planned. Such considerations are part of a larger goal to develop a decarbonization road map that considers the climate impact of astronomy and sets guidelines for future actions.

Conferences and workshops are a very important part of the professional lives of astronomers. They are opportunities to learn about and share current research, to create new ideas, and to interact with a diverse group of students, researchers and experts. However, air travel is well known to be a major contributor to astronomers' GHG emissions: the environmental impact of travel to in-person conferences is significant, and lower impact alternatives should be given full consideration. Specifically, the COVID-19 pandemic has demonstrated that many of the business and professional meetings that CASCA members attend can be carried out online. Not all conferences can be easily replaced by online alternatives, but the COVID-19 pandemic has led to innovative changes to conference schedules (to accommodate time zones) and formats for the formal and social components of meetings. It is possible that an increased rate of remote participation will persist even after the pandemic has been resolved, which would increase equitable access to those who may have restrictions on travel due to financial, family or other reasons. A significant remote presence at meetings will place remote attendees on a more equitable footing, since this mode of attendance will no longer be exceptional. Travel to observatory sites is also an important part of professional astronomy. Remote observing is becoming common and should be adopted whenever possible. However, in-person presence is still sometimes necessary, especially when testing and commissioning new instruments, or training new personnel.

Canadian astronomers should carefully evaluate their need for air travel to conferences and observatories, considering the location and purpose of events. Full consideration should be given to lower impact options such as remote participation, ground travel for smaller distances, combining trips, and prioritizing extended stays options such as remote participation, ground travel for smaller distances, combining trips, and prioritizing extended stays.

Recommendation
We recommend that CASCA make sustainability an explicit part of its ethics and values, as described in its Mission Statement, Values Statement, and Code of Ethics (see preceding section).

Recommendation
We recommend that organizers of astronomy-related events carefully consider the frequency, timing, and locations of these activities, with the goal of minimizing air travel. Remote participation using effective online platforms should be encouraged whenever it does not alter the benefits of in-person participation. Meetings of CASCA committees should take place almost exclusively through videoconferencing, or should be combined with other in-person events (e.g., CASCA annual general meetings). We encourage individual members of CASCA to continually evaluate their need to travel by air and consider institutional funding of carbon offsets where possible.

Recommendation
We recommend that the astronomy community should thoroughly consider the climate impacts of both construction and operations when planning infrastructure.

Recommendation
We recommend that CASCA, through its sustainability committee, support the development and implementation of a decarbonization road map for astronomy. This road map should include plans to convey to governments and granting agencies the community consensus on climate action and ways to enable recommended actions.

Governance and Funding

Astronomical research in Canada is supported by numerous federal and provincial agencies and private organizations. The funding agencies support a broad and diverse field of astronomical research in Canada and have enabled outstanding research achievements. Their roles and mandates are described in Chapter 3. The governance of astronomical research and facilities also involves organizations that represent researchers, universities, and industry: CASCA, ACURA, and the Coalition for Canadian Astronomy (CCA). In this section we make recommendations to these agencies and organizations to facilitate even more efficient governance and coordination that will continue to leverage public investment in astronomy research in Canada. We note that some increase in efficiency and equity of participation in governance, at least on the side of researchers and universities, will be realized as more related business will be accomplished without in-person meetings. This has been necessitated by COVID-19, but should persist afterward to allow individuals with personal or financial constraints to more fully engage in governance.

Increased coordination between the agencies that support Canadian astronomical research will enable better science, will reduce duplication of effort, and will avoid situations where some responsibilities are seen to be outside everyone's mandate and are overlooked. The Agency Committee for Canadian Astronomy was a mechanism previously used for coordination between the relevant agency heads, but has been dormant since 2011.

Recommendation
We recommend that the leadership of agencies which fund or otherwise support astronomical research (NRC, CSA, CFI, NSERC, NDRIO, CIFAR) coordinate efforts through regular meetings. Involving ACURA and/or LRPIC in such meetings could further improve coordination efforts.

NRC and HAA

Access to the world's forefront observatories is essential for any healthy astronomy community. In Canada, the Herzberg Astronomy and Astrophysics Research Centre at NRC ("HAA") has the mandate and responsibility to facilitate Canadian participation in national and international astronomical facilities. HAA provides outstanding support to Canadian astronomers not just through access to some of the world's largest telescopes, but also in the form of associated facility management, operations and governance, data processing and archiving, user support, and technology development. Most of the HAA's expenditure and effort in this regard enables current or anticipated Canadian participation in large, long-term, ground-based observatories (e.g., ALMA, Gemini, CFHT, TMT and SKA1). Facilities with these large budgets and long lifetimes will remain a core need of the Canadian astronomical community for the foreseeable future (see the corresponding recommendations in Chapter 5).

In parallel with investments in these large facilities, mid-scale investments led by universities and funded through the Canada Foundation for Innovation (CFI) have provided an exceptional value per dollar. Mid-scale projects (i.e., with budgets of ~$10M–$30M) have led to an increasing number of world-leading advances and discoveries from Canadian astronomers, and some of these mid-scale projects have relied on substantial contributions from HAA. Looking to the future, HAA should implement a national process for allocating and committing support to the development, design and construction of university-led mid-scale initiatives, covering both engineering support at the conceptual phase and in-kind contributions at the CFI proposal stage. NRC should invest strategically in CFI-funded initiatives, using transparent criteria and with the goal of enabling the largest possible user base for these projects. This support will help create a strong and coordinated case for CFI funding of new astronomy infrastructure, and will ensure maximal scientific return from these activities.

Funding from CFI and its provincial partners primarily goes toward creation of new infrastructure, with an additional smaller amount awarded for a few years of operations and maintenance.[69] Once a mid-scale facility is funded, substantial ongoing additional investment is needed in the form of scientific and engineering support, planning of experiments and surveys, development of processing pipelines, and facilitation of data services and data curation. These activities have all long been part of HAA's focus for Canada's largest facilities, but are now becoming part of the baseline effort needed to ensure maximal science return from mid-scale astronomical investments, especially as the scope of such facilities becomes more ambitious and complex. Recognizing that future mid-scale facilities in Canada will likely depend on close partnerships between universities and HAA, and noting that there is currently a substantial missing human-capital component of these mid-scale projects once they begin operations, HAA and the university community should identify new funding for astronomy personnel, who can then provide the full suite of technical and scientific support activities needed to conduct astronomy research programs on Canada's mid-scale facilities. The focus should be on early-career STEM personnel primarily located at universities, covering a wide range of skills including instrumentation, engineering, software development, and the theoretical and observational expertise needed to optimize new astronomical observations and experiments. A commitment of new funding at the level of ~$1M (~10 FTE-years) per year to support these personnel would cost a small fraction of Canada's current expenditure on astronomical facilities, but would provide an enormous additional return on investment and would help Canadian astronomy maintain clear international leadership. The responsibilities of the HQP in these positions will need to be carefully defined in order to enable a variety of future career paths. Through the addition of these dedicated personnel, Canada can maximally leverage its past and future investments in a growing suite of astronomical facilities, covering a range of scopes and scales.

New instrumentation research fuels Canadian discovery. In addition to the technology development taking place at HAA, there are more than ten universities across Canada that host innovative astrophysics instrumentation laboratories. University-based laboratories are an essential part of the technology ecosystem in Canada: many major Canadian astronomy facilities can trace their origins back to concepts and intellectual developments that arose out of university-based laboratory research. The programs at these laboratories are currently supported by irregular short-term funding, primarily from CFI and CSA, and to a lesser extent from NSERC. The advent of the Dunlap Institute for Astronomy and Astrophysics and the national role it is playing in training young instrument developers is commendable and holds the possibility of furthering its reach by partnering with other institutes. However, as highlighted in LRP2010 and MTR2015, there remains an inherent difficulty in maintaining a stable core of expertise through the short-term funding available. This situation can be addressed through additional funding for instrumentation and technology collaborations between HAA and Canadian universities, possibly including formal personnel links. An NRC collaboration centre[70] in astronomical instrumentation might be one possible vehicle for such a program, which would also build closer ties between HAA and Canadian university-based astronomy researchers.

In our discussion below on ACURA, we argue that ACURA should take the lead in advocating for any new federal funding required for the initiatives recommended above, potentially through an increased funding envelope for HAA.

Recommendation

We recommend that HAA and the university community obtain an additional ~$1M/year for Canadian astronomy, in order to appoint early-career STEM personnel who can provide direct scientific and operational support for Canada's investments in mid-scale astronomical facilities and infrastructure.

69 CFI's infrastructure operating fund (IOF) helps cover a portion of the operating and maintenance costs of a CFI-funded project, typically limited to an additional ~12% of the construction cost.

70 Collaboration centres are established to develop internationally recognized expertise in a certain field, are often based in a university environment, and include NRC-funded personnel.

Recommendation
We recommend that HAA implement a national process for committing significant[71] in-kind contributions to CFI initiatives proposed by astronomers from Canadian universities. These investments can help ensure that the Canadian astronomy community will have broad access to a coherent and effective array of capabilities.

Recommendation
We recommend that HAA and Canadian universities form partnerships to enhance the capabilities of university-based experimental astrophysics laboratories through additional funding, shared personnel, and coordinated infrastructure investments. These partnerships will enable high-risk, high-reward innovations, and will provide the continuity and availability of experts that are essential for successful participation in leading-edge astronomical facilities.

CSA and JCSA

The Canadian Space Agency plays a key role in space astronomy in Canada. Developing the technology required for space astronomy represents one of the most challenging engineering opportunities of our time, and is a significant economic driver for advanced industry and innovation. The promise of discoveries inspires current and future scientists and engineers, and also drives industry to develop new technologies that might not be justified by short-term financial rewards.

The breadth of the Canadian astronomy community's scientific interests and expertise requires participation in many space astronomy missions. However, participation by the traditional route of small hardware contributions (up to $25M) should be limited to a small number of missions, so that the program can focus on one or two mid-scale ($25M-100M) missions each decade. Those space astronomy missions that can successfully compete for funding against other possible expenditures of CSA's finite budget are those in which Canadian science, training of highly-qualified personnel, and technical/industry leadership are clearly standouts. We assert that Canada can lead one flagship or large mission with a budget greater than $100M each decade, but this would rely on funds beyond the CSA A-base budget.

Astronomy is a key pillar of space exploration[72] for Canada. Historically, the cadence for mission and technology development opportunities has been sporadic, resulting in extreme difficulties for Canada in maintaining expertise, development laboratories and know-how. We envision a structured, long-term space exploration program for Canada, in which feedback and advice on CSA programs as they relate to space astronomy is provided by the CASCA-CSA joint committee on space astronomy (JCSA). Such a framework would fuel future innovation driven by the Canadian space science community and their industrial partners. A succession of regular, competitive proposal calls, arranged in cycles that cover ten years, can grow Canadian expertise in space science and technology, inspire our communities, and engage our partners around the world. For each call for proposals, two or three competing projects should be selected to go through a design phase through rigorous peer review. This will ensure both that the final selection will be robust, and that a broad community of researchers and their industrial partners will develop new expertise and new technologies.

In the next year, JWST will be launched, with Canada as a major partner. JWST has been the largest Canadian investment in space astronomy to date, and Canadian scientists built two key instruments for the mission (see Chapters 3 and 6). Looking forward, the CSA will be investing in co-funding for Canadian scientists who are awarded observations on JWST. We commend the CSA for taking this step to invest in the scientific return on missions, in addition to the missions themselves. Furthermore, the CSA has developed several programs to invest in science, in particular the FAST program and the co-investigator program to augment the programs of science concept studies and science maturation studies. To maintain Canada's competitiveness in space, it is crucial to maintain these programs and to follow up on studies with actual missions including support for the scientific returns.

Space astronomy has historically been largely executed through large missions funded and led by governmental agencies. However, the revolution in small satellites—an increasing number of launch options, combined with decreasing costs—is creating new opportunities for jumpstarting the traditional agency-led space mission process. Private space telescope projects are now being developed with diverse funding sources (philanthropy, government research programs, partnership models), and have the potential to produce unique science. Canada has

71 "Significant" should be defined in consultation with the HAA Advisory Board, in the context of HAA's resources and other obligations.

72 The CSA focuses its activities and resources on three main areas: space exploration (including astronomy); space utilization; and space science and technology.

been a leader of high-reward low-cost space telescopes (e.g., MOST, BRITE, NEOSSat), and should be ready to capitalize on opportunities for future investments in small satellites. Pursuing productive ties with the private space industry provides opportunities for the Canadian astronomical community to increase its impact in space astronomy.

Recommendation

We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support missions and mission contributions up to $100M, the preparatory activities (through phase A) for missions and mission contributions of all sizes, and scientific activities for missions to which Canadian astronomers contribute, regardless of whether the CSA has made a formal contribution. Participation in flagship missions requires additional funding beyond this A-base amount and would necessitate separate requests to the Government of Canada. As recommended below, the Coalition for Canadian Astronomy must play a key role in advocating for increased CSA spending on astronomy.

Recommendation

We recommend that the CSA establish a regular and recurring announcement of competitive opportunities of all sizes for Canadian missions and contributions to foreign missions. To facilitate this program, we further recommend that:

- The CSA continue to fund concept and science maturation studies of future missions and mission contributions on a regular basis (for example, every five years to coincide with the LRP and MTR), with the understanding that not every funded study will progress to an approved program.
- The CSA select missions and preparatory studies (Concept Studies, Science Maturation Studies and phase-A studies) within the proposed A-base funding through a competitive and transparently defined process of peer review.
- The CSA select Canadian contributions to international missions and missions beyond the A-base funding with guidance from the LRP, MTR and JCSA.

Recommendation

We recommend that the JCSA continue in the effective role it plays in advising the CSA on space astronomy. The astronomy knowledge contributed from this committee is essential for the effective and efficient use of Canadian resources for space astronomy exploration.

Recommendation

We recommend that the CSA enhance its support for Canadian participation in data analysis and leadership for JWST and the missions prioritized in Chapter 5 (or for any other CSA astrophysics programs in which Canada is the lead or a major partner). This funding should support both data analysis and theoretical investigations and be commensurate to the level of the missions engaged. Such support is required both to maximize the science return on Canada's investments and to ensure that Canadian astronomy remains internationally competitive.

Recommendation

We recommend that the CSA enhance its support for the development of Canada's space technology capacity through the establishment of a regular series of calls and increases in the budget for the STDP, ballooning and micro-satellite programs. Universities are key partners in these development programs. This funding is needed to maximize science return on Canada's investments, and to ensure that Canadian astronomy remains internationally competitive. We recommend that this funding, where possible, should be delivered through the grants and contributions program when directed to universities, as universities are well-equipped to administer grants and contributions, and less well-adapted to contracts.

Recommendation

We recommend that the CSA enhance its support for highly-qualified personnel through the establishment of a regular series of calls (e.g., every two years) and an increase in the budget for the FAST program to at least $10M total per call over all fields. The FAST program is currently heavily oversubscribed.

CASE STUDY

Searching for Earth Twins

Canadian-made instrument is looking for life in the Universe

To build SPIRou, Doyon led a team of

30 technicians
100+ scientists

from 10 institutions in 7 countries

← Étienne Artigau (left) and Neil Cook (right) standing next to a pre-processed SPIRou spectrum produced by their software. Their SPIRou analysis software produces science-ready spectra for a variety of science cases, notably the detection of Earth-like planets in orbit around cool stars.

Image credit: Étienne Artigau, Neil Cook, René Doyon (2020)

René Doyon is an astronomer at the **Université de Montréal** who develops state-of-the-art cameras and spectrographs to search for planets orbiting other stars. His latest creation is SPIRou, an instrument now operating at the Canada-France-Hawaii Telescope in Hawaiʻi. SPIRou can analyse the infrared light from distant stars to a precision of three-billionths of a wavelength, good enough to detect the tiny Doppler shifts caused by the orbits of unseen Earth-like planets. To build SPIRou, Doyon led a team of 30 technicians and over 100 scientists from 10 institutions in seven countries.

Key parts of SPIRou were made at the **Laboratoire d'Astrophysique Expérimentale (LAE) associated with the Observatoire du Mont Mégantic**, based at the Université de Montréal and Université Laval, which is one of Canada's most important university-based centres in experimental astrophysics. The LAE designed and built SPIRou's infrared detector module, and conducted the cryogenic tests of its camera. Another key contributor to SPIRou was **NRC Herzberg Astronomy and Astrophysics**, who designed and built SPIRou's large cryogenic enclosure.

To reach SPIRou's goal of detecting other Earth-like planets, cutting-edge hardware isn't enough: exquisite software is also needed to extract the tiny Doppler shifts buried amidst other much larger effects. Developing that critical software is the job of both **Étienne Artigau**, a seasoned infrared astronomer at UdeM and SPIRou's co-project scientist, and **Neil Cook**, a young postdoctoral fellow who recently joined Artigau and the SPIRou team. Cook's expertise in data processing and automated data analysis were an excellent match to the needs of SPIRou, so when offered the chance to work on this high-profile project, he didn't hesitate and moved from the UK to Montréal to join the adventure.

