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Executive Summary of White Paper (5000 character limit)

The search for life outside our solar system is one of the great frontiers in astronomy. Confirming life and habitability of planets will require a detailed spectroscopic analysis to search for biomarkers over a wide range of wavelengths, from the visible to the thermal infrared. While many observing techniques are being pursued towards that goal, the exoplanet imaging technique, consisting of directly detecting the exoplanet light against the bright diffracted stellar halo, offers several advantages, including the detection and characterization of Earth-sized planets, orbiting around a wide range of stellar hosts without requiring any special orbital alignments.

Exoplanet imaging requires overcoming two main challenges, (1) the telescope resolution limit, motivating a strong interest by the community to operate on the largest possible telescopes, and (2) contrast -- planets can be 10^5 (gas giants) to 10^10 (rocky planets) times fainter than the host star. High-contrast imaging instruments on ground-based telescopes typically include an adaptive optics system to measure and correct (at kHz speeds) the turbulent atmosphere, a coronagraph to block the bright central star, and an imaging spectrograph.

Many breakthrough scientific discoveries were achieved in exoplanet imaging by Canadians during the last decade, from new gas giant planets to leading international campaigns using both ground- and space-based observatories. With the deployment of the Gemini Planet Imager (GPI) at the Gemini South observatory, an instrument part of the first generation of facility-class high-contrast imaging instruments, Canadians are at the forefront of the field. While GPI has achieved a contrast gain of more than 100x compared to previous instruments, new techniques must be developed if we are to detect rocky planets. Imaging rocky planets will require new solutions to overcome the “speckle noise” contrast challenge, improving sensitivity by 10^3 for M dwarfs to 10^5 for Sun-like stars.

The NRC, the Canadian Universities, and industry have been developing key technologies that are crucial for high-contrast imaging. New developments in speckle subtraction include the invention of new adaptive optics systems and coronagraphic masks, powerful focal plane wavefront sensors, and promising new observing methods, such as the high-dispersion spectroscopic technique. The community is ready to integrate all the latest promising technologies into facility-class instruments, but how to integrate such complex approaches is still an open question.

The first high-contrast imaging Canadian laboratory, NEW EARTH, has been recently set up at NRC to test and validate new technologies. The University of Laval-led HiCIBaS’ stratospheric telescope was also developed to validate space technologies. With these foundations now in place, the Canadian community is now in a position to develop and test the new technologies needed to directly image rocky exoplanets.

The next decade will see new science capabilities and exciting exoplanet science discoveries with new instruments, including from a first set of GPI upgrades and the launch of the JWST and WFIRST. ELT telescopes should see their first light before the end of the decade, and their dedicated high-contrast imaging instruments should be well in their design/construction phase. Large flagship exoplanet imaging space missions, such as HABEX and LUVOIR, are being studied in the US, but it is still unclear

if Canada will be a partner of these. Canadians are now well-positioned to develop and contribute key hardware to these initiatives, but some challenges still remain.

We make important recommendations to support the essential high-contrast imaging R&D in the next decade for: developing technologies to reach contrast levels sufficient to image rocky planets and find life for both ground- and space-based telescopes, strategic hires in the field, keeping Gemini/GPI access for the next decade, modifying the funding system to better prepare for large Canadian instrument infrastructures, securing an ELT early access, and the development of long term commitments (pathfinders like HiCIBaS, to flagship missions) by CSA. With this emphasis, Canadians will be positioned at the forefront of the search for life elsewhere in the Universe for decades to come.

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1 The Quest to find another Earth

While the various conditions to sustain life on a planet are still being debated in the community, many factors are believed to play an important role, such as the amount of energy that a planet receives from its star, the planet's atmospheric composition and surface temperature/pressure, the planet's orbital eccentricity, and the existence of powerful flares from an active stellar host. For the foreseeable future, all exoplanets will remain unresolved due to their great distance and their relatively diminutive size. Therefore, our greatest chance of detecting biosignatures will be through measuring the chemical composition of their atmospheres using spectroscopy. In particular, the correct abundances of oxygen, ozone, methane, and carbon-dioxide are chemical signatures of life. By observing such a planet over time, scientists may be able to see seasonal variations in climate, the "red-edge" of vegetation, and even map broad surface features like continents (Meadows, 2008). Detecting life signatures in the atmosphere of another planet is just the first step. Only through detailed comparative planetology can we ultimately understand the conditions required for life. The search for life has also strong ties with other fields, such as planet formation by studying protoplanetary disks and debris disks, and the origin of the solar system (see E013, E016 and E056).

