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Executive Summary of White Paper (5000 character limit)

This proposal advocates for a collective science initiative within Canada to better understand the nature of interstellar dust through its entire life cycle. Interstellar dust grains (solid particles) are a fundamental probe of the Universe. Dust is present across multiple scales that probe the physical properties of (1) dense and diffuse clouds in the multi-phase ISM in galaxies, (2) the atmospheres of evolved stars, (3) the ejecta of stellar remnants, (4) circumstellar disks, and (5) the high-redshift universe.

Even though dust is such a key component in how we perceive entire galaxies, characterize stellar evolution, and trace both star and planet formation, we don't have good physical and chemical constraints on the dust grains themselves. What are dust grains made out of? What is their size distribution? What is their structure? These questions are a key problem in using dust as a probe of the universe. These questions are also non-trivial, because dust grains are expected to vary widely in their composition, size, and structure in the ISM and in different galactic environments. This white paper highlights the challenges that are faced in observational and theoretical studies of the dust life cycle and the direction the Canadian community should take to meet these challenges using current, upcoming, and future technologies.

A robust model of dust requires multi-wavelength observations of different stages of dust in its life cycle, because dust can obscure radiation through extinction and scattering processes and emit radiation from their own thermal energy. Canada is a world leader in studies of the key stages of dust from star and planet formation, stellar populations, galaxy evolution, and cosmology. We have extensive expertise using current facilities, such as the Canada-France-Hawaii Telescope (CFHT), James Clerk Maxwell Telescope (JCMT), and Herschel Space Observatory to conduct multi-wavelength studies of dust extinction, emission, polarization, and scattering processes necessary to characterize the properties of dust. As such, Canadian astronomers are well positioned to lead research projects to investigate dust properties throughout its life cycle.

A full understanding of dust in all of its forms and stages requires statistical studies of dust properties over multiple wavelengths and across stellar evolution, star and planet formation, and redshift. Canada has a rich history of developing and supporting instrumentation ideal for dust studies at optical and near-infrared wavelengths (e.g., WIRCam at CFHT), far-infrared wavelengths (e.g., SPIRE onboard Herschel), submillimeter wavelengths (e.g., POL-2 at JCMT), and millimeter wavelengths (e.g., the Band 3 receivers for ALMA). The Canadian community is also actively involved in future instrument upgrades to these facilities and future technologies and research initiatives that will provide invaluable data for constraining the properties of dust grains: ALMA, BLAST-TNG, CASTOR, CCAT-p, JWST, ngVLA, Origins, SKA, SPICA, WFIRST.

No one facility can solve dust. Dust properties across the life cycle can only be constrained from multi-wavelength technologies that probe a wide range of properties and span a wide range of angular scales, from dust in high-redshift galaxies and tiny protoplanetary disks to dust in nearby supernova remnants and diffuse clouds. For this LRP2020 white paper, we recommend that Canada invest in multi-scale, multi-wavelength projects so that Canadian astronomers have access to world-class facilities to tackle the question of dust composition, size, and structure from the local solar neighbourhood to the distant universe. These projects will enable Canadian astronomers to bridge the gaps between dust production and evolution, and place important constraints on dust models so we can build meaningful and robust conclusions of the universe.

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1 Introduction

The dust life cycle is a multi-disciplinary problem in astronomy. Briefly, dust refers to solid particles of silicates (Mg-rich or Fe-rich inclusions in SiO_n) or carbonaceous materials with various degrees of hydrogenation and aromaticity, such as polycyclic aromatic hydrocarbons (PAHs). These solid grains are found across multiple scales from diffuse ISM clouds in our Galaxy and distant galaxies to the ejecta of evolved stars and circumstellar disks. Thus, dust is an important feature in studies of local clouds and the extragalactic universe, stellar evolution, star and planet formation, and astrochemistry.

Even though dust grains make up a small portion of the interstellar medium (ISM, e.g., dust-to-gas mass ratio is $\sim 1\%$), they have a significant influence on how we perceive the Universe. Roughly 30% of stellar emission in our Galaxy is absorbed by dust and higher fractions are found in dusty starburst galaxies. As a consequence, the spectral energy distribution of individual galaxies can be dominated by thermal dust emission, making it easier to detect objects at high redshift from dust rather than gas or stars. Dust is also an excellent probe of magnetic fields, where non-spherical grains align with their short axes perpendicular to the field direction, and of the radiation field through scattering processes. Dust grains are also the building blocks for planets and they provide a surface for chemical reactions to produce organic molecules necessary for life (e.g., Draine 2003; Andersson et al. 2015).