Thanks to the work of Doyon, Artigau, Cook and their large team, SPIRou will soon uncover new habitable Earth twins, that is, rocky planets with surface temperatures that allow liquid water, and thus where life could develop. After identification of these new worlds, larger telescopes will measure the atmospheric composition and determine if these new planets are host to biological activity. The confirmation that life arose elsewhere is thus within our reach. SPIRou is a crucial stepping stone for nothing less than answering the age-old question: Are we alone? ♦

Recommendation
We recommended that the budget for the CSA Co-Investigator program be increased and a regular (e.g., annual) series of calls established. The Co-Investigator program is currently heavily oversubscribed. This key program allows Canadian astronomers to participate and provide leadership in a wide range of international missions with a very modest investment from the CSA, regardless of whether the CSA has made a formal hardware contribution.

Recommendation
We recommend that the CSA streamline the application process for the FAST and Co-Investigator programs. This will increase the accessibility of these programs to a wider community as well as the ultimate scientific impact. The application process could be structured to resemble that of the NSERC Discovery Program.

CFI

Many of the successful small—and mid-scale Canadian astronomy projects discussed in Chapter 3 have been funded by the CFI's Innovation Fund and corresponding matching funding requests to individual provinces.[73] CFI support is critical for the development of cutting-edge astronomical instruments in the Canadian community and has yielded multiple successes in recent years, for example in CHIME and SPIRou. There is a push by some research communities to enable the use of CFI funding for larger scale projects, such as underground physics experiments, or telescope consortia, through multi-stage project proposals. If there is a move to also support larger scale projects within CFI, its role as a nimble, fast time scale engine for midscale projects must be safeguarded. This role has been CFI's most notable success in astronomy and physics.

The ability to develop prototypes, conceptual designs and associated cost estimates can ensure that the scope, schedule, and budget of Innovation-scale projects are well-developed and risk-minimized, and will significantly increase the likelihood of successful project completion. NRC can be a valuable partner for some small—to-mid-scale technology development. However, much of the preliminary development that leads to CFI-funded instrumentation programs takes place in university laboratories, and needs to be funded within CFI's mandate to enhance the research capabilities of the higher education sector.

Some institutions view the purpose of CFI's programs as supporting multi-million-dollar purchases of equipment for largely independent work at multiple institutions. This can complicate implementation and scientific output for astronomy and physics projects, where the instruments are unique, custom-designed, follow a staged technology development path, and are the result of close collaboration from multiple institutions. Institutions are often unaware of or unwilling to accommodate best practices for astronomy facilities, including reserving adequate funding for project management and project reviews, adopting strategies for efficient use of university provincial tax rebates, strategically organizing and assigning in-kind contributions, incorporating sufficient time in the project schedule for meaningful land-use consultation, and building justifiable time and cost contingencies into budget line items

CFI has a relatively narrow one-size-fits-all prescription for the infrastructure operating funding that accompanies its funded infrastructure: this sometimes results in inefficiencies, because construction funding can be easier to obtain than operations funding. By evaluating projects based on full cost over the project period (construction plus operations) and allowing additional flexibility on the ratio of construction to operations cost, the CFI infrastructure program can be more cost-efficient, adaptable to the realities of mid—and large-scale science, and provide better infrastructure to scientists across Canada. This might take the form of operations costs being included explicitly in the total project budget, and growing the allowed operations fraction to be up to 50% of the CFI funding request. Individual proposals would be able to optimize the fraction of their institution's allocation that is spent on operations, with the aim of producing the most competitive infrastructure evaluated against its life cycle cost.

Recommendation
We recommend that CFI identify ways to support full utilization of scientific infrastructure. Having a pre-defined allocation for operations based on project costs may, at times, lead to inefficiencies. Flexibility in the construction to operations ratio, with the total cost reflected in the competition, will increase the impact of CFI infrastructure for astronomy.

73 The CFI review process takes LRP priorities into account; confidential summaries of the LRP2020 recommendations were provided to CFI in April and September 2020 for use by their expert and multidisciplinary assessment committees.

Recommendation
We recommend that CFI and institutions receiving CFI funds identify ways to fund the gaps in technology development between the small-scale work funded by NSERC Discovery Grants and the large-scale requests made in CFI Innovation proposals.

Recommendation
We recommend that, before the next CFI Innovation Fund proposal deadline, a special, short-term CASCA committee be established to work with CFI to clarify agency-supported best practices for astronomy facilities. The committee's report will inform institutions who guide applicants for best practices but are oftentimes not aware of facility special needs, and will also level the playing field for applicants from different institutions.

Recommendation
We recommend that CFI's regulations be adjusted to allow a small fraction of funds awarded for large projects to be spent on education and public outreach activities. This will help scientists inform the Canadian public about the research enabled by public support. CFI should also ensure that all its grantees are aware of CFI's ability to promote their work through the CFI external relations and communications team.

NSERC

NSERC supports astronomical data analysis and theoretical astrophysics through a variety of programs (e.g., Discovery Grants, funding for CITA through Discovery Institutes Support, Canada Research Chairs, and student scholarships and fellowships), at the level of roughly $11M per year. The total Canadian spending on telescopes and other facilities through CFI, CSA, and NRC, is about three times this value (see Chapter 3). More support for the HQP who carry out data analysis and theoretical investigations would maximize the science coming out of this infrastructure. The LRP panel asserts that federal investments in Discovery Grants are the most efficient value-per-dollar that can be made in Canadian astronomy, and are also the most effective means of supporting training of new HQP.

Previous LRP reports have noted that support for postdoctoral researchers from NSERC is significantly lacking. NSERC Postdoctoral Fellowships do not have internationally competitive salaries,[74] last for only two years, and are available only to Canadian citizens and permanent residents. These conditions are incompatible with attracting and retaining the world's best early-career astronomers. Since substantial research output in astronomy comes from postdoctoral researchers (see Chapter 3), the small number of postdoctoral positions, their relatively low funding and duration, and the exclusion of foreigners all hinder Canadian astronomy's ability to compete on the world stage. Furthermore, the lack of postdoctoral opportunities forces local graduates to seek international positions, making it difficult for a Canadian to conduct the entirety of their astronomy career in Canada. This creates an inequitable environment: personal situations mean that not everyone is able to go abroad for postdoctoral employment. Any nation that envisages itself as a research leader should be able to offer a full STEM career path to its own people in their own country.

Because research in astronomy uses national and international facilities, it is possible to do world-class astronomical research at small or undergraduate-only universities. These institutions often have special roles in providing equity of access into STEM careers for students from remote, rural or Indigenous communities. There are particular challenges in research involvement for faculty at Canadian comprehensive research universities, which could be overcome by modest, targeted funding such as was provided through NSERC's former Research Capacity Development in Small Universities (RCDSU) program. NSERC's Discovery Development Grants are intended to achieve the same goals of supporting research at smaller institutions. However, the small amounts of funding involved limit the ability of researchers to participate in national networks or large programs. This is particularly important for researchers with few local collaborators, either other faculty or HQP.

Additional specific recommendations for support of theoretical astrophysics by NSERC are contained in Chapter 6.

74 NSERC Postdoctoral Fellowships have a value of CA$45,000 per year for two years. International astronomy prize fellowships typically have durations of 3+ years and most (but not all) have no citizenship or residency restrictions. Starting salaries or stipends for 2020 include: Dunlap Fellowships (CA$71,000), NRC Plaskett/Covington Fellowships (CA$72,000), NASA Hubble Fellowships (US$69,500), NSF Astronomy and Astrophysics Fellowships (US$69,000), ESO Fellowships (€36,000, tax free), Australian DECRA Fellowships (AU$81,600), Berkeley Miller Fellowships (US$68,000), Harvard ITC Fellowships (US$69,500) and Flatiron Fellowships (US$87,000). Many of these fellowships are also accompanied by annual research budgets, which NSERC Postdoctoral Fellowships do not provide.

Recommendation
We recommend that NSERC find ways to fund postdoctoral positions in astrophysics that have internationally competitive salaries, a duration of at least three years as per international standards and no citizenship or nationality restrictions, with the goal of attracting and retaining the world's best early-career astronomers.[75]

Recommendation
We recommend that NSERC explore additional methods beyond Discovery Development Grants to support research at smaller Canadian universities.

CASCA, ACURA, and LRPIC

CASCA has provided advocacy and a national focus for Canadian astronomers for decades. It operates as an incredibly lean organization, with substantial volunteer effort supplemented by minimal (but critical!) paid staff. Implementing many of the recommendations in this Chapter is most logically led by the Society; implementing some (for example, establishing a national astronomy education and public outreach coordinator position) will require expenditures well beyond CASCA's current budget. The CASCA Board of Directors and membership will need to decide whether they are willing to support such an expansion of the Society's role.

One way to enhance CASCA's EPO activities and fund the position of an EPO coordinator would be to leverage CASCATrust, a registered charity, to take advantage of opportunities for educational grants and funds from federal and provincial sources with the specific goals of enhancing EPO. There are also many corporations that do philanthropic outreach and provide local educational funding. CASCA's ability to tap into those avenues to fund EPO activities could be enhanced by association with individuals with connections to the corporate community. Ideally, we would be able to appoint people to the CASCA Board or as CASCA Trustees who are both professional astronomers and have strong ties to corporate communities. Given that it may be difficult to continuously have such a skill set on the Board, CASCA could consider changing its by-laws to allow one non-professional astronomer on the Board at any given time, so as to allow a broader skill set to be accessible to the organization.

CASCA's Long Range Plan Implementation Committee (LRPIC) was formed as a recommendation of LRP2010. LRPIC has responsibility for overseeing the implementation of the LRP and providing expert opinion on its developments. The LRPIC provides advice to the CASCA Board and to the Coalition for Canadian Astronomy (see below). The LRPIC may also propose to change the recommendations or the priorities of the LRP as the international or national parameters change. This is especially relevant now: the future directions of large international astronomical facilities are particularly uncertain at the present time. Discussions over land use, funding uncertainties due to the economic climate, and of course the long-term effects of the COVID-19 pandemic all play a role.

The Association of Canadian Universities for Research in Astronomy (ACURA) has for many years represented the astronomy interests of Canada's universities. ACURA has developed strategies to advocate for the highest priority observational facilities in previous Long Range Plans, and has helped coordinate the pursuit of these strategies at the highest levels. In Chapter 6, we argued that ACURA should broaden its scope to ensure that computational facilities meet the needs of Canadian astronomers. In addition, ACURA has a role to play in securing the additional federal funding for astronomy needed to fulfill the recommendations of this LRP.

Both ACURA and LRPIC have played effective but relatively separate roles: ACURA is uniquely positioned as an organization with access to funding and with significant buy-in from senior university administrators, while LRPIC provides the community's highest levels of expertise on national and international developments, and is able to respond rapidly to evolving circumstances. Given the relative strengths of these two organisations, there is an opportunity to significantly increase their effectiveness by combining their efforts. Through enhanced cooperation, the community can better coordinate a response to the full set of recommendations in the LRP report and will be better positioned to secure the required funding and resources.

75 A similar recommendation for CITA Fellowships and CITA National Fellowships is made in Chapter 6.

Recommendation
We recommend that CASCA explore the charitable status of CASCATrust as a means to access charitable contributions specifically targeting EPO initiatives. CASCA should seek to broaden the skill set regarding outreach and charitable activities on the CASCA Board, with the goal of funding a spectrum of EPO activities plus the EPO coordinator mentioned above.

Recommendation
We recommend that ACURA and LRPIC expand their mutual consultation and coordinate their efforts more closely, in order to advance the suite of priorities identified in this report more effectively. In particular, we recommend that ACURA receive recommendations from LRPIC on possible uses of their funds.

Recommendation
We recommend that the mandate of LRPIC be revised to implement not only facility recommendations, but also the broader range of non-facility recommendations listed in this report. LRPIC should also estimate the cost of implementing the LRP2020 recommendations addressed specifically to CASCA (e.g., on equity and inclusion and on education and public outreach), and should provide these cost estimates to the CASCA Board.

Recommendation
We recommend that ACURA take the lead in advocating for additional federal funding for Canadian astronomy, potentially through an increased funding envelope for HAA. We particularly prioritize the funding needed for early-career STEM personnel and university-based experimental astrophysics laboratories, as recommended above.

Recommendation
We recommend that ACURA fund the press officer position recommended above. By promoting the initiatives and the success stories of Canadian astronomers to journalists and the public, the work of the press officer will contribute to creating a global sense of pride and support for Canadian astronomy, thereby enhancing ACURA's effectiveness in advocating for the priorities of this LRP.

CCA

The Coalition for Canadian Astronomy was formed in 2000, with the goals of advocating for the long-term health of Canadian astronomy, and of securing federal funding to support the projects endorsed by the LRP process. The Coalition is an umbrella organization that brings together representatives from all the major non-governmental stakeholders in Canadian astronomy (CASCA, ACURA, and industry partners). It has organized briefings on astronomy projects for Members of Parliament, ministerial staff and senior civil servants, has responded to pre-budget consultations on behalf of the Canadian astronomy community, and works with a government relations and communications firm to promote Canadian astronomy priorities to the federal government. The Coalition played a particularly pivotal role in securing federal funding for participation in TMT.

There have been extended periods when lobbying government has not been feasible or appropriate, which has sapped momentum from the Coalition's activities. The astronomical and governmental landscapes have evolved substantially since the Coalition was founded, and the list of relevant industry partners looks very different from that of twenty years ago. The Coalition remains a vital component of the astronomy community's engagement: it can maintain its effectiveness by maintaining an ongoing minimum level of activity, and by adopting new partners and strategies that reflect the complex interdependencies of community priorities.

CASE STUDY

Understanding the Diversity of Early Galaxies and Their Evolution

A Canadian-trained astronomer comes full circle to train the next generation of Canadian scientists

Damjanov's work has shown that many **"red nugget" galaxies** have persisted over cosmic time, and have avoided being subsumed by larger galaxies

← Dr. Ivana Damjanov first came to Canada as a PhD student, and returned to join the faculty at Saint Mary's University in 2017.

Image credit: Danielle Boudreau, Communications Officer, Faculty of Science and Science Outreach Centre, Saint Mary's University

Ivana Damjanov has a passion for understanding how galaxies evolved from the early Universe through to the present. As part of her PhD thesis at the University of Toronto, she used detailed images from the Hubble Space Telescope to discover an entirely new class of galaxies, which she named "red nuggets." These galaxies were only seen when the Universe was very young, and look completely different from the typical galaxies found around us today.

Where did these red nuggets go at later times, as the Universe evolved? Some astronomers proposed that the red nuggets must have been subsequently swallowed by larger galaxies like our own Milky Way. Damjanov realised that it was crucial to look for evidence of red nuggets at times between the earliest galaxies and those we see today, and she scrutinised some of the faintest images available to see if she could find the red nuggets evolving over time. She found them, misclassified as stars!

Damjanov's work has shown that many of these galaxies have persisted over cosmic time, and have avoided being subsumed by larger galaxies. She now uses enormous high-quality data sets to learn how galaxies have evolved over billions of years, and to relate that evolution to where galaxies live in the Universe.

Damjanov credits strong mentoring during her PhD and postdoctoral research, which gave her the support and openness needed to pursue her own research ideas. She works now to provide the same support to her own students at **Saint Mary's University** in Halifax, where she is an associate professor and Canada Research Chair.

Damjanov's path to Saint Mary's originated in the town of Vršac, Serbia. She moved to Canada in 2006 to pursue a PhD at the University of Toronto, and then held the Menzel Fellowship and an NSERC Postdoctoral Fellowship at the Harvard-Smithsonian Center for Astrophysics in Boston. In 2017, Damjanov was delighted to return to Canada to take up a tenure-track faculty position at Saint Mary's University. ◆

Recommendation
We recommend that the Coalition for Canadian Astronomy develop strategies for astronomy advocacy to the Canadian government that cover all the highest priority facilities recommended by the LRP, and that the CCA build and maintain relationships with a diverse set of Canadian industry partners who are willing to actively engage to help deliver these priorities. We further recommend that the Coalition adopt an annual schedule of events, deliverables and activities for its constituent stakeholders, while still retaining the flexibility to respond rapidly to developments as needed. Time periods when engagement with government is not feasible should be used for community consultation, and in particular should involve regular dialogue with LRPIC.

Recommendation
We recommend that the Coalition for Canadian Astronomy and its individual members continue to advocate to Innovation, Science and Economic Development Canada, both directly and via relevant advisory bodies, for increased CSA science spending. As Chapter 5 demonstrates, the Canadian astronomy community has ambitious goals for space-based facilities. Although there are clear benefits to Canada in realizing these goals, the current science budget of the CSA is wholly inadequate for this purpose. As the "Vision for Canadian Space Exploration" document and LRP2020 white paper on space astronomy discuss in more detail, spending on the order of $1B per decade would enable a robust space science program in Canada.