To identify and characterize Earth-size planets by high-contrast imaging, astronomers will need to use the world's largest optical telescopes combined with specialized instruments that are still under development. The search for life outside our solar system was one of the four main themes identified in Long Range Plan (LRP) 2010. With the support of the previous LRP, the last decade saw many exciting discoveries and the invention of innovative new technologies by Canadians. With a growing Canadian exoplanet community, future larger observatories, and new instruments, we expect the next decade to be even more exhilarating.

The foundations are now in place for Canadians to play a central role in the search for life using an array of complementary techniques, but work is still needed to reach our goal. Scientific teams around the world are competing to find the best path forward in developing instruments to enable habitable zone surveys of M dwarfs and Sun-like stars. With the right support and investment into basic instrumentation research today, Canadians will drive innovation and play a major role in this profound endeavor for decades to come.

2 Solar neighbourhood exoplanets: Current techniques and their limitations

Four main distinct techniques are currently being developed to study planets in the solar neighbourhood ($<$ 20 pc): (1) velocimetry, which measures the star's radial speed variation as it moves around the system's center-of-mass, (2) astrometry, which measures the on-sky stellar motion around the system's center-of-mass, (3) transit, which searches for line-of-sight instances when the planet masks a fraction of the star's disk for a fraction of its orbit, and (4) direct imaging, which directly detects the planet's light. Each of these techniques has advantages and limitations: some require very special alignments (transit); some are more sensitive to planets that orbit closer in to lower mass stars (transit and velocimetry) or further out (imaging and astrometry); and some have limited potential for characterizing planets (velocimetry and astrometry). To date, more than 4000 planets, with sizes ranging from the Earth to Jupiter, have been discovered, mainly through the velocimetry and transit techniques. Although the orbits of these planets are usually well known, most lack an in-depth characterization except for a small number of Neptune to Jupiter-mass objects using transit spectroscopy or direct imaging.

3 The Unique potential of Exoplanet Imaging

Over the next decade, direct imaging is expected to be the most efficient technique to enable both the detection and the characterization of Earth-size temperate planets around a wide range of stellar hosts, from M dwarfs to Sun-like stars. It can enable detections without the transit method's need for special alignments, thus permitting an in-depth survey of nearby stars to find the closest Earth-like planet to our solar system. These nearby planets will be the best candidates for in-depth characterization, and could one day be humanity's first destination outside of our Solar system.

The direct imaging technique needs new technologies to reach its full potential; thus far it has discovered only a relatively small number of young gas giants in a few nearby young systems. Key requirements for direct exoplanet imaging are a high angular resolution to resolve other planetary systems and a high dynamic range to detect the faint glow of planets located only a few diffraction bandwidths away from their bright central star. This range must span the contrasts of 10^4 (the intensity ratio between the star and the planet, for the thermal imaging of young gas giants) to 10^{10} (for Earth-sized planets seen in reflected visible light). The contrast between a planet and its host star is also wavelength dependent, for example, an Earth-like planet has a contrast of 10^{10} in reflected visible light, while it has a contrast of 10^7 in thermal emission at $10\,\mu$m. While high-contrast imaging instruments are being mainly designed for exoplanet studies, these instruments are also being used for high-Strehl imaging of solar system planets and satellites, binaries and disks. In particular, as direct imaging is the main technique for detecting recently formed planets embedded in disks, imaging exoplanets is closely related to imaging their gravitationally induced structures in protoplanetary disks. Such structures can help constrain the conditions of planet formation. In the PDS 70 system, NIR imaging observations using Subaru/HiCIAO first discovered a huge central cavity (Hashimoto et al., 2012); numerical modeling subsequently showed that such cavities may be opened by multiple giant planets (Dong et al., 2015); finally, two accreting planets have been found in direct imaging at NIR and optical wavelengths (Keppler et al., 2018; Haffert et al., 2019).

4 Current state of Exoplanet Imaging & challenges

Canadians have been pioneers in the field of high-contrast imaging for the past three decades, from leading the develop of new instruments, inventing new optimize observing techniques (Marois et al., 2000, 2006) and post-processing algorithms (Lafrenière et al., 2007), to leading international campaigns, and to performing frontier discoveries (see Fig. 1 for some examples, all involving Gemini observatory data).

Current high-contrast imaging systems include several key components: an adaptive optics (AO) system to measure and correct, using a deformable mirror (DM), at kHz speed aberrations coming from the Earth's turbulent atmosphere; a coronagraph to block the central star; and a near-infrared science camera. The main highlight of the last decade is the deployment of the first generation of extreme high-contrast imaging facilities on ground-based telescopes: the Gemini Planet Imager (GPI), an instrument that Canadians are heavily involved in from its design phase (2004-2014) to current science operation (2014-now), SPHERE (at VLT) and SCExAO (at Subaru). GPI is now completing its large campaign of more than 500 stars (PI B. Macintosh), $2-5\times$ the size of prior surveys, to derive the most accurate demography of gas giants in wide $>$ 10 AU orbits to date (Nielsen et al., 2019). A library of spectra of known gas giants have also been observed to deepen our understanding of these planet's atmospheres. GPI represents a major step forward in performance, routinely obtaining $100\times$ better contrast than instruments that were available only a decade ago, achieving 10^5 to 10^6 contrast at a few diffraction bandwidth, which is sufficient to detect the faint glow of young $10-300$ million year old gas giants.