Training of Highly-Qualified Personnel

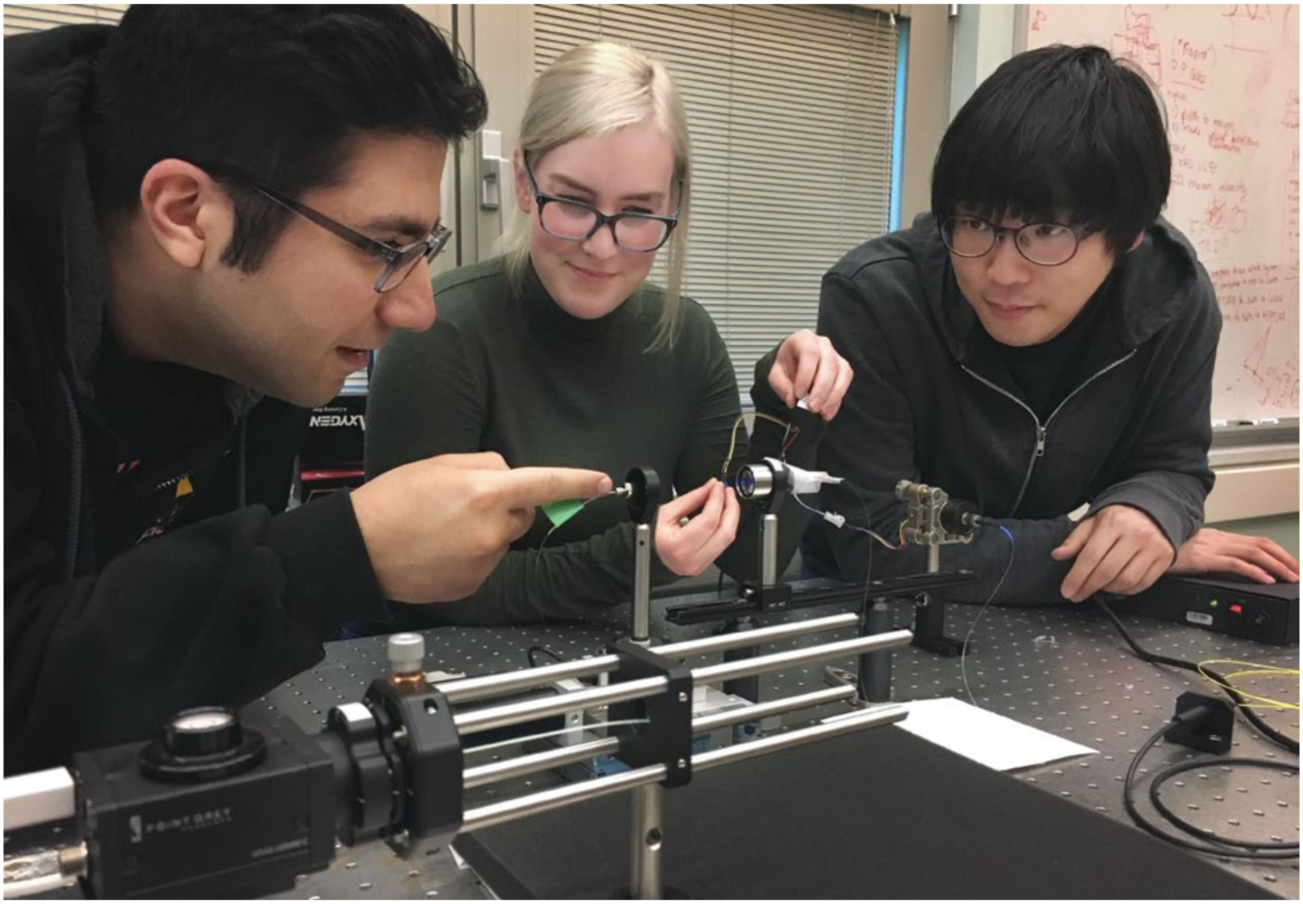
Students and postdoctoral researchers,[76] often broadly characterized under the umbrellas of highly-qualified personnel (HQP), trainees and/or early-career researchers, form a vital part of the ecosphere of Canadian astronomy. Most of the major programs in Canadian astronomy hinge on the research output, technical contributions and leadership of students and postdoctoral researchers. These personnel will go on to careers not only in astronomy and academia, but also in technology, finance, medical research, defence and other highly-skilled sectors, thereby making a wide range of important contributions to society and to the economy. For both these reasons, it is vital that students and postdoctoral researchers have productive and positive experiences as astronomers, and that they also gain the skills needed to be successful in their future careers in or beyond astronomy.

The traditional view of the training and career trajectories in astronomy is that someone will undertake an undergraduate degree majoring in physics and/or astronomy, will obtain an MSc and PhD, will take up one or two postdoctoral appointments, and then will obtain a long-term astronomy position at a university, observatory or national laboratory. However, the modern reality is that people undertake studies in astronomy with a variety of different motivations and goals, and that these aspirations change as they progress through their degrees and then through their subsequent careers. Some Canadian students indeed follow the traditional trajectory, as demonstrated by the many prominent Canadian astronomers holding senior positions across Canada and throughout the world. Other students decide at the outset that they do not want to have a career in astronomy, but nevertheless first want to pursue an astronomy graduate degree. Some who are initially keen on a career in professional astronomy later come to a realization during their studies or postdoctoral research that the traditional astronomy career path does not meet their needs or ambitions, and decide to transition to a different career.

An analysis of the trajectories of recent Canadian astronomy graduates has found that around 50% of astronomy PhDs take up a postdoctoral position immediately after graduating, and that 20%-25% of these graduates end up in faculty positions or equivalent. These numbers, while averaging over a variety of personal situations and circumstances, broadly indicate that many astronomy graduate students and postdoctoral researchers in Canada will end up in long-term astronomy-related jobs, but that the majority will not. As a community, we need to adequately train and prepare students and postdocs for a range of outcomes, while providing a rewarding experience that stands on its own as a positive and worthwhile investment of time. Specifically, students and postdoctoral researchers need training not just in astronomy research, but also in scientific writing, presentation skills, computation, time and project management, budgeting, conflict resolution, and supervision and mentoring. All of these skills are valuable and exportable to other careers beyond astronomy, academia, research, or science.

Below we review two areas in which the community can better support students, postdoctoral researchers, and other HQP: professional training and career development. The corresponding recommendations will lead to a more productive astronomy community, and to better long-term outcomes for Canadian society.

76 Research associates are formally a separate category of employee from postdoctoral researchers, but for the purposes of this document, we use "postdoctoral researchers" to refer to both groups.



Students of NTCO CREATE. Image credit: uvic.ca

Professional Training and Skills Development

As astronomical facilities and programs grow to encompass larger teams and larger datasets, the challenge of training the next generation of astronomers grows as well. As discussed above, most current students and postdoctoral researchers will not have long-term careers in academia or astronomical research. The astronomy community therefore has a duty to provide training for a complex and varied skill set, both at the undergraduate and graduate student levels. The fact that the majority of astronomy graduate students will ultimately join the workforce outside of astronomy enhances the need to modernize and broaden the training offered (for example, including less-technical skills such as science communication and public speaking). This will better equip our early-career researchers and trainees, whether their future is in astronomy research, in areas broadly related to astronomy instrumentation and technology, or in technically skilled positions elsewhere in the workforce.

Enhanced training in the areas of statistics, “big data” and machine learning is particularly critical as part of a foundation for a successful career. While at the undergraduate level, courses can be provided through mathematics, statistics, and/or computer science departments, at the graduate level, there is an expressed need for astronomy-focussed courses in areas such as astrostatistics and machine learning. One solution may be to sustain enhanced learning opportunities for graduate students via online courses, taking advantage of the acceleration of this model precipitated by COVID-19. Significant advantages can be gained by improved coordination of courses across institutions. As we have seen in the pandemic era, the technology to do this is largely mature, but funding, organization, accreditation and governance remain challenges. Many of these difficulties are being rapidly overcome: we can take lessons learned as to what has worked effectively under COVID, and should incorporate and expand on those developments in the post-COVID era. Digital presentation archives and visitor programs currently provide a means of broadening the education of students, but these too are primarily offered through larger centres of learning or research. At the postdoctoral level, individuals tend to favour focussed-short term workshops to provide enhanced learning opportunities.

There are now increased opportunities for students to experience training opportunities in industry, due to partnerships forged under programs such as NSERC CREATE, NSERC Alliance, and Mitacs. Such initiatives are effective at expanding the skill sets of students and improving the links between academia and industrial partners.

Recommendation
We recommend that members of Canadian physics and astronomy departments develop opportunities for students and postdoctoral researchers to acquire a broad set of skills relevant to careers in both astronomy and industry, including but not limited to science communication, scientific writing, mentoring, statistics, high-performance computing and machine learning. In particular, CASCA should identify resources that allow students and postdoctoral researchers to participate in relevant workshops, internships, summer schools and boot camps organized by external institutions or organizations.

Recommendation
We recommend that members of Canadian physics and astronomy departments and their associated institutions develop a coordinated, expanded and enhanced approach to student training. In particular, remote access to courses across institutions would greatly broaden the training opportunities for students across Canada, by optimizing the knowledge transfer offered by a limited number of experts, and by providing equitable access to students at smaller universities who otherwise might not be able to take specialized classes.

Recommendation
We recommend that Canadian astronomers supplement their training programs for students and postdoctoral researchers through industrial partnerships, as can be facilitated through programs such as NSERC CREATE and Alliance, and Mitacs Elevate and Accelerate.

Career Development and Progression

In Chapter 3, we have demonstrated that postdoctoral researchers produce the highest-impact papers in Canadian astronomy. In Chapter 6 and earlier in Chapter 7, we have advocated (as previous LRP reports have done) for an increased number of postdoctoral positions in Canadian astronomy, with internationally competitive salaries.

Postdoctoral researchers are valued members of the astronomy workforce, since they are highly skilled experts who usually have significant time available for research activities. The vital importance of postdoctoral scientists to research programs and infrastructure/technology development is such that they are the key workers in the execution of many projects. While this career stage includes the most productive years (generally the first eight years post-PhD for most researchers), it is also a very precarious employment phase. In Canada, postdoctoral researchers are ineligible to apply for their own NSERC Discovery Grants, and so are usually dependent for employment on named fellowships, grants held by faculty members, or some combination. A postdoctoral position is a short-term contract (typically 2–3 years), often requiring a relocation to a new city or country. After completing their doctorate, an astronomer might take on several postdoctoral positions in succession, relocating each time, before either obtaining a permanent position in astronomy, or moving on to another career. This model is not equitable, since family situations and other factors may make relocations challenging and restrict options for some excellent researchers; COVID-19 currently presents another barrier to mobility, for which the long-term effects remain to be seen. Overall, many postdoctoral researchers face complex decisions due to life circumstances, and opt for or are forced to choose the stability of a job outside of astronomy.

The precarity and inequity of postdoctoral positions have been exacerbated by the pandemic, during which schooling and childcare have not been readily available for many families. Such burdens have historically and disproportionately fallen on women, and contribute to a "leaky pipeline" for women in astronomy. In order to retain skilled researchers and to ensure the ongoing recruitment of a diverse cohort, postdoctoral positions need to offer flexibility. We encourage CASCA to develop best-practice guidelines for the community on postdoctoral hiring practices and employment, with the goal of accommodating a range of life circumstances, and of providing consistent benefits across Canada to postdoctoral researchers and their families. The motivating mentality should be a desire to identify creative solutions and to recognize different working modes, as have emerged during the pandemic. COVID-19 has shown us that many aspects of astronomy can continue in ways we previously would not have allowed or would have thought impossible: we should maintain this commitment to flexibility into a post-pandemic future. For example, all postdoctoral positions should provide for paid family and parental leave, and should allow options for reduced/flexible hours or part-time employment[77] (without disclosure of such preferences to hiring committees). Versatility in working arrangements is a significant factor in recruitment and retention of the most diverse workforce possible.

While CASCA has had a graduate student committee for around 25 years, there has never been an equivalent committee to represent postdoctoral researchers. CASCA should establish such a committee, which could promote networking opportunities and information sharing amongst postdoctoral researchers in Canadian astronomy, could gather information about best-practice for postdoctoral employment (e.g., hiring processes, employment benefits, remote work, mentoring programs, eligibility for teaching and supervision opportunities, cross-appointments) and could advocate to CASCA for initiatives that would benefit the postdoctoral community and beyond. In particular, it is important that postdoctoral researchers are treated by our community as early-career professionals. This means that the community should commit to offering fair, internationally competitive compensation and benefits for every postdoctoral position, including reimbursement of expenses associated with immigration, health checks, security clearances, relocation, and quarantine, for both the person being hired and their families. CASCA should develop minimum recommended standards for these benefits, and should advocate to relevant funding agencies that these all be eligible expenditures on research grants. Furthermore, while CASCA cannot control the hiring and employment policies of institutions across Canada, it should develop and impose minimum basic requirements (e.g., an explicit starting salary, specified term of contract, and stated list of benefits) on the content of advertisements for postdoctoral positions to be circulated to CASCA's email exploder.

Individual astronomers recruiting for astronomy postdoctoral positions in Canada should impose[78] a maximum (e.g., 5 years) on the time elapsed between awarding of a PhD and commencement of a postdoctoral appointment, as an eligibility criterion for all applicants. Such restrictions should also allow appropriate accommodation for career interruptions and other extenuating circumstances. These limits are important because they guard against exploitative scenarios, in which an employer does not compensate a researcher in accordance with their seniority or experience or is not motivated to provide opportunities for career progression. Imposition of such a time limit would close off employment opportunities in astronomy to some applicants, but such concerns are outweighed by the need to prioritize career development and fair working conditions.

The fixed terms of postdoctoral positions in Canadian astronomy result in significant career uncertainty. Longer term contracts (e.g., staff scientist positions) are often not feasible or advisable at many institutions: due to a lack of long-term funding, either such a position cannot be created in the first place, or the position faces termination or redundancy as soon as the relevant funding source is exhausted. It is also important to note that postdoctoral positions are exempt from the Canadian government's requirement of a labour market impact assessment, while long-term staff-scientist positions are not. A continued emphasis on postdoctoral positions will therefore maintain the community's ability to bring international expertise to Canadian astronomy, thereby also strengthening the international reputation of Canadian astronomy. Overall, it is important to maintain the flexibility offered by postdoctoral research programs, while acknowledging that this is accompanied by a lack of long-term job security.

A frustration and barrier for postdoctoral astronomers in Canada is that they usually cannot apply for funding to support their own salaries. NSERC, CFI, CSA and other agencies do not allow postdoctoral researchers to compete for most of their funding programs, while many institutions have a strict policy that their postdoctoral employees cannot lead funding applications. In addition, the average award amount for an early-career physicist's NSERC Discovery grant ($29,000/year) is insufficient to fund a postdoctoral salary, while funding for researcher salaries sits outside the CFI's eligibility rules and mandate. Because of these restrictions and limitations, there would need to be major structural changes to Canada's research landscape in order to accommodate self-funding applications from postdoctoral researchers. Such changes would have effects well beyond astronomy, and in our view are infeasible without substantial increases in funding to the overall research ecosystem.

77 Immigration, Refugees and Citizenship Canada expects foreign workers to have sufficient funds to support themselves, and defines full-time work as at least 30 hours per week for which wages are paid and/or commission is earned.

78 At some Canadian institutions, there is already an overall institutional policy imposing this requirement.

Mentoring by more senior astronomers is extremely important for postdoctoral scientists, graduate students and other early-career researchers, as this provides opportunities to learn from those who have seen or experienced a wide range of circumstances. However, in order to be functional and beneficial within Canadian astronomy's relatively small community, mentoring should take the form of a hierarchical structure that spans institutions across the country, as has been successfully implemented in other communities. Networking and mentoring are also especially crucial when applying for jobs, most notably when seeking an industry career and its associated significant change in direction and environment. In order to facilitate such connections, CASCA should allow and encourage those who have left astronomy or who are no longer CASCA members to maintain information in CASCA's member database on their contact details and career trajectories.

Recommendation
We recommend that CASCA establish a committee to represent and advocate for astronomy postdoctoral researchers in Canada. This committee can help develop the guidelines and standards proposed in the recommendations below.

Recommendation
We recommend that postdoctoral researchers in Canadian astronomy be paid at internationally competitive levels,[79] with the goal of attracting and retaining the world's best early-career astronomers.

Recommendation
We recommend that CASCA develop and maintain a set of best-practice guidelines for postdoctoral recruitment and flexible employment.

Recommendation
We recommend that all astronomy postdoctoral positions in Canada be advertised with options for reduced/flexible hours or part-time employment. Applicants should not be required to indicate their interest in this option until an offer is made.

Recommendation
We recommend that CASCA develop recommended minimum standards for reimbursable relocation costs (including fees for visa applications, security clearances, health checks, and quarantine upon arrival) associated with all postdoctoral hires in Canadian astronomy. CASCA should also advocate to the relevant funding agencies that such needs all be considered eligible expenditures.

Recommendation
We recommend that CASCA introduce content requirements that advertisements for postdoctoral positions must meet in order to be disseminated by CASCA. These requirements should include the starting salary, term of contract, and employment benefits.

Recommendation
We recommend that eligibility criteria be introduced for all astronomy postdoctoral positions in Canada, placing an explicit maximum limit (e.g., 5 years) on the time elapsed since awarding of an applicant's PhD. Career interruptions and other extenuating circumstances must be accommodated when implementing this limit.

Recommendation
We recommend that the CASCA endorse a national mentoring strategy for early-career astronomers, in which relationships are built across the country by pairing mentors and mentees aligned in their personal or professional experiences.

Recommendation
We recommend that CASCA's membership database incorporate the subsequent trajectories, current positions and contact details of former astronomy graduate students and postdoctoral researchers. A complete census is impractical and unnecessary, but a clear overall picture of career paths will be highly valuable for current students and postdoctoral researchers wanting to assess career options and identify networking opportunities.

79 Similar recommendations are made elsewhere in this report specifically for CITA Fellowships and for NSERC Postdoctoral Fellowships.

Chapter 8

Epilogue

At the start of a new decade, Canadian astronomy is poised to make great discoveries about the cosmos, and to deliver substantive benefits to Canada and to the world. Our community comprises scientists, engineers, technicians, administrators and trainees, working together to understand the Universe, to develop new technologies, to foster the next generation, and to share the results of these activities with all Canadians. We have a multitude of opportunities to lead the development of next-generation observatories and to upgrade and enhance our existing telescopes, and then to make discoveries with these world-class facilities. We are fortunate to have the support of national agencies that are respected as international partners and as catalysts to link academia and industry. We are at a new and exciting frontier, beyond which we can address some of humanity's oldest and most fundamental questions.

We know that astronomy in 2030 will look different from the field today: a new generation of researchers will be participating in new facilities, projects and experiments designed to answer the new science questions that arise from tackling the exciting questions of today. Long-distance virtual collaboration, already an important feature of astronomy research, will inevitably increase, as will the use of technology in facilitating astronomers' efforts to bring the excitement of our science to the public. If the recommendations of this report are enacted, we will have the necessary ingredients for success: the equitable participation of a diverse cohort of motivated people, competitive and fairly-distributed funding for fundamental science across theory, experiment, and observation; a balanced multi-wavelength portfolio of cutting-edge observational facilities on the ground and in space; and access to the powerful digital research infrastructure needed for theoretical computations and data processing.

Individual astronomers and the overall astronomy community each have crucial roles to play, both in advancing our understanding of the Universe and in contributing meaningfully to society and the economy. However, we must also recognize that there are challenges that are outside of our direct control. Many of the large facilities recommended in this report require cooperation, funding and decisions from international partners. Such decisions will be made in the context of the long-term global economic impact and recovery from the COVID-19 pandemic, which provides constraints that are unknown at the time of writing. Other uncertainties include the renewal of the master lease that governs the future of astronomical facilities on Maunakea, the possible deleterious effects of satellite constellations on ground- and space-based observatories, and the ramifications of any future cancellations, delays or equipment failures experienced by major astronomical

Many aspects of Canadian astronomy are within the control of individual astronomers, particularly those concerning how we relate to each other and society. Our discipline must become more inclusive, and needs to engage better with both Indigenous peoples and with the Canadian public.

facilities. Some or all of these issues, plus the inevitable unknown unknowns, will need to be considered by the Canadian astronomy Mid-Term Review in 2025.

Many aspects of Canadian astronomy are within the control of individual astronomers, particularly those concerning how we relate to each other and society. Our discipline must become more inclusive, and needs to engage better with both Indigenous peoples and with the Canadian public. We must be mindful of our responsibilities to building a sustainable society, and to equitable treatment and responsible training of students and postdoctoral researchers. This report attempts to provide more than just a wish list of new facilities in an uncertain landscape; it is also a call to action for researchers to recognize their individual responsibilities, including their responsibility to work toward realizing the LRP priorities.

The LRP2020 report represents not just the work of the eight LRP panel members, but a true community effort from everyone in Canadian astronomy. Hundreds of researchers contributed white papers, reports, ideas, detailed critiques, and commentary. Dozens of staff members from funding agencies and other organizations participated in consultations and provided feedback. We thank the many colleagues who responded to our requests for information and updates throughout the process. We are grateful for the support of funding agencies and panel members' institutions that enabled release time, travel, and community town halls, along with design, translation, and printing of the final report. We hope that the result reflects Canadian astronomers' aspirations and passion for understanding the Universe. We look forward to the future answers — and new questions — that lie ahead.

Chapter 9

Reference Material and Appendices

Acknowledgements

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White paper authors and co-authors (alphabetical)

R. Abraham
N. Afsari
J. Albert
L. Albert
R. Alexandroff
M. Ali-Dib
D. Andersen
E. Artigau
J. Atwood
A. Bahramian
M. Balogh
K. Bandura
M. Bannister
P. Barmby
F. Baron
N. Bartel
P. Bastien
S. Basu
S. Baum
M. Beaudoin
S. Beauvais
T. Bell
T. Belloni
L. Belostotski
B. Benneke
M. Bietenholz
D. Bingham
C. Blain
J. Blakeslee
J. Bolduc-Duval
A. Boley
J. Bond
J. Bovy
C. Boyer
P. Boyle
C. Bradley
R. Brandenberger
A. Brazier
P. Breysse
T. Bridges
J. Brown
T. Brown
T. Brunner
A. Burgasser
S. Burke-Spolaor
G. Burley
J. Busler
A. Butko
C. Byers
M. Byers
P. Byrnes
E. Cackett
C. Cadieux
I. Caiazzo
D. Caldwell
J. Cami
P. Capak
R. Carlberg
B. Carlson
D. Chalmers
J. Chan
E. Chapin
S. Chapman
P. Chastenay
F. Chateauneuf
A. Chauhan
A. Chen
M. Chen
C. Chiang
H. Chiang
E. Chisholm
E. Choi
K. Cleary
R. Cloutier
R. Cockcroft
M. Connors
D. Contreras
N. Cook
J. Cordes
B. Cote
P. Côté
S. Côté
S. Coude
L. Coulombe
S. Courteau
N. Cowan
D. Crabtree
R. Craiu
J. Crane
D. Crichton
A. Crites
A. Cumming
A. Damascelli
I. Damjanov
L. Dang
A. Darveau-Bernier
T. David
T. Davidge
B. Davids
G. Davis
A. De Rosa
P. Demorest
N. Denman
A. Densmore
J. Di Francesco
I. Dillmann
O. Djazovski,
M. Dobbs
T. Dolch
R. Dong
P. Dosanjh
R. Doyon
L. Drissen
M. Drout
X. Du
J. Dunn
J. Dupuis
H. Dykaar
G. Eadie
A. Ellery
A. Ellison
S. Ellison
J. English
C. Evans
M. Evans
S. Fabbro
J. Faherty
G. Fahlman
N. Fantin
R. Fernandez
M. Feroci
L. Ferrarese
M. Fich
L. Fissel
J. Fitzsimmons
J. Folk
E. Fonseca
S. Foreman

T. Foster
W. Fraser
R. Friesen
R. Friessen
A. Frolov
B. Gaensler
J. Gagné
S. Gallagher
L. Gallo
S. Gaudet
B. Gerard
T. Girard
J. Gizis
B. Gladman
R. Gleisinger
P. Godin
C. Goldblatt
V. Graber
M. Graham
F. Grandmont
D. Gregoris
E. Griffin
B. Guest
P. Gupta
S. Gwyn
D. Haggard
E. Haine-Bennett
P. Hall
T. Hallatt
M. Halpern
D. Hanna
T. Hardy
B. Harris
P. Harrison
T. Harrison
Y. Hayano
J. Hazboun
J. Hedgepeth
C. Heinke
M. Hellmich
V. Hénault-Brunet
M. Herman
G. Herriot
F. Herwig
Y. Hezaveh
J. Heyl
P. Hickson
A. Hill
G. Hinshaw
J. Hlavacek-Larrondo
R. Hložek
B. Hoff
K. Hoffman
M. Houde
M. Hudson
J. Hutchings
A. Ingram
J. Irwin
K. Jackson
P. Jasiobedzki
K. Jessen
C. Johnson
M. Johnson
T. Johnson
D. Johnstone
G. Joncas
V. Kaspi
J. Kastner
J. Kavelaars
D. Keating
D. Kendall
D. Kerley
V. Khatu
H. Kirk
D. Kirmizibayrak
L. Knee
E. Koch
R. Kothes
M. Kramer
R. Kruecken
J. Kshtriya
D. Lafrenière
M. Lamb
T. Landecker
D. Lang
P. Langill
C. Laporte
O. Lardiere
J. Larkin
D. Laurin
J. Lavigne
S. Lawler
D. Leahy
C. Lee
E. Lee
J. Lee
L. Lehner
K. Lepo
L. Levasseur
O. Lim
D. Lisman
A. Liu
S. Locke
M. Lokken
C. Lovekin
J. Luo
R. Lynch
B. Macintosh
M. Mader
L. Malo
A. Man
M. Mandy
C. Mann
C. Marois
M. Marquette
H. Marshall
P. Martin
K. Masui
B. Matthews
J. Matthews
C. Matzner
D. Mawet
S. Mazrouei
D. McCabe
A. McConnachie
S. McGee
J. McIver
M. McLaughlin
B. McNamara
J. Mena
K. Menou
S. Metchev
B. Meyers
K. Michelakis
D. Michilli
P. Miles-Páez
M. Millar-Blanchar
C. Mingarelli
J. Mirocha
A. Moffat
F. Mohammad
R. Monsalve
K. Moo Yi
D. Moon
K. Moore
J. Moores
S. Morsink
T. Moutard
A. Murphy
N. Murray
A. Muzzin
A. Naidu
M. Naud
T. Navarro
D. Naylor
H. Neilson
L. Nelson
J. Nemec
B. Netterfield
C. Netterfield
C. Ng
H. Ngo
G. Nguyen
Y. Ni
D. Nice
S. Nikzad
M. Nomandeau
C. O'Dea
S. Oh
G. Osinski
N. Ouellette
H. Padmanabhan
L. Parker
E. Pass
D. Patton
J. Pazder
E. Peeters
S. Pelletier
U. Pen
W. Percival
L. Perreault-Levasseur
L. Philpott
C. Piaulet
R. Plume
C. Pritchet
R. Pudritz
A. Pullen
M. Radica
M. Rahman
Z. Rana
S. Ransom
W. Rau
S. Ravanbakhsh
J. Rhodes
H. Richer
D. Riechers
P. Ripoche
C. Robert
S. Roberts
T. Robishaw
J. Roediger
J. Rogerson
E. Rosolowsky
L. Rousseau-Nepton
J. Rowe
N. Rowlands
J. Ruan
S. Rucinski
M. Rupen
B. Rutledge
S. Sadavoy
S. Safi-Harb
C. Sakara
R. Sanchez-Janssen
V. Sanghai
M. Sawicki
D. Schade
G. Schieven
A. Schneider
P. Scholz
A. Scott
D. Scott
C. Shapiro
R. Shaw
E. Shkolnik
D. Siegel
S. Siegel
X. Siemens
J. Sievers
K. Sigurdson
A. Sills
L. Simard
D. Simons
S. Singh
G. Sivakoff
S. Sivanandam
K. Smith
M. Smith
W. Soh
I. Song
J. Speedie
K. Spekkens
L. Spencer
N. St-Louis
I. Stairs
E. Steinbring
L. Stella
D. Stenning
D. Stevens
J. Stil
D. Stinebring
J. Stocks
K. Strong
R. Suzuki
D. Swetz
K. Szeto
M. Tahani
G. Talens
J. Taylor
S. Taylor
H. Teimoorinia
S. Tendulkar
S. Tesfamariam
R. Thacker
K. Thanjavur
S. Thibault
S. Thibeault
G. Thomas
W. Thompson
D. Thorngren
A. Tohuvavohu
S. Tulin
N. Turok
J. Ullom
D. Valencia
N. van der Marel
C. van Eck
M. van Kerkwijk
L. van Waerbeke
K. Vanderlinde
B. Veidt
K. Venn
J. Veran
N. Vieira
C. Virtue
G. Wade
J. Wadsley
J. Wall
J. Webb
T. Webb
B. Weber
L. Weiss
T. Wenger
J. West
J. White
L. Widrow
P. Wiegert
J. Willis
C. Willott
C. Wilson
R. Winslow
J. Woo
T. Woods
S. Wright
Y. Wu
D. Wulf
H. Yee
J. Young
CASCA Heritage Committee
CASCA EPO Committee

Consultation participation and written feedback submission

M. Balogh
A. Barr
S. Baum
M. Beaudry
M. Bergeron
J. Bolduc-Duval
A. Boley
D. Bond
E. Boston
D. Brooks
J. Cami
S. Chapman
S. Côté
P. Côté
N. Cowan
D. Devost
J. Di Francesco
J. Doherty
E. Dupuis
J. Dupuis
S. Ellison
G. Fahlman
M. Fich
L. Fissel
S. Gallagher
L. Gallo
B. Gerard
F. Grandmont
L. Groer
D. Haggard
P. Hall
M. Halpern
J. Holloway
M. Houde
M. Hudson
J. Hutchings
D. Johnstone
G. Joncas
JJ. Kavelaars
H. Kirk
C. Lange
D. Laurin
M. Laychak
C. Loken
C. Lovekin
U. Maile
P. Martin
A. McConnachie
N. Murray
P. Narayanan
M. Nasser-Eddine
D. Naylor
H. Neilson
C. O'Dea
L. Parker
E. Peeters
K. Phillips
R. Plume
E. Rosolowsky
G. Ross
J. Rowe
M. Rupen
S. Sadavoy
C. Samson
D. Scott
A. Sheinis
L. Simard
D. Simons
K. Spekkens
L. Spencer
M. Tahani
J. Taylor
R. Thacker
R. Thompson
C. Wilson
CATAC

Collation of All LRP2020 Recommendations

Recommendations are presented here in the order in which they appear in Chapters 5, 6, and 7. All recommendations in Chapter 5 are also contained in either Chapter 6 or Chapter 7 (Chapter 7 also contains additional recommendations that are not in Chapter 5); each recommendation is listed only once here. Some recommendations relate to relative priorities of recommended facilities: the explicit rankings for these priorities are given in Table 5.1.

Rec No.	Recommendation	Topic	Page	Comment
1	We recommend that the Canadian astronomical community (e.g., ACURA, CASCA and NRC-HAA) work together with Indigenous representatives and other relevant communities to develop and adopt a comprehensive set of guiding principles for the locations of astronomy facilities and associated infrastructure in which Canada participates. These principles should be centred on consent from the Indigenous Peoples and traditional title holders who would be affected by any astronomy project. In addition, when such consent does not exist, the principles should recognize that the use or threat of force is an unacceptable avenue for developing or accessing an astronomical site. The principles should also acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime. These principles should be developed as soon as possible, and then applied to *all* future Canadian participation in new or existing astronomical programs, projects and national and international facilities. Engagement and implementation should be consistent with the spirit of the Calls to Action of the Truth and Reconciliation Commission of Canada and of the United Nations Declaration on the Rights of Indigenous Peoples.	Ethics and Values	59	Astronomy projects not only require telescopes and observatories, but also need support facilities, headquarters, project offices, instrumentation laboratories, integration and test facilities, computing and processing centres, etc.
2	We recommend that the leadership of agencies which fund or otherwise support astronomical research (NRC, CSA, CFI, NSERC, NDRIO, CIFAR) coordinate efforts through regular meetings. Involving ACURA and/or LRPIC in such meetings could further improve coordination efforts.	Governance and Funding	59	
3	We recommend that CITA strengthen its national role by committing ~40% of its annual NSERC funding to postdoctoral fellowships based outside the University of Toronto. These positions should be fully funded by CITA, without any host contributions allowed or required, and with a limit on the number of National/Canada Fellows per institution, in analogy with the NASA Hubble Fellowship program. The University of Toronto should remain ineligible to host CITA National Fellowships or the first half of Canada Fellowships, as is presently the case.	Theoretical Astrophysics	59	
4	We recommend that CITA offer salaries and research allowances for CITA Fellows, Canada Fellows, and CITA National Fellows at identical levels and durations. We further recommend that the remuneration should be competitive with commensurate national and international prize fellowships, with the goal of attracting and retaining the world's best early-career theorists.	Theoretical Astrophysics	59	See also recommendations 69 and 82

Rec No.	Recommendation	Topic	Page	Comment
5	We recommend that CITA seek an expansion of its postdoctoral program in its next funding proposal to NSERC. Additional funding should be used to prioritize recommendations 3 and 4 above before increasing the overall number of fellowship positions supported.	Theoretical Astrophysics	59	
6	We recommend that CITA increase its focus on training for students and postdoctoral fellows and on organizing theory-focused meetings, in coordination with the Perimeter Institute and the broader theory community.	Theoretical Astrophysics	59	
7	We recommend that CITA and CASCA work together to recognize the role of theoretical astrophysics by establishing and awarding national prizes in this field.	Theoretical Astrophysics	59	
8	We recommend that Canada maintain its commitment to digital research infrastructure outlined in Budget 2018, through an initial investment of $375M plus an ongoing expenditure of $50M per year over the next decade. This major investment in Canada's New Digital Research Infrastructure Organization (NDRIO) is needed to revitalize and then sustain Canada's research capabilities across all disciplines.	Digital Research Infrastructure	60	
9	We recommend that CASCA and ACURA work to ensure that NDRIO meets the unique computational resource requirements of theoretical and observational astrophysics, which we estimate as 100 petaflop-years each of CPU and GPU calculations and 75 PB of online storage by 2025. CASCA's Computation and Data Committee should monitor developments within NDRIO and should vigorously represent the interests of astronomy researchers through NDRIO's Researcher Council and other governance and advisory structures.	Digital Research Infrastructure	60	
10	We recommend that NRC's Canadian Astronomy Data Centre (CADC) continue to receive strong support, both as a provider of astronomy-specific service layers that use NDRIO infrastructure, and as a coordinator of long-term archiving of digital data products for astronomy.	Digital Research Infrastructure	60	
11	We recommend that HAA and the university community obtain an additional ~$1M/year for Canadian astronomy, in order to appoint early-career STEM personnel who can provide direct scientific and operational support for Canada's investments in mid-scale astronomical facilities and infrastructure.	NRC-University Partnerships	60	
12	We recommend that HAA implement a national process for committing significant in-kind contributions to CFI initiatives proposed by astronomers from Canadian universities. These investments can help ensure that the Canadian astronomy community will have broad access to a coherent and effective array of capabilities.	NRC-University Partnerships	60	"Significant" should be defined in consultation with the HAA Advisory Board, in the context of HAA's resources and other obligations.