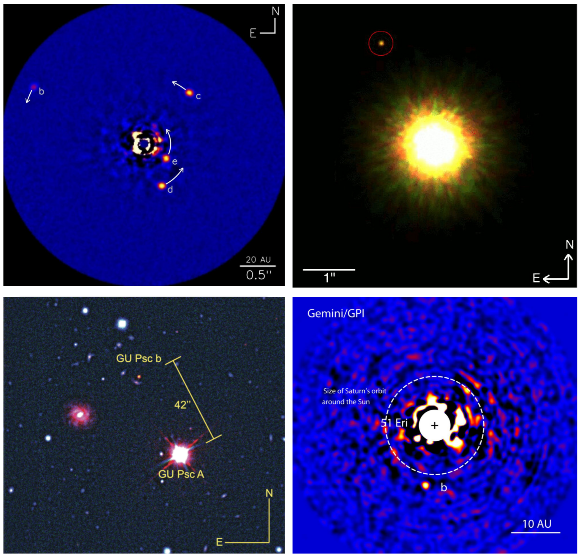


Figure 1: A subset of Canadian-led discoveries: HR 8799 (upper left; Marois et al., 2008, 2010), 1RXS J160929.1-210524 b (upper right; Lafrenière et al., 2008), GU Psc b (bottom left; Naud et al., 2014) and 51 Eri b, the first GPI planet (bottom right; Macintosh et al., 2015).

Canadian teams have also led several other campaigns in the last decade to look for more distant (larger orbits) gas giant planets (PIs M-E Naud, E. Artigau & F. Baron) around young stars, using both ground- and space-based telescopes around a variety of stellar hosts. These surveys lead to breakthrough Canadian discoveries and to in-depth statistical analyses of distant gas giants (Baron et al., 2019). Detail studies of TMT first light high-contrast capabilities with the Canadian NFIRAOS adaptive optics system and the IRIS instrument (see E062) have also been performed to give recommendations to optimize first light performances.

Today's technology is still a factor 10^3 (nearby M dwarfs) to 10^5 (Sun-like stars) from the contrast required to characterize another Earth in the near-infrared. New high-contrast imaging technologies and larger telescopes are needed to bridge this gap. To reach higher contrasts, systems need to reduce or remove what is called "speckle noise," a noise that originates from the central stellar host that is diffracted off-axis by optical aberrations in the system. This noise is also the main limiting factor for high-contrast imaging space observatories. Speckle noise can have several sources and can be short or long lived, the main sources being:

1. residual aberrations from the AO system (time-lag, aliasing, photon noise, fitting errors & flexures)
2. non-common path aberrations (different aberrations between the AO wave-front sensor (WFS) and the science camera)
3. chromatic errors (e.g., between the WFS wavelength and science wavelength and/or varying across a science wavelength band-pass)
4. a limited number of photons to perform high-level wave-front corrections.

Solving these challenges is the main objective for the coming decade. LRP support is needed to enable this research and development in Canada, to ensure that Canadian astronomers have access to future high-contrast imaging instruments on current 10-m class telescopes, and to future ELTs, that reaches the target capabilities.

5 Key technologies for the next decade

The exoplanet imaging field has seen major advances over the last two decades. With the development of high-performing coronagraphs, such as the Vortex mask (Foo et al., 2005) and the phase-induced amplitude apodization (PIAA; Guyon, 2003), to focal plane wavefront sensors, and speckle nulling/phase retrieval techniques, the field is flourishing with new ideas and possibilities. A recent innovation was the extension of the original simultaneous differential imaging technique (SDI; Marois et al., 2000) to very high spectral resolution, the high-dispersion spectroscopy approach or HDS (Snellen et al., 2013, see also E068). How to best combine and optimize these various approaches into a final facility-class instrument is still an open question. Over the years, the Canadian community and their industrial partners has been developing new technologies (see below) that are expected to play a central role in the design of future high-contrast imaging instruments.

5.1 Canadian adaptive optics innovations

Canadian AO experts have been testing new wave-front sensors at the NRC AO laboratory (PI J-P Véran) and faster real time computer architectures for ground-based telescopes. Work has recently begun on advanced control algorithms to predict the wave-front in advance, instead of lagging milliseconds behind and waiting for a measurement to apply a DM correction. These new wave-front control methods are expected to lower the AO residual speckle noise propagated to the coronagraph and science camera (Jensen-Clem et al., 2019).