Rec No.	Recommendation	Topic	Page	Comment
13	We recommend that HAA and Canadian universities form partnerships to enhance the capabilities of university-based experimental astrophysics laboratories through additional funding, shared personnel, and coordinated infrastructure investments. These partnerships will enable high-risk, high-reward innovations, and will provide the continuity and availability of experts that are essential for successful participation in leading-edge astronomical facilities.	NRC-University Partnerships	60	
14	We recommend that Canada participate in a very large optical telescope (VLOT), and that this participation be at a level that provides compelling opportunities for Canadian leadership in science, technology and instrumentation. Canadian access to and participation in a VLOT remains the community's highest ground-based priority; NRC, CASCA and ACURA must ensure that Canada's share in a VLOT remains at the level needed to fulfil the community's ambitions and requirements for scientific discovery, and to maintain a leadership role in facility governance and overall science and technology development. Canada has been a significant partner in the Thirty Meter Telescope (TMT) project since 2003 and has a clear scientific and technical leadership role enabled by funding and support from the federal government and NRC. Noting that the situation is complex and rapidly evolving, at the time of writing Canadian VLOT access is best implemented by continued participation in TMT, either at the currently proposed Maunakea site or at the scientifically acceptable alternative of Observatorio del Roque de los Muchachos. Canadian participation in TMT or in any other VLOT should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed site from Indigenous Peoples and traditional title holders.	Ground-Based Facilities	64	A VLOT is an optical/ infrared telescope with a mirror of effective diameter ~30 metres.
15	We recommend that the Canadian community maintain its leadership and expertise in VLOT instrumentation development, which will ensure access to instruments that meet the needs of the community.	Ground-Based Facilities	64	
16	We recommend that NRC address any lack of access to a VLOT due to delays in TMT construction through arrangements that give Canadians access to other VLOT facilities.	Ground-Based Facilities	64	

Rec No.	Recommendation	Topic	Page	Comment
17	We recommend that Canada participate in the construction and operation of Phase 1 of the Square Kilometre Array, in its network of regional centres, and in the project's governance. This will allow Canada to play a world-leading role in a number of transformational projects to be carried out with SKA1. The scientific goals of SKA1 align well with the strengths of Canadian researchers, and scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the past twenty years. Canada's highest priority for radio astronomy should be to fund and participate in SKA1 Design Baseline construction, operations, the accompanying network of regional centres and a staged technology development program at an overall 6% level, commensurate with Canadian scientific ambitions. We emphasize that developing the relevant infrastructure, incorporating the capabilities of a Canadian SKA1 regional centre or equivalent, is necessary for successful Canadian participation in SKA1, and will ensure community access to the processing, storage and user support required to scientifically exploit SKA1. Canada should identify a membership model for Canadian participation in the SKA Intergovernmental Organisation that can provide leadership rights for Canadian researchers and industry, with full scientific access and maximal opportunities for technological tender and procurement. Canadian participation in SKA1 should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of SKA1 sites from Indigenous Peoples and traditional title holders.	Ground-Based Facilities	64	
18	We recommend that Canada play a leading and substantive role in a next-generation widefield spectroscopic survey facility. Meaningful Canadian participation should be at a level of at least 20%, which will also ensure a prominent Canadian role in driving and participating in the VLOT science that will be enabled by such a facility. The best option at present is to pursue the development, design and construction of the Maunakea Spectroscopic Explorer (MSE) at the current CFHT site on Maunakea; this offers a compelling and timely science case with significant history of and potential for Canadian leadership. Should it not prove possible to transition CFHT into MSE, we recommend that Canada play a substantive leadership role in developing the MSE concept at a different site. We recommend that the MSE project build on its mature science case and well-developed design, and now undertake essential future steps on the path toward construction. These include obtaining consent from Indigenous Peoples and traditional title holders for the use of any sites needed for the MSE project, and establishing the governance structure and funding model needed to effectively advance this exciting project.	Ground-Based Facilities	64	

Rec No.	Recommendation	Topic	Page	Comment
19	We recommend that Canada pursue technical contributions to and scientific leadership in the proposed Next Generation Very Large Array (ngVLA), pending a positive recommendation on this project from the US Astro2020 Decadal Survey. The capabilities provided by the ngVLA will enable transformational science across many areas of astrophysics. Canada should correspondingly seek engagement with ngVLA that would result in a ~6% share of observing time, comparable with the access sought for SKA1. Canadian participation in ngVLA should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any ngVLA sites from Indigenous Peoples and traditional title holders. We recommend that Canada focus its technical contributions to ngVLA on areas that leverage existing or ongoing Canadian work on SKA1 and other facilities. We also encourage exploration of the proposed scientific alliance between SKA1 and ngVLA, which would allow an exchange of observing time between the two facilities.	Ground-Based Facilities	65	
20	We recommend that Canada continue to fund the Atacama Large Millimeter/submillimeter Array (ALMA) at the amount needed to maintain our current level of access, that the Canadian community identify components of future ALMA development in which we can play a role, that Canadians continue to seek leadership of ALMA large programs, and that we keep Canadians fully trained and engaged in ALMA as new capabilities become available. ALMA is an unquestioned success story, and has become a world-leading scientific facility that has had significant Canadian uptake, benefit, and output. ALMA remains the key facility for answering many frontier scientific questions. In the 2030s and beyond, there will be many exciting options for ALMA upgrades and expansions, which are likely to be considerations for future mid-term reviews and long-range plans. Canadian participation in ALMA should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.	Ground-Based Facilities	65	

Rec No.	Recommendation	Topic	Page	Comment
21	We recommend that Canada remain an active participant in the Gemini Observatory over the next decade. Gemini continues to be a foundational component of Canadian observational capabilities, plays a key role in training and instrumentation development, and enables research across an incredibly wide range of science topics. Substantial recent investments and new instrumentation make it an exciting time for Canada to be a Gemini partner, and should lead to increased productivity, impact and oversubscription rates. The Gemini Observatory will be a key part of Canada's observational capabilities in the era of 30-metre telescopes. Gemini will be an important testbed for future instrumentation and will offer capabilities not offered by 30 metre-class telescopes until well into the 2030s. We encourage broad community consultation leading up to the next Gemini assessment point in 2024 on what specific share of Gemini is appropriate for Canada in the next Gemini International Agreement, and on how the negotiation of the Maunakea master lease will affect the status of Gemini North. Canadian participation in Gemini should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.	Ground-Based Facilities	65	
22	We recommend continued Canadian participation in the Canada-France-Hawaii Telescope (CFHT) at least until the ongoing Large Programs are complete. During this period, Canada should work with the other CFHT partners to maximize unique high-impact science while reducing costs, for example by reducing the instrument complement or by further prioritizing Large Programs. Once the ongoing Large Programs are complete, Canadian involvement in CFHT will depend on whether CFHT transitions into MSE. Should MSE go ahead at the CFHT site, we recommend that Canada, its CFHT partners, and other relevant stakeholders plan for a future that involves moving SPIRou to another telescope, as this new instrument has the capability to provide high-impact science for at least a decade. Should CFHT not transition into MSE, we recommend that the Canadian astronomy community decide what approach will provide optimal access to northern wide-field capabilities in the optical, ultraviolet and near-infrared, which may mean leaving the CFHT partnership in order to pursue other opportunities (participation in Subaru is one possibility). Canadian participation in CFHT should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.	Ground-Based Facilities	67	

Rec No.	Recommendation	Topic	Page	Comment
23	We recommend funding and implementation of the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD). CHORD is a unique facility that leverages existing Canadian world scientific leadership, designed from the outset as a national facility. The expansion of capabilities and community access from CHIME will enable exciting and timely science on fast radio bursts, line intensity mapping, pulsars, and many other science areas. The very large data flows anticipated from CHORD will require an expansion of Canada's digital research infrastructure capabilities in radio astronomy, and will help the community prepare for the data challenges of SKA1. Construction and operation of CHORD should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders.	Ground-Based Facilities	67	
24	We recommend participation in the Cosmic Microwave Background Stage 4 (CMB-S4) experiment, or other comparable facility. Involvement now will let us take leadership roles in defining the overall project. Canadians are world-leaders in all areas of cosmic microwave background research, including detector readout systems, systems integration, pipeline, mapmaking, theory, and interpretation. For continued leadership in this field, it is essential that Canada be involved in CMB-S4 or another comparable facility. Such participation is also highly complementary to LiteBIRD, which we recommend as a space-based priority in recommendation 29 below. Canadian participation in CMB-S4 or a comparable facility should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders.	Ground-Based Facilities	67	
25	We recommend that Canada pursue a route for national membership in the Legacy Survey of Space and Time (LSST). The science enabled by the LSST dataset is unprecedented and will provide foundational data for projects on facilities such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1. At this time, LSST and its funding agencies are still in the process of defining the parameters and requirements for a Canadian partnership in this project. Successful and meaningful Canadian participation in LSST will require development of the relevant digital infrastructure, which will also contribute significantly to the overall international success of the facility. Canadian participation in LSST should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.	Ground-Based Facilities	67	

Rec No.	Recommendation	Topic	Page	Comment
26	We recommend that the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) be approved for development toward launch. The CASTOR mission is a mature concept that has a world-leading and transformational science case, strong and long-standing community support, substantial interest and involvement from Canadian industry, and enthusiastic international partners who are looking to Canadian leadership to develop and fly a wide-field optical-ultraviolet space telescope. CASTOR will also provide a superb complement to JWST and other forthcoming optical and infrared facilities. A top priority in LRP2010 and MTR2015, CASTOR continues to be an outstanding prospect for Canada's first marquee space astronomy mission. It will be vital to engage with the federal government to fund this very large mission, and to work closely with international partners like JPL/NASA and IIA/ISRO.	Space Astronomy	68	
27	We recommend that Canada contribute ~$100M in hardware to a flagship astrophysics mission selected by NASA, and also contribute scientifically and technically to such a mission as per recommendation 34 below. However, such a hardware contribution should be regarded overall as a lower priority than investing in CASTOR and LiteBIRD at the recommended levels. A significant hardware contribution to a NASA flagship astrophysics mission would strengthen Canada's standing as a strong international partner in space astronomy. Ahead of the 2025 midterm review, Canadian astronomers should work with the CSA and industrial partners to identify potential hardware contributions to the selected NASA flagship(s) and, where appropriate, the CSA should support technology development studies. CASCA's LRP midterm review in 2025 would then be in a good position to provide guidance on an eventual contribution to a flagship mission.	Space Astronomy	68	
28	We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support missions and mission contributions up to $100M. Participation in flagship missions requires additional funding beyond this A-base amount and would necessitate separate requests to the Government of Canada. As recommended below, the Coalition for Canadian Astronomy must play a key role in advocating for increased CSA spending on astronomy.	Space Astronomy	68	
29	We recommend Canadian participation in the Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD). This participation should correspond to the complete life cycle of LiteBIRD, including hardware, mission operations, and science analysis. By focusing on the polarization of the cosmic microwave background at large angular scales, LiteBIRD will be an excellent complement to the ground-based CMB-S4 facility, and will provide an outstanding opportunity for Canadian cosmologists to make unique discoveries.	Space Astronomy	68	

Rec No.	Recommendation	Topic	Page	Comment
30	We recommend that Canada explore opportunities for substantive participation in a large, cooled, infrared international space observatory mission. Such a mission can leverage Canada's substantial scientific and technological leadership in infrared space astronomy derived from work on Herschel and SPICA, and can revolutionize our understanding of cold gas and dust throughout the Universe through unique access to far-infrared wavelengths.	Space Astronomy	69	
31	We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support the preparatory activities (through phase A) for missions and mission contributions of all sizes, and scientific activities for missions to which Canadian astronomers contribute, regardless of whether the CSA has made a formal contribution.	Space Astronomy	69	
32	We recommend that the CSA maintain financial support to the James Webb Space Telescope (JWST) mission and associated Canadian science for the entirety of the observatory's lifetime. Canada has already made a very large investment in this project, and continued support will leverage this investment for the highest possible science yield.	Space Astronomy	69	
33	We recommend development of the Photometric Observations of Extrasolar Planets (POEP) mission. The goal should be to enable a launch in the 2025 timeframe, to allow follow-up of exoplanet discoveries made with TESS and CHEOPS, and to provide significant overlap with complementary future space astronomy missions such as JWST, ARIEL, PLATO and CASTOR. POEP has the potential to provide high science impact on exoplanets and the outer solar system for a relatively small investment, and will allow Canada to maintain leadership in small-satellite astronomy.	Space Astronomy	69	
34	We recommend that the CSA provide funding that enables Canadian scientific and technical participation in preparatory activities for the NASA flagship mission(s), through design reference missions, analysis software, instrument design, science teams, working groups, etc. Any such opportunities should be disseminated widely, and appointments made by CSA should take place through an open and competitive process. These scientific and technical contributions should be pursued as soon as circumstances allow.	Space Astronomy	69	
35	We recommend that all Canadian astronomers make a personal commitment to equity and inclusion, focused on making significant structural changes to their workplaces, classrooms, professional communities and collaborations. Every astronomer in Canada needs to be aware of the evidence for systemic racism and discrimination in astronomy (and in science more generally), must listen to the experiences and concerns of the marginalized members of our community, and must take specific actions that remove barriers and increase support for those from underrepresented groups.	Equity and Inclusion	109	

Rec No.	Recommendation	Topic	Page	Comment
36	We recommend that CASCA make equity, diversity and inclusion in Canadian astronomy an explicit part of its ethics and values, as described in its Mission Statement, Values statement, and Code of Ethics (see recommendation 42 below).	Equity and Inclusion	109	
37	We recommend that CASCA publicly commit to the principles of the Dimensions Charter to foster increased research excellence, innovation and creativity through greater equity, diversity and inclusion, and that CASCA encourage its members and their institutions to do the same. CASCA should encourage its members at the chosen Dimensions pilot project institutions to participate in the pilot over the next two years, and CASCA should then assess the outcome with respect to its own mission and values as they pertain to equity and inclusion.	Equity and Inclusion	110	
38	We recommend that CASCA update its code of conduct (see recommendation 42 below) to explicitly include equity, diversity and inclusion, and to meaningfully address and prevent racism, discrimination and harassment perpetrated by CASCA members or occurring at CASCA events. This should be accompanied by a formalized complaints and investigation process, such as that offered by the American Astronomical Society.	Equity and Inclusion	110	
39	We recommend that CASCA adopt an explicit goal to have its membership continuously diversify to better reflect the demographics of Canada at all levels. CASCA should set targets to increase participation at all levels of membership from marginalized groups, including, but not limited to Indigenous people, Black people and all people of colour who are underrepresented in our community; CASCA should formulate and then implement the strategies and partnerships needed to reach these targets, with particular emphasis on retention of marginalized groups in the professional astronomy pipeline. Since Canadian undergraduate students are one of the main sources of future CASCA members, this work should include an analysis of relevant undergraduate demographic data collected by Canadian universities, and should identify ways to expand astronomy research opportunities for Canadian undergraduate students from minoritized groups.	Equity and Inclusion	110	
40	We recommend that CASCA create and maintain a means to securely collect self-reported demographic information from its members, compiled in such a way as to ensure anonymity for individuals. The CASCA Board should direct funding toward hiring professionals to create such a modern database that is easy for members to update and that its members can trust to be secure. By 2030, with a robust system in place, CASCA should have reliable demographic information (broad in scope and with high uptake) and the ability to track its progress in diversifying its community.	Equity and Inclusion	110	

Rec No.	Recommendation	Topic	Page	Comment
41	We recommend that CASCA and ACURA require their Board members, committee members and officers to complete training on equity, inclusion and anti-racism as a condition of their nomination, service, or employment. CASCA and ACURA should advocate for similar requirements for other national and international leadership positions in Canadian astronomy. CASCA should also fund workshops, student activities and focused plenary sessions of CASCA Annual Meetings, at which relevant experts can provide training on equity, inclusion and anti-racism to the entire Canadian astronomy community.	Equity and Inclusion	110	See also recommendation 47 below on the specific issue of Indigeneity training.
42	We recommend that CASCA prioritize the updating of the CASCA Mission Statement (including education and public outreach, as also recommended in MTR2015) and Code of Ethics, and that CASCA create an associated Values Statement. These documents are essential for providing a basic framework for all CASCA's programs and initiatives. These documents, along with relevant Codes of Conduct, need to be self-consistent, enforceable, and subject to regular revision.	Ethics and Values	111	
43	We recommend that CASCA regularly review its investment portfolio to ensure accordance with its Code of Ethics and Values Statement.	Ethics and Values	111	
44	We recommend that CASCA, with guidance from its Equity and Inclusion Committee, support and advance the needs of Indigenous astronomers and students.	Indigenous Engagement	112	
45	We recommend that Canadian universities and research institutions provide funding for astronomers and astronomy students to participate in the activities and meetings of organizations that promote the inclusion of Indigenous Peoples in STEM.	Indigenous Engagement	113	
46	We recommend that CASCA establish a new committee dedicated to facilitating engagement and relationships with Indigenous communities, and that can partner with existing groups working to promote STEM programs that embrace both Western and Indigenous approaches. The goals should be to listen to Indigenous communities, to discover mutual interests, and to identify opportunities to learn from and support each other. Potentially in partnership with the CASCA Education and Public Outreach committee, this committee can forge partnerships with Indigenous organizations, support Indigenous education in astronomy and STEM, and can develop astronomical learning material in Indigenous languages in collaboration with relevant teachers and programs.	Indigenous Engagement	113	