5.2 Seeing no light with FAST, a new Canadian focal plane wavefront sensor

For the last few years, the NRC and the University of Victoria have been developing a new imaging technique that would, in theory, allow a major gain in contrast for both ground- and space-based instruments by actively removing residual speckles at kHz speeds, achieving a hundred-fold gain in contrast on bright stars relative to current instruments such as GPI. The technique, called the Fast Atmospheric Self-Coherent Camera Technique (FAST; Gerard et al. 2018a,b; see Fig 2 below), consists of using a new type of focal plane coronagraph mask that transforms the stellar light into a common-path interferometer. This technique is based on the Self-Coherent Camera (Baudoz et al., 2006). The resulting focal plane image can then be analyzed at kHz speeds using a noiseless camera to reconstruct the speckle noise in a single image and (1) remove the achromatic part of it with the deformable mirror or (2) perform a post-processing subtraction (called Coherent Differential Imaging, or CDI). By stacking residual frames, the sensitivity to fainter exoplanets improves with increasing exposure time. This approach has the potential to solve many problems at once, by sensing/allowing the removal of AO residuals and non-common path errors, while allowing polychromatic wavefront sensing/post-processing.

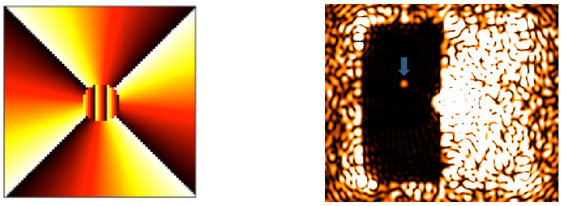


Figure 2: Left: The FAST coronagraph mask. Right: Long FAST integration reaching close to the photon noise limit inside the DM control area (dark region to the left of the star where a faint planet is now detected).

5.3 Photon counting with noise free Canadian cameras

A new generation of cameras for both the visible and the near-infrared have or are being developed by the Canadian industry and NRC/Canadian Universities. The Nüvü cameras, made by a Montréal company, offers kHz frame rates using EMCCDs. These cameras have been deployed in several wavefront sensors around the world. The University of Toronto (PI S. Sivanandam) and NRC have been designing a near-infrared camera based-on the SAPHIRA avalanche photodiode detector. Both cameras have new models being developed with larger-size and/or faster frame rates. These advances will be central for future visible/NIR-band wavefront sensors running at faster speed with less delay, including photon-counting focal plane wavefront sensors such as FAST.

5.4 Toward a new low-voltage Canadian deformable mirror

Conventional DM (e.g. piezoelectric, voice coil) are expensive, bulky, power hungry, and operate at limited speed. These DMs, currently available for use in ground-based AO systems, and especially for space-based AO, have considerable limitations and shortcomings. This is especially true looking forward to the TMT era (e.g., for the IRMOS instrument currently being planned, considering cost, power consumption, compact design, large stroke, stability to creep, etc.), with many of these aspects being crucial for space as well. To circumvent these current limitations, a development of a next generation DM technology (in early stages of pursuit) is underway through a collaboration between NRC, U. Manitoba and Dalhousie University. The work takes a novel approach to solving this solution by integrating low-voltage/low-current MEMS (Micro-Electro-Mechanical System) DM technologies with dedicated ASIC (Application Specific Integrated Circuit) driver electronics and integrated FPGA wave forming.

5.5 An orbital LASER guide star system

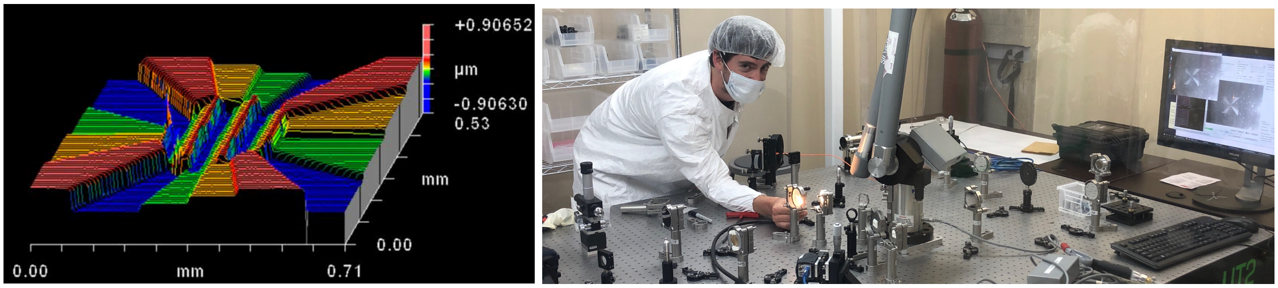
A Canadian team has recently proposed (AO4ELT6 proceeding, Thompson et al. in prep) to launch a constellation of small satellites into high-eccentricity Earth-orbit where they can act as artificial guide stars using a LASER of moderate power. Such orbital guide beacons could bright (apparent magnitudes of -5 to -10) enabling incredibly high speed correction of very high order aberrations. Because such guide beacons would orbit at high altitude, they would effectively be an in-band point source at infinity. A constellation of several satellites in close proximity could be used to perform tomographic atmospheric reconstruction and to implement a predictive controller. This would surmount many of the drawbacks associated with current faint LASER guide star systems that excite the sodium layer of the upper $\sim$ 75-km atmosphere: it would not suffer from chromatic effects, spot elongation, or the cone-effect. With the satellite orbit apogee being close to the Moon, this system could piggy-back on the Lunar Gateway initiative.

6 From simulations to validation

While a lot of the initial work of designing new technologies can be done with computer simulations, it is an important step to validate new ideas using laboratory experiments and small path finder missions before integrating these concepts in multi-million or billion dollar-worth facility-class instruments and observatories. While a Canadian infrastructure was missing a decade ago to perform initial laboratory testing, recent efforts have seen the establishment of the first Canadian high-contrast imaging laboratory, The NRC Extreme Wavefront laboratory for the Exoplanet Advanced Research Theme at Herzberg (NEW EARTH).

6.1 The NEW EARTH Laboratory

The NEW EARTH Laboratory (PI C. Marois) has recently been assembled at NRC in Victoria. NEW EARTH is the first Canadian test-bed focused on high-contrast imaging. The bench design allows a wide range of applications, such as adding a variety of turbulent phase screens for ground-based applications, the use of segmented pupils, testing different coronagraphic systems and various wavefront sensing techniques (including standard adaptive optics wavefront sensors to focal plane wavefront sensing approaches). Super-polished off-axis parabolas are implemented to minimize optical aberrations and chromaticity while maximizing throughput, in addition to an ALPAO deformable mirror, Shack Hartmann WFS, phase screens of adaptive optics residuals, custom coronagraphic masks and custom Lyot reflecting masks. This laboratory (Fig. 3) provides a new platform to the astronomical community to test and develop new hardware and wavefront control software, and help leading future instrumentation projects for extremely large telescopes and space-based observatories.



(a) (b)

Figure 3: (a) Interferometer measurement of surface profile for a custom coronagraphic mask (see Sec. 5.2), fabricated by 4-layer aluminum deposition at King Abdullah University of Science and Technology's Computational Imaging Group (PI W. Heidrich) (b) Laboratory image during optical alignment of the coronagraphic mask.

The laboratory's initial goal is to validate the FAST focal plane WFS scheme. Future work will be aimed at expanding the technique to operate in broadband light, to further test various possible implementations of the HDS technique in a focal plane wavefront sensor framework, and to work with a segmented ELT pupil. The laboratory has also a longer term goal to upgrade the bench toward a 10^8 or more contrast facility for space applications. Ensuring a strong collaboration with Canadian Universities is central to ensure NEW EARTH's success, but such community is small at this time. Hiring experts in high-contrast instrumentation is needed, for example in fields such as coronagraph mask technologies, focal plane sensors, and high-contrast polarimetry.

6.2 Pathfinders for field testing new technologies

While the infrastructure is now in place to develop and test new technologies at the NEW EARTH laboratory, field testing new high-contrast imaging capabilities in low-cost pathfinders is a challenge in Canada for both ground- and space-based imaging. This fundamental step is required to showcase the approaches in actual on-sky conditions before considering their deployment on larger scale instruments and observatories.

Figure 4: Left, the GPI instrument currently in operation at the Gemini South observatory. Right: The HiCIBaS' team and the telescope just before launch.

For ground-based imaging, only the GPI instrument (see Fig. 4) is currently available to the community for field testing, but being a facility-class instrument at the telescope Cassegrain focus, it does offer various challenges, such as limited access to perform upgrades, design complexities due to the continuously changing gravity vector, and high design/construction cost. It is thus critical to retain Gemini and GPI access for the next decade (see E045). Having official access to a 2nd high-contrast imaging instrument, such as SCExAO at the Subaru telescope that is located on a stable optical table on the Nasmyth platform, would open new possibilities. The SCExAO team has already invited several Canadians to collaborate on, and in some cases lead, SCExAO science programs (e.g., Gerard et al., 2019), but an official collaboration with Subaru (see E006) would allow a greater Canadian participation in both science operation, and in the instrument future development. Such a partnership would also be important in forging new collaborations toward joint TMT instrument developments between the two countries.