Rec No.	Recommendation	Topic	Page	Comment
47	We recommend that CASCA and ACURA require their Board members, committee members and officers to complete training on Indigenous issues as a condition of their nomination, service, or employment. CASCA and ACURA should advocate for similar requirements for other national and international leadership positions in Canadian astronomy. Relevant Canadian-made training programs are readily available and their uptake would be an important first step. CASCA should also fund workshops, student activities and plenary sessions of CASCA Annual Meetings, in which relevant experts can provide training on Indigenous issues to the entire Canadian astronomy community.	Indigenous Engagement	113	See also recommendation 41 above on the broader issue of equity, inclusion and anti-racism training.
48	We recommend that CASCA and ACURA engage external experts on issues outside of astronomy (e.g., those holding local or cultural knowledge) to provide balance and insight to decision-making. Where relevant, members of Indigenous groups should be represented.	Indigenous Engagement	113	
49	We recommend that CASCA adopt and pursue the four National Pillars proposed by CASCA's Education and Public Outreach Committee (Digital CASCA, Discover the Universe, the CASCA-Westar Lectureship, and national activities initiated by the International Astronomical Union), along with a fifth pillar centred on upcoming solar and lunar eclipses.	Education and Public Outreach	115	
50	We recommend that CASCA hire a paid EPO coordinator, whose primary responsibility would be to oversee implementation and progression of the National EPO Pillars. This person would also serve as the CASCA Press Officer and social media manager, assisting CASCA members and their institutions in disseminating new scientific results to the media and to the public.	Education and Public Outreach	115	
51	We recommend that CASCA and its EPO committee revise and expand the CASCA-Westar Lectureship. The mandate of the CASCA-Westar Lectureship to support remote and under-served communities should be made explicit, and participants in the program should have training and support available to build connections with these communities.	Education and Public Outreach	115	
52	We recommend that CASCA develop deliberate collaborations with science centres and astronomy clubs. This would include sending CASCA members to the Canadian Association of Science Centres' annual conference, and inviting science centre professionals and members of astronomy clubs to the EPO session of CASCA's annual meeting.	Education and Public Outreach	115	
53	We recommend that CASCA and ACURA advocate to funding agencies such as NSERC and CFI that a portion of funding awarded for large grants (e.g., Innovation Funds, CREATE) be usable for EPO and communication activities.	Education and Public Outreach	115	

Rec No.	Recommendation	Topic	Page	Comment
54	We recommend that CASCA make sustainability an explicit part of its ethics and values, as described in its Mission Statement, Values Statement, and Code of Ethics (see recommendation 42 above).	Sustainability	116	
55	We recommend that organizers of astronomy-related events carefully consider the frequency, timing, and locations of these activities, with the goal of minimizing air travel. Remote participation using effective online platforms should be encouraged whenever it does not alter the benefits of in-person participation. Meetings of CASCA committees should take place almost exclusively through videoconferencing, or should be combined with other in-person events (e.g., CASCA annual science meetings). We encourage individual members of CASCA to continually evaluate their need to travel by air and consider institutional funding of carbon offsets where possible.	Sustainability	116	
56	We recommend that the astronomy community should thoroughly consider the climate impacts of both construction and operations when planning infrastructure.	Sustainability	116	
57	We recommend that CASCA, through its sustainability committee, support the development and implementation of a decarbonization road map for astronomy. This road map should include plans to convey to governments and granting agencies the community consensus on climate action and ways to enable recommended actions.	Sustainability	116	
58	We recommend that the CSA establish a regular and recurring announcement of competitive opportunities of all sizes for Canadian missions and contributions to foreign missions. To facilitate this program, we further recommend that: • The CSA continue to fund concept and science maturation studies of future missions and mission contributions on a regular basis (for example, every five years to coincide with the LRP and MTR), with the understanding that not every funded study will progress to an approved program. • The CSA select missions and preparatory studies (Concept Studies, Science Maturation Studies and phase-A studies) within the proposed A-base funding through a competitive and transparently defined process of peer review. • The CSA select Canadian contributions to international missions and missions beyond the A-base funding with guidance from the LRP, MTR and JCSA.	CSA and JCSA	119	
59	We recommend that the JCSA continue in the effective role it plays in advising the CSA on space astronomy. The astronomy knowledge contributed from this committee is essential for the effective and efficient use of Canadian resources for space astronomy exploration.	CSA and JCSA	119	

Rec No.	Recommendation	Topic	Page	Comment
60	We recommend that the CSA enhance its support for Canadian participation in data analysis and leadership for JWST and the missions prioritized in recommendations 26 through 34 (or for any other CSA astrophysics programs in which Canada is the lead or a major partner). This funding should support both data analysis and theoretical investigations and be commensurate to the level of the missions engaged. Such support is required both to maximize the science return on Canada's investments and to ensure that Canadian astronomy remains internationally competitive.	CSA and JCSA	120	
61	We recommend that the CSA enhance its support for the development of Canada's space technology capacity through the establishment of a regular series of calls and increases in the budget for the STDP, ballooning and micro-satellite programs. Universities are key partners in these development programs. This funding is needed to maximize science return on Canada's investments, and to ensure that Canadian astronomy remains internationally competitive. We recommend that this funding, where possible, should be delivered through the grants and contributions program when directed to universities, as universities are well-equipped to administer grants and contributions, and less well-adapted to contracts.	CSA and JCSA	120	
62	We recommend that the CSA enhance its support for highly-qualified personnel through the establishment of a regular series of calls (e.g., every two years) and an increase in the budget for the FAST program to at least $10M total per call over all fields. The FAST program is currently heavily oversubscribed.	CSA and JCSA	120	
63	We recommended that the budget for the CSA Co-Investigator program be increased and a regular (e.g., annual) series of calls established. The Co-Investigator program is currently heavily oversubscribed. This key program allows Canadian astronomers to participate and provide leadership in a wide range of international missions with a very modest investment from the CSA, regardless of whether the CSA has made a formal hardware contribution.	CSA and JCSA	120	
64	We recommend that the CSA streamline the application process for the FAST and Co-Investigator programs. This will increase the accessibility of these programs to a wider community as well as the ultimate scientific impact. The application process could be structured to resemble that of the NSERC Discovery Program.	CSA and JCSA	120	
65	We recommend that CFI identify ways to support full utilization of scientific infrastructure. Having a pre-defined allocation for operations based on project costs may, at times, lead to inefficiencies. Flexibility in the construction to operations ratio, with the total cost reflected in the competition, will increase the impact of CFI infrastructure for astronomy.	CFI	121	

Rec No.	Recommendation	Topic	Page	Comment
66	We recommend that CFI and institutions receiving CFI funds identify ways to fund the gaps in technology development between the small-scale work funded by NSERC Discovery Grants and the large-scale requests made in CFI Innovation proposals.	CFI	121	
67	We recommend that, before the next CFI Innovation Fund proposal deadline, a special, short-term CASCA committee be established to work with CFI to clarify agency-supported best practices for astronomy facilities.. The committee's report will inform institutions who guide applicants for best practices but are oftentimes not aware of facility special needs, and will also level the playing field for applicants from different institutions.	CFI	121	
68	We recommend that CFI's regulations be adjusted to allow a small fraction of funds awarded for large projects to be spent on education and public outreach activities. This will help scientists inform the Canadian public about the research enabled by public support. CFI should also ensure that all its grantees are aware of CFI's ability to promote their work through the CFI external relations and communications team.	CFI	121	
69	We recommend that NSERC find ways to fund postdoctoral positions in astrophysics that have internationally competitive salaries, a duration of at least three years as per international standards and no citizenship or nationality restrictions, with the goal of attracting and retaining the world's best early-career astronomers.	NSERC	122	See also recommendations 4 and 82
70	We recommend that NSERC explore additional methods beyond Discovery Development Grants to support research at smaller Canadian universities.	NSERC	122	
71	We recommend that CASCA explore the charitable status of CASCATrust as a means to access charitable contributions specifically targeting EPO initiatives. CASCA should seek to broaden the skill set regarding outreach and charitable activities on the CASCA Board, with the goal of funding a spectrum of EPO activities plus the EPO coordinator mentioned in recommendation 50 above.	CASCA, ACURA, and LRPIC	123	
72	We recommend that ACURA and LRPIC expand their mutual consultation and coordinate their efforts more closely, in order to advance the suite of priorities identified in this report more effectively. In particular, we recommend that ACURA receive recommendations from LRPIC on possible uses of their funds.	CASCA, ACURA, and LRPIC	123	
73	We recommend that the mandate of LRPIC be revised to implement not only facility recommendations, but also the broader range of non-facility recommendations listed in this report. LRPIC should also estimate the cost of implementing the LRP2020 recommendations addressed specifically to CASCA (e.g., on equity and inclusion and on education and public outreach), and should provide these cost estimates to the CASCA Board.	CASCA, ACURA, and LRPIC	123	

Rec No.	Recommendation	Topic	Page	Comment
74	We recommend that ACURA take the lead in advocating for additional federal funding for Canadian astronomy, potentially through an increased funding envelope for HAA. We particularly prioritize the funding needed for early-career STEM personnel and university-based experimental astrophysics laboratories, as recommended in recommendations 11 and 13 above.	CASCA, ACURA, and LRPIC	123	
75	We recommend that ACURA fund the press officer position recommended in recommendation 50 above. By promoting the initiatives and the success stories of Canadian astronomers to journalists and the public, the work of the press officer will contribute to creating a global sense of pride and support for Canadian astronomy, thereby enhancing ACURA's effectiveness in advocating for the priorities of this LRP.	CASCA, ACURA, and LRPIC	123	
76	We recommend that the Coalition for Canadian Astronomy develop strategies for astronomy advocacy to the Canadian government that cover all the highest priority facilities recommended by the LRP, and that the CCA build and maintain relationships with a diverse set of Canadian industry partners who are willing to actively engage to help deliver these priorities. We further recommend that the Coalition adopt an annual schedule of events, deliverables and activities for its constituent stakeholders, while still retaining the flexibility to respond rapidly to developments as needed. Time periods when engagement with government is not feasible should be used for community consultation, and in particular should involve regular dialogue with LRPIC.	Coalition for Canadian Astronomy	124	
77	We recommend that the Coalition for Canadian Astronomy and its individual members continue to advocate to Innovation, Science and Economic Development Canada, both directly and via relevant advisory bodies, for increased CSA science spending. As Chapter 5 demonstrates, the Canadian astronomy community has ambitious goals for space-based facilities. Although there are clear benefits to Canada in realizing these goals, the current science budget of the CSA is wholly inadequate for this purpose. As the "Vision for Canadian Space Exploration" document and LRP2020 white paper on space astronomy discuss in more detail, spending on the order of $1B per decade would enable a robust space science program in Canada.	Coalition for Canadian Astronomy	124	
78	We recommend that members of Canadian physics and astronomy departments develop opportunities for students and postdoctoral researchers to acquire a broad set of skills relevant to careers in both astronomy and industry, including but not limited to science communication, scientific writing, mentoring, statistics, high-performance computing and machine learning. In particular, CASCA should identify resources that allow students and postdoctoral researchers to participate in relevant workshops, internships, summer schools and boot camps organized by external institutions or organizations.	Professional Training and Skills Development	125	

Rec No.	Recommendation	Topic	Page	Comment
79	We recommend that members of Canadian physics and astronomy departments and their associated institutions develop a coordinated, expanded and enhanced approach to student training. In particular, remote access to courses across institutions would greatly broaden the training opportunities for students across Canada, by optimizing the knowledge transfer offered by a limited number of experts, and by providing equitable access to students at smaller universities who otherwise might not be able to take specialized classes.	Professional Training and Skills Development	125	
80	We recommend that Canadian astronomers supplement their training programs for students and postdoctoral researchers through industrial partnerships, as can be facilitated through programs such as NSERC CREATE and Alliance, and Mitacs Elevate and Accelerate.	Professional Training and Skills Development	125	
81	We recommend that CASCA establish a committee to represent and advocate for astronomy postdoctoral researchers in Canada. This committee can help develop the guidelines and standards proposed in recommendations 83 through 89 below.	Career Development and Progression	128	
82	We recommend that postdoctoral researchers in Canadian astronomy be paid at internationally competitive levels, with the goal of attracting and retaining the world's best early-career astronomers.	Career Development and Progression	128	See also recommendations 4 and 69
83	We recommend that CASCA develop and maintain a set of best-practice guidelines for postdoctoral recruitment and flexible employment.	Career Development and Progression	128	
84	We recommend that all astronomy postdoctoral positions in Canada be advertised with options for reduced/flexible hours or part-time employment. Applicants should not be required to indicate their interest in this option until an offer is made.	Career Development and Progression	128	
85	We recommend that CASCA develop recommended minimum standards for reimbursable relocation costs (including fees for visa applications, security clearances, health checks, and quarantine upon arrival) associated with all postdoctoral hires in Canadian astronomy. CASCA should also advocate to the relevant funding agencies that such needs all be considered eligible expenditures.	Career Development and Progression	129	
86	We recommend that CASCA introduce content requirements that advertisements for postdoctoral positions must meet in order to be disseminated by CASCA. These requirements should include the starting salary, term of contract, and employment benefits.	Career Development and Progression	129	
87	We recommend that eligibility criteria be introduced for all astronomy postdoctoral positions in Canada, placing an explicit maximum limit (e.g., 5 years) on the time elapsed since awarding of an applicant's PhD. Career interruptions and other extenuating circumstances must be accommodated when implementing this limit.	Career Development and Progression	129	

Rec No.	Recommendation	Topic	Page	Comment
88	We recommend that the CASCA endorse a national mentoring strategy for early-career astronomers, in which relationships are built across the country by pairing mentors and mentees aligned in their personal or professional experiences.	Career Development and Progression	129	
89	We recommend that CASCA's membership database incorporate the subsequent trajectories, current positions and contact details of former astronomy graduate students and postdoctoral researchers. A complete census is impractical and unnecessary, but a clear overall picture of career paths will be highly valuable for current students and postdoctoral researchers wanting to assess career options and identify networking opportunities.	Career Development and Progression	129	

LRP Terms of Reference

Canadian Astronomy Long Range Plan 2020: Terms of Reference

Context

Astronomy and astrophysics play a significant role in our society, informing us about the nature of the Universe and our place within it. The development and funding of astronomical research in the 21st century is both a collaborative and competitive process. By identifying scientific, and hence funding, priorities in the 2010 Long Range Plan (hereafter LRP2010), the Canadian astronomical community successfully facilitated the creation of the current generation of world class astronomical research and facilities. However, in the ten years since the previous plan, unanticipated avenues of research have opened up and a new generation of facilities are on the drawing board. These new developments need to be assessed and incorporated into an updated long range plan, LRP2020, which looks forward to the 2030 time frame.

The development of LRP2020 will be a collaborative process initiated by the Canadian Astronomical Society / Société canadienne d'astronomie (CASCA) with the support of all Canadian national agencies and organisations that fund or administer astronomical research. As with LRP2010, the initial review of the field and subsequent formulation of LRP2020 will be undertaken by a primary Author Panel (hereafter "the panel"), led by two co-Chairs. Primary input is expected to come from the astronomical community through a combination of white-paper submissions, online discussion, and open webinars, town halls and other meetings.

The scope, structure, panel membership, and community input processes for LRP2020 are described within this document.

Statement of Task

The panel will review the field of astronomy and astrophysics, along with the associated education, training, and outreach. Both current and future scientific goals and the various needs of the different Canadian communities in astronomy and astrophysics will be considered. From this review, the author panel will then produce a list of recommended priorities for the next decade, to be outlined within LRP2020. These priorities will only include those considered to be essential to the success of the Canadian astronomical community. The resulting plan will serve as a single unified vision for the highest priority projects in astronomy in Canada over the coming decade.

Scope

Formulation of LRP2020 is in outline a two-step process, namely a review followed by a prioritisation exercise. It is anticipated that LRP2020 will address the following issues:

1. Assessment of the state of astronomy and astrophysics in Canada in the context of available astronomical facilities and the direct support of ongoing research programs. The review will consider all aspects of astronomy and astrophysics, with the primary task of the review being the consideration of the infrastructure that enables new discoveries. This review process will necessarily be in the context of LRP2010 and will address both the successes and failures of previous planning processes.

2. Assessment of additional infrastructure and processes critical to the success of the Canadian astronomical community. While the primary evaluation task of LRP2020 is anticipated to encompass astronomical facilities, additional infrastructure must also be considered. This includes, but is not limited to, facilities relevant to laboratory astrophysics, instrument design and development, processing of, storage of and access to astronomical data, computer infrastructure used in the analysis and modelling of astronomical phenomena, and, importantly, the education and training of highly-qualified personnel. The success of our field is also dependent on ensuring equitable access and representation, requiring consideration of equity, diversity and inclusion (EDI). Considerations of these various aspects of the subject will then inform decisions on whether the appropriate infrastructure exists or needs to be developed to support future priorities.

3. Identification of potential new research directions or areas of opportunity, and articulation of the types of facilities and support needed to pursue them. This assessment will be science driven (first) and program driven (second) rather than facility oriented. This review is anticipated to primarily fill any gaps that have opened in the coverage provided by LRP2010. The possibilities for new facilities will be assessed separately.