For space-based imaging, the HiCIBaS stratospheric platform (PI S. Thibault, see Fig. 4) was recently developed using a CSA Flights and Fieldwork for the Advancement of Science and Technology (FAST) grant to give Canadian researchers and their international partners a low cost access to a space-like environment. The new platform uses a commercial 14-in Celestron telescope and custom-built alt/az mount. For instruments, it has a low-order WFS to study the high-altitude residual seeing and gondola motion/vibrations, and a high-contrast imaging channel that includes an IRIS-AO deformable mirror, a vector-apodized phase plate (vAPP) and a Nüvü camera with their space controller. The HiCIBaS' mission made its inaugural flight from Timmins Ontario during the summer of 2018 for 37 h. The mission was a success from the point of view of student training and demonstration of some key technology elements in a near space environment such as the flight version of Nuvu's EMCCD controller. The positive results obtained from the test were highly influential in bringing NASA JPL to consider the Canadian technology for the WFIRST coronagraph channels (Low Order WFS and imager). HiCIBaS' platform is unique worldwide, but the current CSA FAST funding process makes it difficult to retain expertise and perform regular flights to further develop and test hardware. To achieve its full potential, the HiCIBaS' project would require a multi-year/several flights commitment by CSA, but such program currently does not exist. The two year FAST funding cycle, the win/lose reality of competitive funding, and the inability to retain expertise mean that progress that could be done in a few years will likely take more than a decade. Having access to long duration flights would be of great interest once the HiCIBaS observatory is fully operational (see E073).

7 The 2020-2030 landscape and beyond

The Canadian exoplanet imaging community and its industrial partners now have a strong foundation to innovate in all main areas in high-contrast imaging, from wavefront sensors, to real time computers, to noise-free cameras, to deformable mirrors, to coronagraph masks and to focal plane wavefront sensors. With our long legacy of designing and building imagers and spectrographs, Canadians now have the ability to fully design and build state-of-the-art facility-class high-contrast imaging instruments. With ELT high-contrast instruments starting or about to start their in-depth design phase, it is crucial for Canada to position itself as a leader in new technologies, and to play a central role in the design and the construction of these instruments. Investments in high-contrast imaging R&D in the next decade will carry over to ELTs, but also for world-class facilities to come in the second half of the 21st century.

The next decade is expected to be even more exciting for exoplanet science and instrument development in Canada (see Fig. 5), with the first phase of GPI upgrades that was recently funded in the US (focusing on its AO system and integral field spectrograph), the launch of the JWST (see E038), the construction of the ELTs, the design and construction of ELT high-contrast imaging instruments (such as MODHIS, HIRES (ESO), PSI and MICHI), and the expected launch of WFIRST in 2026. With the impressive resolution and contrast gains from using larger telescopes, it is clear that a timely Canadian access to a large 30-m class ground-based telescope and to a specialized space observatory is required for a Canadian participation in the direct imaging searches for life outside our solar system.

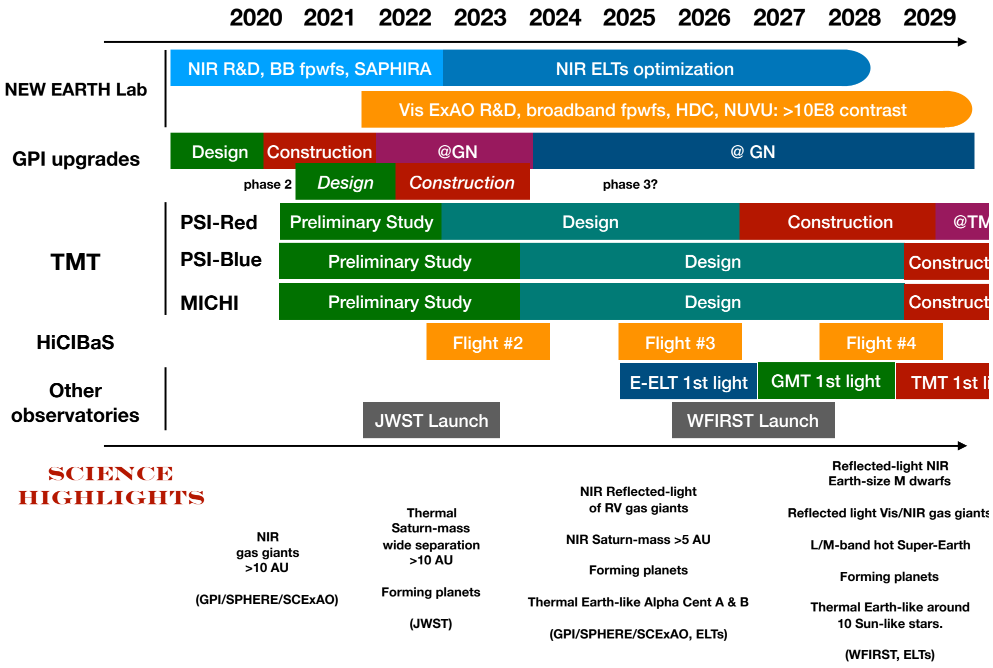


Figure 5: A 10 year perspective of high-contrast imaging science, R&D and instrumentation. Note that a lot of these date ranges are approximate and/or dependent of funding, possible delays, etc..

Beyond 2030, beside possible 100-m class ground-based telescopes that would go well beyond upcoming ELTs capabilities, large international space projects, such as HABEX and LUVOIR, are expected to dramatically open-up the search space and characterization potential of Earth-like planets at visible and NIR wavelengths. These missions will require a long term effort to develop a Canadian contribution, and to secure a JWST-like level investment from CSA, to guarantee access to Canadian astronomers. The idea of deploying a starshade pathfinder to CASTOR is particularly interesting if a starshade is finally selected for one or both flagship missions (see E007 and E012). Contributions for HABEX and LUVOIR could go from simple hardware, such as star trackers, to more complex imagers/spectrographs, to more critical hardware, such as coronagraph masks or focal plane wavefront sensing schemes. Such work should be supported and started as early as possible in the next decade to avoid a last minute effort, similar to what happened to CSA's studied IFS contribution to WFIRST. In the end, after years of CSA investments in developing a space-qualified EMCCD, such Canadian detector will fly on WFIRST with interesting economic return, but without any science return to Canadian astronomers. Being part of the WFIRST coronagraph science team would have been important to position Canada toward HABEX and LUVOIR by forging stronger collaborations with the US high-contrast imaging community.

8 Recommendations for high-contrast Exoplanet Imaging in the next decade

1. Support the development of high-contrast technologies, at NRC at the NEW EARTH laboratory, in Universities and in the industry. This is mandatory for new instruments to reach the sensitivity to search for life signatures on other planets.

2. Stress the importance to hire Canadian high-contrast expertise at NRC and in universities. These will ensure that we have a strong diversified workforce that can lead to major Canadian deliverables to future large-scale instruments/observatories for both ground and space.

3. Retain Gemini/GPI access, as this is the main ground-based facility where Canadian can deploy new technologies for ground-based telescopes.
4. Subaru/SCExAO partnership is worth exploring for both its science potential and instrument program.
5. The Canadian funding system is inadequate to prepare for projects on the scale of ELT instruments. The current funding stream is mainly through CFI or observatories. For example, the main expertise in high-contrast imaging is located at NRC where CFI funding can't be transferred to support instruments for Canadian observatories, limiting the scope of observatory-independent funding to develop visitor-class pathfinders/upgrades.
6. Stress the importance of seed funding for instrument proposal preparation to large funding agency, such as CFI. With instruments becoming larger, more complex and more expensive for ELTs, the lack of funding to properly design and cost instruments is a real concerned, potentially generating issues once money is awarded and actual in-depth work in design and costing is performed.
7. Early access to an ELT is crucial. It is important to further stress the importance of a GMT/E-ELT/TMT partnership to share telescope time and get access to both hemispheres. For example, Alpha Centauri A and B, along with Proxima Centauri, important targets in high-contrast imaging given their prioximity, are only visible from the southern hemisphere with no equivalent in the northern hemisphere.
8. CSA stratospheric balloon flights and its FAST program are crucial to test space technologies and increase their technology readiness level (TRL). A new funding scheme is necessary to enable long-term support for strategic initiatives.
9. Discussions are needed as soon as possible to develop contributions (at the JWST level) and a funding plan for future participation in B$ flagship space missions such as HABEX and LUVOIR.

1: How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?

The search for life outside our solar system is a recent field in astronomy, while being a more than 2 000-year old question. It is driving key ELT requirements and the design of future 6 to 15-m space observatories. With the future launch of the JWST and upcoming ELTs, and development of innovating new instruments, humanity has never been so close to confirm the discovery of life on another planet. Exoplanet imaging is central in that quest, as it allows the search for habitable exoplanets around a wide range of stellar hosts, for small M dwarfs to Sun-like stars, and does not have any requirements of the system alignment relative to Earth. In addition, it can detect the exoplanet light in both reflected light at visible and near infrared wavelengths to the thermal emission at 10 μm, allowing a complete spectral analysis, and identification of biomarkers, to establish the presence of life and evaluate the planet's habitability.

2: What are the main scientific risks and how will they be mitigated?

In this white paper we are requesting support from the LRP for mitigating risks for imaging and characterizing habitable exoplanets. Our approach is to develop new ideas by doing in-depth numerical simulations, then to validate these concepts using the NEW EARTH laboratory, and to finally field test these methods using pathfinders, including GPI for ground-based instruments and HiCIBaS for space observatories.