4. Assessment of proposed new National and International facilities or programs, including space missions, and their relevance to the Canadian astronomical community. Several new facilities are on the drawing-board that were unanticipated in either LRP2010 or in the 2015 Mid-Term Review (MTR). Updating the Long Range Plan requires that we review these facilities/missions and assess their potential impact and possible benefits to the Canadian astronomical community. Understanding the possibilities for Canadian participation in major new international projects is anticipated to be a key component of this assessment. Given that Canadian researchers are also increasingly collaborating with international partners and many future facilities are likely to be built by international consortia, whether any distinction is drawn between National and International opportunities is at the discretion of the panel.

5. Formulation of a prioritised list of facilities and programs that are essential to the success of the Canadian astronomical community. Building upon the previous assessments, the list of priorities will only include those considered essential to the success of the community. This will inevitably entail comparative and qualitative assessments, since during the review process different sub-disciplines or facilities will be compared with one another. The panel may also choose to make recommendations for reorganisation of research programs if current structures are deemed inappropriate for future endeavours. The decision on priorities will lie solely in the hands of the panel and is ultimately the most important aspect of LRP2020, setting the foundation for the highest priority projects in Canada over the coming decade.

6. Budgetary recommendations for said facilities and programs and, where possible, suggestions of solutions to current funding challenges. It is recognised that estimating construction and operating costs for future facilities is challenging and that LRP2020 does not have the resources to perform detailed cost estimates or technical risk assessments. Where available from other sources, these estimates should be incorporated into the LRP2020 process; where unavailable, the author panel will make best-effort estimates.

The review will also take into account that funding within the Canadian community comes from multiple agencies, and ranges in size from small individual grants to large community-driven projects. The suggested funding strategy will incorporate some measure of the relative risk associated with a given facility or program. In cases where funding is considered to be difficult, for whatever reason including such issues as inter-agency cooperation, the panel will make suggestions for possible resolutions.

The final outcome of the review process will be the production of an updated Long Range Plan for astronomy and astrophysics in Canada for the next decade. LRP2020 will be formulated in priority order within different categories to be decided upon by the author panel.

Approach

Projects that were approved by LRP2010 and its MTR that are partly funded or underway need not be reassessed in detail. However, the impact of these facilities or programs and their relevance to astronomy and astrophysics through to 2030 must be incorporated within LRP2020. Throughout the process of determining research priorities, the panel will necessarily have to make judgements on the feasibility, technical readiness and risks involved in supporting a particular facility or program. The panel is expected to maintain independence in this process (see Conflicts of Interest), and will consult with independent authorities when necessary. It is critical to the overall success of LRP2020 that the assessment of science capability and budgetary demands is seen as a fair and rigorous process. The increasing overlap between fundamental physics and various areas of astronomy, in particular cosmology, makes it difficult to consider these areas as distinct subjects. In situations where notable overlaps with other subject areas arise, the review will pay close attention to any goals that have been set in similar fields while still maintaining independence of process.

Selection of Co-Chairs of the Author Panel

The selection of the Co-Chairs is a critical issue since the LRP2020 process must be viewed to be open and without bias. Co-Chairs that are viewed favourably by the entire community will thus bring goodwill toward the planning process. As a consequence of the sensitive nature of the choice of the Co-Chairs, the selection process will involve the Board of Directors of CASCA and the agencies participating in LRP2020. The Co-Chairs will jointly determine their individual responsibilities and those of the author panel.

Selection of Main Author Panel

Once the Co-Chairs of the main author panel have been appointed, the selection of the remaining panel members will begin. Up to six additional panel members will be appointed, one of whom is affiliated with a non-Canadian institution. Since the panel will be required at certain points to make comparative assessments of the relative merits of different subject fields and programs, it is necessary that the panel have significant breadth in expertise. The panel members will be selected by the CASCA President and Panel Co-Chairs, in consultation with agency designates and the CASCA Board.

Structure of Review

LRP2020 and its MTR relied upon CASCA standing committees to provide reports to the author panel. The author panel will decide on any (sub-)committee structure to be used in LRP2020.

Deliverables

The author panel will deliver the final version of LRP2020 (in English) and associated recommendations to the President of CASCA. The LRP will then be simultaneously released, in both official languages, to all relevant parties including NSERC, NRC, CFI, CSA and relevant Ministries of the Government of Canada.

Schedule

The review process will begin upon appointment of the Co-Chairs of the author panel. Community input to the panel will take place in the first half of 2019, including a dedicated Slack workspace, and a town hall discussion at the CASCA 2019 AGM. Additional input will follow the AGM, including possible submission of white papers in Fall 2019, and then panel deliberations tin late 2019 and early 2020. Town halls to present draft priorities and receive final feedback will take place before CASCA 2020. The final report will be completed in time for the public launch of LRP2020 in late 2020.

Conflicts of Interest

The members of the author panel and any LRP2020 committees and sub-committees will ensure that all relevant work conducted under the auspices of LRP2020 is pursued in a manner free from conflicts of interest. For the purposes of this review, a conflict of interest is defined to be a situation where any member or their family is able to benefit scientifically or financially from involvement in the review process, or if a prioritised process is perceived to benefit the individual's place of work or research program. If a conflict of interest arises, it must be declared so that the Co-Chairs may take appropriate action. It may be necessary to exclude a panel, committee or sub-committee member from participation in debate about a particular project priority. Members are also requested to provide early notification of the possibility of conflicts occurring. As members of the professional community, author panel members are recognised as having specific expertise, interests and facility biases. They are expected to maintain their independence during the LRP2020 process, putting the best interests of the community ahead of their personal interests or those of their own sub-communities.

Confidentiality

The review is expected to be an accountable and open process. Submissions to the project will be made public; however proprietary information may be indicated as such and kept confidential. However, prior to mutually agreed upon release dates, all author panel members are to agree that they will not disclose or give to any person any information or documents relating to LRP2020.

Decision Criteria

Assessment and prioritisation of facilities and programs in LRP2020 will be based on a predefined set of criteria:

1. How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?
2. What are the main scientific risks and how will they be mitigated?
3. Is there the expectation of and capacity for Canadian scientific, technical or strategic leadership?
4. Is there support from, involvement from, and coordination within the relevant Canadian community and more broadly?
5. Will this program position Canadian astronomy for future opportunities and returns in 2020–2030 or beyond 2030?
6. In what ways is the cost-benefit ratio, including existing investments and future operating costs, favourable?
7. What are the main programmatic risks and how will they be mitigated?
8. Does the proposed initiative offer specific tangible benefits to Canadians, including but not limited to interdisciplinary research, industry opportunities, HQP training, EDI, outreach or education?

In addition, the following overall criterion will be applied to the final ensemble of prioritisations and recommendations:

9. The sum of the recommendations will be for a set of facilities and programs that reflects Canada's strengths and breadth, with a range of project sizes, time scales, science areas and degrees of Canadian participation, offering strong prospects for Canadian HQP training, and providing specific tangible benefits to Canadians. Where appropriate and feasible, the recommendations will be aligned with the priorities of government and funding agencies and with the recommendations of previous Long Range Plans.

Panel and Process

Panel Membership

Pauline Barmby (Western University)—co-chair
Matt Dobbs (McGill University)
Bryan Gaensler (University of Toronto)—co-chair
Jeremy Heyl (University of British Columbia)
Natasha Ivanova (University of Alberta)
David Lafrenière (Université de Montréal)
Brenda Matthews (National Research Council of Canada)—ex-officio
Alice Shapley (University of California Los Angeles)—international member

Timeline

Table 9.2: Timeline of LRP2020 activities

Date	Activity
Mar 1, 2019	Call for white papers
Mar 15, 2019	Call for CASCA committee reports
Apr 15, 2019	Due date for expressions of interest for white papers.
May 31, 2019	Due date for initial CASCA committee reports
	Due date for gap-filling white paper expressions of interest.
Jun 2019	LRP2020 information session, CASCA annual meeting, Montréal
Jun 2019	Announce dates and locations for community town halls
Sep 30, 2019	Due date for white papers
Sep 30, 2019	Due date for final CASCA committee reports
Oct-Nov 2019	Community town halls: schedules archived here, slides from individual sessions linked below. Oct 31: CSA headquarters, Saint-Hubert QC Nov 1: U. de Montréal, Montréal QC Nov 12: U. Toronto, Toronto ON Nov 26: UBC, Vancouver BC Nov 27: NRC Herzberg, Victoria BC Nov 29: U. Alberta, Edmonton AB
May 2020	LRP exposure draft released
May 2020	LRP2020 discussion, CASCA annual meeting, online
Sep 2020	Final facilities recommendations released
Dec 2020	Full text of report released, English version
Dec 2020/Feb 2021	Final report in English, designed and typeset in electronic form only
Mar 2021	Full release of English and French reports, hardcopy and electronic

Meeting Dates

In addition to the public meetings listed above in "timeline," the LRP2020 panel met weekly or bi-weekly by video conference more than 60 times from April 2019 through November 2020. The panel met in-person for a writing retreat in February 2020 and held a number of videoconference or telephone meetings for consultations with members of specific groups, committees, or agencies.

Panel Conflicts of Interest

The highly-collaborative nature of astronomy projects and the small size of the Canadian astronomical community made it inevitable that some LRP2020 panel members would be involved in projects under consideration by the panel. The process for dealing with the resulting conflicts of interest varied according to the severity of the conflict, where a level 1 was the least severe (for example, being a member of a committee about which the panel makes recommendations) and level 4 was the most severe (for example, being the principal investigator of a mission or project). The description of conflict levels and actions is below.

0: No conflict—No action needed

1: Disclose—Conflict to be entered in register as soon as possible, but no other action taken.

2: Declare—Conflict to be entered in register as soon as possible, and to be stated explicitly (verbally or in writing as appropriate) whenever discussion begins on the relevant topic. Declaration to be minuted by co-chairs.

3: Recuse—Conflict to be entered in register as soon as possible, and to be stated explicitly (verbally or in writing as appropriate) whenever discussion begins on the relevant topic. Person must refrain from speaking during discussion, except to answer direct questions. Recusal to be minuted by co-chairs.

4: Withdraw—Conflict to be entered in register as soon as possible, and to be stated explicitly (verbally or in writing as appropriate) whenever discussion begins on the relevant topic. Person must not be present during discussion. Questions can be asked, but only in writing to give parity with people outside the panel, and because it leaves a record. Withdrawal to be minuted by co-chairs.

Table 9.3: Conflict of interest register for LRP2020 panel members.

Panel Member	Conflict	Rating
P. Barmby	TMT ISDT	2
P. Barmby	member NCOA Mgmt Oversight Cmte (to June 2019)	1
P. Barmby	LSST CFI Co-I (CLASP)	2
P. Barmby	MSE CFI collab	2
P. Barmby	PI CANFAR ComputeCanada allocation	2
M. Dobbs	PI CHORD	4
M. Dobbs	Cdn PI for LiteBIRD	4
M. Dobbs	CHIME & CHIME FRB	2
M. Dobbs	HIRAX	2
M. Dobbs	Ground-based CMB	3
B. Gaensler	PI CIRADA	2
B. Gaensler	Co-I, NTCO	1
B. Gaensler	SKA: Past Board member, Past AACS Chair, current SWG member	3
B. Gaensler	MWA Board member	2
B. Gaensler	VLASS leadership	2
B. Gaensler	Co-I, CHIME-FRB	2
B. Gaensler	Co-I, CHORD	3
B. Gaensler	Co-I, CLASP	2
B. Gaensler	Canadian signatory and former PI on LSST	3
J. Heyl	PI Colibrì	4
J. Heyl	Co-I IXPE	3
J. Heyl	TMT ISDT	2
J. Heyl	eXTP science team	2
J. Heyl	JCSA	1
N. Ivanova	Chair, Astronomy and Subatomic Physics Committee (RAC, Compute Canada)	1
D. Lafrenière	Member CATAC	3
D. Lafrenière	CFHT SAC	2 (SAC) 3 (Spirou)
D. Lafrenière	NIRISS@JWST	1
B. Matthews	ngVLA (member, SAC; chair of a working group)	3
B. Matthews	Co-I, NTCO	1
B. Matthews	NRC	3
A. Shapley	None	N/A

Solicitations for community input

Call for white papers

Dear colleagues,

We are pleased to announce the call for white papers for the Canadian Astronomy Long Range Plan for 2020–2030 (LRP2020). Due dates are as follows:

- Expressions of interest: **UT 2300 on Apr 15th, 2019**
- White papers: **UT 2300 on Sep 30th, 2019** (instructions provided to those who submit EoIs)

LRP2020 will review the Canadian landscape for astronomy and astrophysics, and will produce a list of recommended priorities for the next decade. The resulting plan will serve as a single unified vision for the highest priority projects in astronomy in Canada over the period 2020 to 2030. See https://casca.ca/lrp2020 for details and terms of reference.

We now solicit white papers to inform the LRP2020 report. A white paper should be a self-contained description of a future opportunity for Canadian astronomy. *A white paper will be most effective and useful if it concisely summarises an option that the LRP2020 panel should be considering for prioritisation*.

White papers should adhere to the following guidelines:

Expressions of Interest: An expression of interest (EoI) must be submitted in advance of a full white paper. An EoI submission requires a title, a contact person, a proposed list of co-authors (optional) and a 2000-character summary, and is submitted entirely via a web form (see below).

Scope of EoI's and White Papers:
Topics may include (but are not limited to):

- New facilities, experiments and missions
- Proposed upgrades to current facilities, experiments and missions
- Science programs, science topics and science themes
- Instrument design and development
- Laboratory astrophysics
- High-performance computing
- Data analysis, data management and data storage
- Outreach, education and teaching
- State of the profession
- Training, careers, demographics and professional development
- Equity, diversity and inclusion

Authorship: Each EoI and white paper must have a designated contact person. Anonymous submissions will not be considered and all submitted EoIs and white papers will be made public via the LRP2020 web site. Confidential supplementary material (e.g., budgets, proprietary technical information) can be submitted separately to the LRP2020 panel; the relevance of this material should be described in the public submission. There are no restrictions on the affiliations of co-authors, and no limit on the number of co-authors. Note that the number of co-authors will not necessarily be taken as an indication of the level of community interest.

Format and Length: Submissions may be made in English or in French. White papers must be submitted as PDF files, **capped at a length of ten 8.5"x 11" pages** (including figures, tables, references and appendices), with a minimum of 11-point font and 2-cm margins. Submissions must be in PDF format, and should not exceed a file size of 30 MB. Submissions not meeting these requirements will not be considered.

White papers are not required to contain a specific set of sections or headings. Depending on the content, the following topics may be appropriate to include:

- Connection or relevance to Canada
- Timeline
- Cost
- Description of risk
- Governance / membership structure
- Justification for private submission of supplementary information

Submission and Due Dates:

- EoIs: UT 2300 on Apr 15th, 2019
- White papers: UT 2300 on Sep 30th, 2019 (instructions provided to those who submit EoIs)

Publication: All submitted EoIs and white papers will be posted as public documents on the LRP2020 web page. Teams wishing to submit supplementary confidential material will be able to indicate as such through the white paper submission process.

Discussion and Questions: We encourage open discussion on the coordination of EoIs and white papers using the LRP Slack workspace (see https://casca.ca/lrp2020 for links). Participants may use the existing topical channels, or to make new channels as appropriate. Questions about any aspect of the LRP2020 process can be posted on the #general channel on Slack, or sent by email to chairs@lrp2020.groups.io.

Call for Committee Reports

Dear colleagues,

We're writing to you in our capacity as co-chairs for CASCA's Long Range Plan for 2020 (see http://casca.ca/lrp2020 for a timeline and overview), to request a report from <COMMITTEE NAME>

LRP2020 is a two-step process: (1) a review, followed by (2) a prioritisation exercise. The formal charge for the review component is to produce "an assessment of the state of astronomy and astrophysics in Canada in the context of available astronomical facilities and the direct support of ongoing research programs." This review will rely heavily on input provided by the national committees that serve CASCA and the broader astronomical community, and we thus seek a submission from you. Below we summarise what we request:

Scope: Within the purview of your committee, what has happened since LRP2010 (and particularly since MTR2015), and where are we now? What do you think the LRP2020 panel needs to know to undertake prioritisations and to make recommendations? Note that this report should cover the past and present rather than making recommendations for the future. On the other hand, in some cases it may be useful to explain upcoming decision points and what's on the table as possible future options. If appropriate and relevant, we encourage you to draw upon the semi-annual reports that you have previously submitted to the CASCA Board. If your committee has members who serve as representatives from other groups or external committees, please make sure you consult these external stakeholders in developing your report.

Suggested Topics for Your Committee to Cover:
<See lists below>

Format: PDF file, maximum of 30 MB. No length restrictions.

Due Date: May 31st 2019 for initial report, can be resubmitted and updated for second deadline on Sep 30th, 2019. We might request additional info after May 31st.

Submission Instructions: Please upload both your initial and final reports. To revise a previously submitted report, please resubmit.

LRP2020—Call for Expressions of Interest for Gap-Filling White Papers, Released 6 May 2019

Dear colleagues,

We understand that some members of the community were expecting a substantial number of LRP2020 white papers to be commissioned to fill any gaps in coverage represented by the submitted expressions of interest. We'd like to clarify that we have no plans to solicit additional WPs, beyond one to broadly cover theoretical astrophysics requested from the CITA Council.