3: Is there the expectation of and capacity for Canadian scientific, technical or strategic leadership?

Canadians have a long legacy of leadership and breakthrough discoveries in high-contrast imaging, having pioneered the field in the 90s. Over the last decade, with strategic investments, Canadians now have the laboratories to develop new capabilities. With University and industrial partners developing key new hardware and having the infrastructure to validate these on sky, the community is well positioned to play a leadership role in designing new instruments for current and future observatories.

4: Is there support from, involvement from, and coordination within the relevant Canadian community and more broadly?

There is strong synergy in Canada in exoplanet imaging. NRC is involved in many key developments with Canadian Universities, from wavefront sensors, to real time computers, to new DMs and the APD NIR camera. The University of Victoria is leading the coronagraph mask design with NRC (testing at NEW EARTH) and Canadian Universities and international partners, while the University of Toronto is co-developing the APD NIR camera. The University of Laval has an advanced optical laboratory and can manufacture new optical components, coat mirrors, lead optical design work, and is also leading the HiCIBaS mission. Montréal is leading the field for high-contrast imaging with the JWST. Two NSERC CREATE exoplanet/instrumentation programs are also further expanding the Canadian collaboration by enabling internships, monthly online seminars and yearly face-to-face meetings, allowing various teams and students to exchange on a regular basis.

5: Will this program position Canadian astronomy for future opportunities and returns in 2020-2030 or beyond 2030?

Exoplanet imaging is driven by technology. A strong R&D program will ensure that Canadian astronomers are at the fore front of the field for the next decade and beyond, for both ground and space. New technologies are needed for future instruments on current and future observatories (ground and space) to reach the sensitivity required to search for life on other planets. Actual contributions to these instruments/observatories will guarantee that Canadian scientists are involved in future flagship instruments/observatories.

6: In what ways is the cost-benefit ratio, including existing investments and future operating costs, favourable?

Small R&D cost using existing infrastructure in the next decade will enable the development of new technologies that will trigger new science capabilities and opportunities for Canadian astronomers. The multi-step approach ensures that our technology is well proven and that it is ready for large scale deployment.

7: What are the main programmatic risks and how will they be mitigated?

Technologies that are deployed on current facility-class high-contrast imaging instruments, such as GPI, have reached unprecedented performances, but these are not good enough to reach the sensitivity to directly image and characterize rocky planets. Solutions to improve current contrast performances by a factor of up to $10^3 - 10^5$ are needed to reach Earth-sized exoplanets. Early testing is fundamental in learning from experiences to propose proven and robust solutions for future facility-class instruments. Only through a vigorous R&D program can Canadians position themselves to significantly contribute to the search for life outside our solar system. There are opportunities to propose advanced hardware to instrument upgrades, such as GPI, with the aim of opening up new science capabilities in the next decade, while performing early field testing of new technologies for ELTs. There is a CFI proposal (PI R. Doyon) to contribute to ELT instruments, especially focusing on HDS such as MODHIS for TMT and HIRES for E-ELT. A more complete implementation of a full coronagraphic high-spectral resolution system is expected in PSI for TMT, but funding for this instrument has not yet been secured from TMT. It is important to start the PSI design early, but it is unclear where the funding would come from at this time. For space missions, it is too late to contribute to WFIRST, but there is still time for HABEX and LUVOIR if we start this process early using HiCIBaS as the main testing platform.

8: Does the proposed initiative offer specific tangible benefits to Canadians, including but not limited to interdisciplinary research, industry opportunities, HQP training, EDI, equity, diversity and inclusion outreach or education?

Exoplanets, and the search for life outside our solar system, captivate the general public and the media. Research in the field is very interdisciplinary, involving researchers doing instrumentation, data processing, exoplanet atmosphere modeling, planet formation/evolution, disk, orbital dynamics and astrobiology. It also has strong ties to the search for life in our solar system by planetary scientists. High-contrast imaging instruments requires advance technology, specialized mirrors and camera/hardware, requiring a strong connection with opto/mechanical engineers and the industry. HQP training is quite diverse, from numerical simulations, to laboratory work, to opto-mechanical design work, to project management, to field testing and telescope operation/science data acquisition. While still very young, the NEW EARTH laboratory is training or has already trained one PhD student, one Master student and one postdoctoral researcher. The HiCIBaS' mission has trained five Master's students and 3 undergraduate students. The GPI design and the GPIES campaign have involved 19 undergraduates, 29 graduate students and 22 postdoctoral researchers mostly in the US and Canada. NSERC CREATE grants, like TEPS, focusing on exoplanets, and NTCO, focusing on instruments for ELTs, have been used by graduate students to perform internships in industry, including Nüvü and Honeywell, and international internships.

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