In case there were misunderstandings, we would like to provide the community with a final chance to propose additional white papers. The LRP panel will have the final decision on whether these will be accepted. If you would like to propose such a gap-filling white paper, please do so by emailing panel@lrp2020.groups.io with the following information, by **May 31 2019**.

- Title
- Topic area
- Summary/abstract
- Contact person and affiliation
- Email address of contact
- Other proposed authors and affiliations

Thank you for your participation in LRP2020!

List of White Papers Received

Table 9.4: List of LRP2020 white papers received.

ID	Title	Lead Author
W001	Space astronomy	J. Hutchings
W002	The Role of NewSpace in Furthering Canadian Astronomy	A. Boley
W003	The Opportunity of Young Nearby Associations with the Advent of the Gaia Mission	J. Gagné
W004	Machine Learning Advantages in Canadian Astrophysics	K. Venn
W005	Signposts of planet formation in protoplanetary disks	N. van der Marel
W006	Science, Technical and Strategic benefits of Canadian partnership with Subaru	M. Balogh
W007	Indigenizing the next decade of Astronomy	H. Neilson
W008	Canadian Astronomy on Maunakea: On Respecting Indigenous Rights	H. Neilson
W009	Low-redshift 21cm Cosmology in Canada	A. Liu
W010	Astrostatistics in Canada	G. Eadie
W011	Back to the Future: Supporting New Science with our Legacy Data	E. Griffin
W012	High-redshift 21cm Cosmology in Canada	A. Liu
W013	Small and Moderate Aperture Telescopes for Research and Education	A. Boley
W014	Canada's astronomy performance based on bibliometrics	D. Crabtree
W015	Canadian Participation in the LSST	W. Fraser
W016	Pulsar Timing Arrays: Gravitational Waves from Supermassive Black Holes and More	I. Stairs
W017	Star Formation in the Galactic Ecosystem	E. Rosolowsky
W018	CASTOR: A Flagship Canadian Space Telescope	P. Côté
W019	Development Plans for the Atacama Large Millimeter/submillimeter Array (ALMA)	C. Wilson
W020	The Euclid Mission	W. Percival
W021	Astronomy in a Low-Carbon Future	C. Matzner
W022	GEMINI in the coming decade	S. Côté
W023	Fundamental Physics with Pulsars	E. Fonseca
W024	Star Clusters Near and Far	V. Hénault-Brunet
W025	The next decade of optical wide field astronomy in Canada	A. McConnachie
W026	Probing Diverse Phenomena through Data-Intensive Astronomy	M. Rahman
W027	Astronomy and UNESCO's Sustainable Development Goals	J. Bolduc-Duval
W028	The Canadian Hydrogen Observatory and Radio-transient Detector	K. Vanderlinde
W029	The Life Cycle of Dust	S. Sadavoy
W030	The Maunakea Spectroscopic Explorer	Pat Hall
W031	The Colibrì Mission: Canada's Flag-ship X-ray Telescope	K. Hoffman

ID	Title	Lead Author
W032	The Next Generation Very Large Array (ngVLA)	J. Di Francesco
W033	LRP2020: CASCA's EPO Committee White Paper: Proposed National EPO Projects for CASCA	P. Langill
W034	Revealing the Origin and Cosmic Evolution of Supermassive Black Holes	T. E. Woods
W035	Mid- Through Far-Infrared Astronomy: The Path to Tomorrow	D. Johnstone
W036	Unveiling the secrets of black holes and neutron stars with high-throughput, high-energy resolution X-ray spectroscopy	I. Caiazzo
W037	DRAO Synthesis Telescope	T. Landecker
W038	Astrophysics and Cosmology with Line Intensity Mapping	P. Breysse
W039	The Canadian Roots of the TMT First Light Instruments NFIRAOS and IRIS	D. Andersen
W040	Theoretical Astrophysics in Canada	J. Taylor
W041	The cosmic origin and evolution of the elements	R. Fernandez
W042	A Vision for Canadian Leadership in Multi-Messenger Astrophysics in the Next Decade	J. Ruan
W043	Balloon astrophysics in Canada over the next decade	L. Fissel
W044	Canadian investigations of the interstellar medium	A. Hill
W045	Astronomy Advocacy and Engagement	N. Ouellette
W046	Canada and the Square Kilometer Array from 2020-2030	K. Spekkens
W047	Astronomy Research at Canadian Comprehensive Research Universities	J. Rowe
W048	Science with ground based, single dish Submillimeter Wave Telescopes	S. Chapman
W049	SPICA: the next observatory class infrared space astronomy mission	D. Naylor
W050	CMB science in Canada	R. Hložek
W051	Science with the Large Synoptic Survey Telescope	R. Hložek
W052	Planetary Astronomy: Understanding the Origin of the Solar System	S. Lawler
W053	Cosmology in front of the background: studying the growth of structure at CMB wavelengths	D. Scott
W054	Continuing Canadian Leadership in Small-satellite Astronomy	S. Metchev
W055	Cosmic Magnetism	J. West
W056	Molecular Astrophysics and Astrochemistry	J. Cami
W057	Entering a new Era of Astrophysics with the James Webb Space Telescope	R. Doyon
W058	LRP2020 White Paper on Radio Transients	V. Kaspi
W059	Exoplanet Imaging: a technological and scientific roadmap for finding Life signatures on other Worlds	C. Marois
W060	Characterizing Galaxies in the Early Universe	A. Man
W061	Equity, Diversity and Inclusion in the Canadian Astronomical Society in the next decade	K. Spekkens
W062	Digital Research Infrastructure in Astronomy	JJ Kavelaars

ID	Title	Lead Author
W063	The Formation of Stars—From Filaments to Cores to Protostars and Protoplanetary Systems	J. Di Francesco
W064	Opportunities and Outcomes for Postdocs in Canada	H. Ngo
W065	Exoplanet instrumentation in the 2020s: Canada's pathway towards searching for life on potentially Earth-like exoplanets	B. Benneke
W066	Debris disks as probes of exoplanetary systems	B. Matthews
W067	Industrial Initiatives in Canadian Astronomy	K. Venn

List of Reports received

ACURA Advisory Council on the SKA (AACS)
CASCA Awards Committee
CASCA Computation and Data Committee (CDC)
CASCA Education & Public Outreach Committee (EPOC)
CASCA Equity & Inclusivity Committee (EIC)
CASCA Ground-based Astronomy Committee (GAC)
CASCA Heritage Committee
CASCA Long-Range Plan Implementation Committee (LRPIC)
CASCA-ACURA TMT Advisory Committee (CATAC)
CASCA/CSA Joint Committee on Space Astronomy (JCSA)
Canadian Astronomy Funding, D. Crabtree
Canadian Astronomy Faculty Demographics, D. Crabtree
Canadian Astronomy Career Outcomes, D. Crabtree
Canadian Time Allocation Committee, D. Crabtree
Herzberg Astronomy and Astrophysics Science Council

Abbreviations and Acronyms

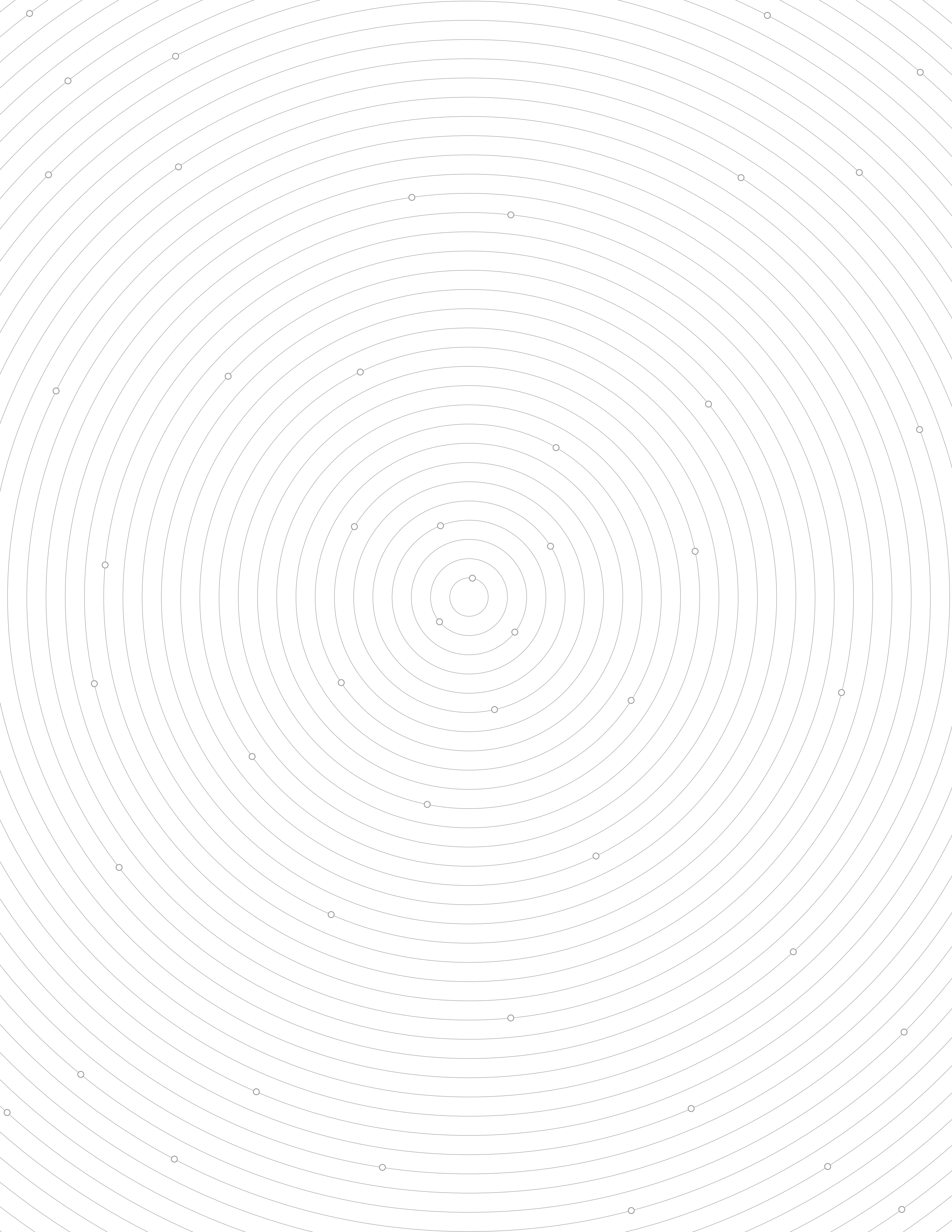
Table 9.5: Abbreviations and acronyms used in this report.

AACS	ACURA-CASCA Advisory Council on the SKA
AAS	American Astronomical Society
ACT	Atacama Cosmology Telescope
ACURA	Association of Canadian Universities for Research in Astronomy
ALMA	Atacama Large Millimeter/sub-millimeter Array
AoT	Astronomy on Tap
ARIEL	Atmospheric Remote-sensing Infrared Exoplanet Large-survey
ASI	Agenzia Spaziale Italiana
ATHENA	Advanced Telescope for High-ENergy Astrophysics
BCKDF	British Columbia Knowledge Development Fund
BLASTPol	Balloon-Borne Large Aperture Sub-mm Telescope for Polarimetry
BRITE	BRight Target Explorer
CADC	Canadian Astronomy Data Centre
CANFAR	Canadian Advanced Network For Astronomical Research
CanTAC	Canadian Time Allocation Committee
CANVAS	CANadian Virtual Astronomy Seminar Series
CANUCS	CAnadian NIRISS Unbiased Cluster Survey
CAP	Canadian Association of Physicists
CASCA	Canadian Astronomical Society
CASTOR	Cosmological Advanced Survey Telescope for Optical and ultraviolet Research
CATAC	CASCA-ACURA TMT advisory committee
CC	Compute Canada
CCA	Coalition for Canadian Astronomy
CCD	charge-coupled devices
CERC	Canada Excellence Research Chairs
CFHT	Canada-France-Hawaii Telescope
CFI	Canada Foundation for Innovation
CFIS	Canada-France Imaging Survey
CHIME	Canadian Hydrogen Intensity Mapping Experiment
CHORD	Canadian Hydrogen Observatory and Radio-transient Detector
CIRADA	Canadian Initiative for Radio Astronomy Data Analysis
CITA	Canadian Institute for Theoretical Astrophysics
CMB-S4	Cosmic Microwave Background Stage 4
CNES	Centre national d'études spactiale

COVID-19	Coronavirus disease 2019
CPSX	Centre for Planetary Science and Exploration
CRAQ	Centre for Research in Astrophysics in Québec
CREATE	Collaborative Research and Training Experience
CSA	Canadian Space Agency
CSBF	Columbia Scientific Balloon Facility
DAO	Dominion Astrophysical Observatory
DRAO	Dominion Radio Astrophysical Observatory
DRI	digital research infrastructure
DSL	Dynamic Structures Ltd
EBEX	E and B Experiment
EDI	Equity, diversity and inclusion
EHT	Event Horizon Telescope
ELT	Extremely Large Telescope
emCCD	electron-multiplying charge-coupled devices
EPO	Education and public outreach
ÉPPÉ	Extrasolar Planet Polarimetry Explorer
ERA	Early Researcher Awards
ESA	European Space Agency
ESO	European Southern Observatory
FAAQ	Fédération des astronomes amateurs du Québec
FAST	Flights and Fieldwork for the Advancement of Science and Technology
FGS	Fine Guidance Sensor
FRB	fast radio burst
FRQNT	Fonds de recherche du Québec - Nature et technologies
FYST	Fred Young Submillimeter Telescope
GBA+	Gender-Based Analysis Plus
GHOST	Gemini High resolution Optical SpecTrograph
GHG	greenhouse gas
GIRMOS	Gemini Infrared Multi-Object Spectrograph
GMT	Giant Magellan Telescope
GPI	Gemini Planet Imager
GRACES	Gemini Remote access to CFHT/Espadons
GTO	guaranteed-time observation
HAA	Herzberg Astronomy and Astrophysics Research Centre
HABEX	Habitable Exoplanet Observatory

HAL	Hickling, Arthurs and Low
HELIX	High Energy Light Isotope eXperiment (HELIX)
HiCIBAS	High Contrast Imaging Balloon System
HPC	high-performance computing
HQP	highly-qualified personnel
IAU	International Astronomical Union
IOF	Infrastructure Operating Fund
ISED	Innovation, Science and Economic Development Canada
ISRO	Indian Space Research Organization
IXO	International X-ray Observatory
IYA2009	International Year of Astronomy in 2009
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope
JCSA	Joint Committee on Space Astronomy
JELF	John R. Evans Leaders Fund
JWST	James Webb Space Telescope
LiteBIRD	Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
LRP2000	2000 Long Range Plan for Canadian Astronomy
LRP2010	2010 Long Range Plan for Canadian Astronomy
LRP2020	2020 Long Range Plan for Canadian Astronomy
LRPIC	Long-Range Plan Implementation Committee
LSST	Legacy Survey of Space and Time
LUVOIR	Large UV/Optical/IR Surveyor
MOST	Microvariability and Oscillations of STars
MSE	Maunakea Spectroscopic Explorer
MTR	mid-term review
MTR2005	2005 Mid-Term Review of Canadian Astronomy
MTR2015	2015 Mid-Term Review of Canadian Astronomy
MTR2025	2025 Mid-Term Review of Canadian Astronomy
MWA	Murchison Widefield Array
NASA	National Aeronautics and Space Administration
NEAT	NIRSS Exploration of the Atmospheric diversity of Transitioning Exoplanets
NDRIO	New Digital Research Infrastructure Organization
NEOSSat	Near-Earth Object Surveillance Satellite
NFIRAOS	Narrow Field InfraRed Adaptive Optics System
ngVLA	Next-Generation Very Large Array

NIRISS	Near Infrared Imager and Slitless Spectrograph
NIST	National Institute of Standards and Technology
NRAO	National Radio Astronomy Observatory
NRC	National Research Council Canada
NSERC	Natural Sciences and Engineering Research Council of Canada
NSSE	National Survey of Student Engagement
ORF	Ontario Research Fund
OSSOS	Outer Solar System Origins Survey
PIPER	Primordial Inflation Polarization Explorer (PIPER),
POEP	Photometric Observations of Extrasolar Planets
RAO	Rothney Astrophysical Observatory
RASC	Royal Astronomical Society of Canada
ROI	return on investment
SCUBA-2	Submillimetre Common-User Bolometer Array 2
SDSS	Sloan Digital Sky Survey
SITELLE	Spectromètre Imageur à Transformée de Fourier pour l'Etude en Long et en Large de raies d'Emission
SKA1	Square Kilometer Array phase 1
SRC	SKA1 Regional Centre
SO	Simons Observatory
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPIrou	SPectropolarimètre InfraROUge
SPT	South Pole Telescope
STDP	Science and Technology Development Program
STEM	Science, Technology, Engineering and Mathematics
STRATOS	Stratospheric Balloon Program
SuperBIT	Super pressure Balloon-borne Imaging Telescope (SuperBIT)
TES	transition-edge sensor
TMT	Thirty Meter Telescope
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
UVIT	Ultraviolet Imaging Telescope
VLOT	very large optical telescope
XRISM	X-Ray Imaging and Spectroscopy Mission



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