The main complication to using dust as a probe of the universe is that the grains are constantly evolving. Figure 1 illustrates the dust life cycle. Here, metallic elements are first produced in the interiors of stars and released into the ISM during the final stages of stellar evolution. These elements condense in the ejecta and/or outflows of the stars, or in the ISM itself to form dust grains. These newly-formed grains may be processed or destroyed by shocks from supernova events or strong radiation, and they can also collect into clouds that are then cooled by their radiative processes. The production of cold, dense clouds is paramount for star and planet formation, and in these environments, dust grains will grow in size through coagulation and in disks form the seeds for planets (e.g., Draine 2003; Dwek et al. 2009). The cycle begins again when the next generations of stars evolve off the main sequence.

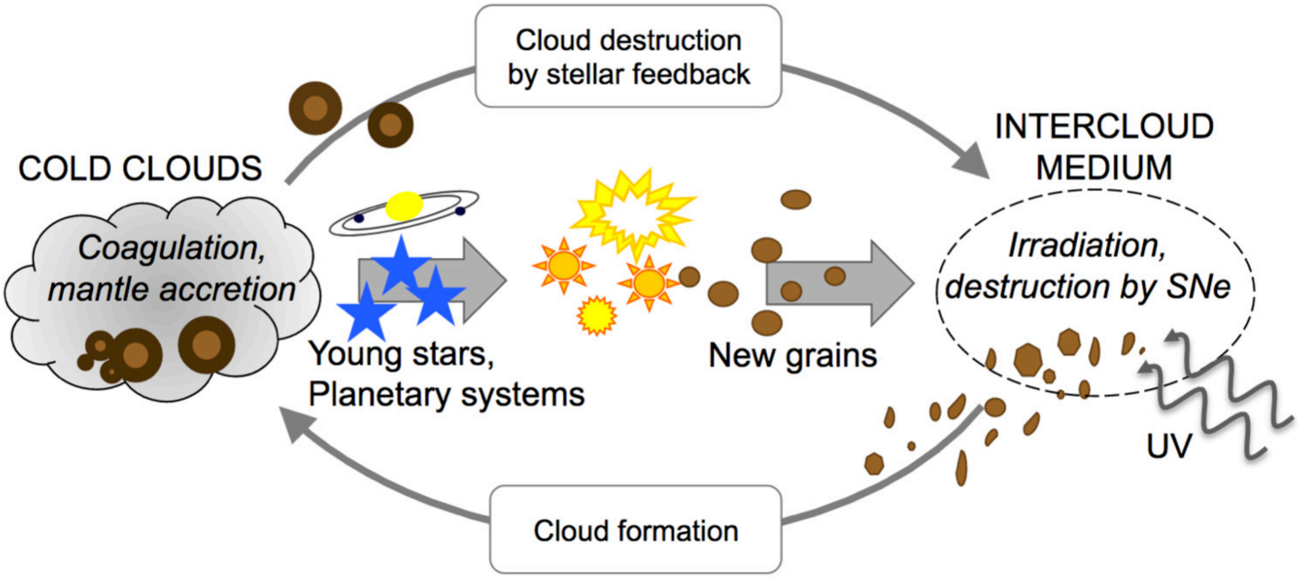

Figure 1: *The life cycle of dust from (Zhukovska & Henning 2014). See text for details.*

The Canadian community is extremely active in astrophysics research at each stage of the dust life cycle (see science topics in the next section). Changes to dust grain sizes, compositions, and structures throughout the life cycle will have profound effects on various astrophysical phenomena: (I) absorption and scattering cross sections, (II) masses inferred from thermal dust emission, (III) how H_2 molecules form on grain surfaces, (IV) coupling efficiencies with an external magnetic field, (V) metal, gas, and ice chemistry on grain surfaces, and (VI) radiative coupling between UV photons and neutral gas. Astrophysical models need to reproduce all of these dependencies, which is a challenging task (e.g., Ysard et al. 2018).

Interstellar dust is best characterized with continuum studies, polarization studies, and spectral line studies from UV to radio wavelengths that can constrain the size distribution, composition, structure, and shape of dust grains in the local Universe and at early times. This white paper advocates for a collective science initiative within Canada to improve our understanding of the nature of interstellar dust. There is already ongoing engagement within our community to investigate dust and dust properties in different corners of astrophysics and to build instruments that are well-suited to constraining dust properties. Canadians can become leaders in this subject if we combine our research and instrumentation expertise and invest in new technological advances with the next generation of telescopes.

2 Main Science Themes

2.1 The origins of interstellar dust

How interstellar dust grains first form is greatly debated. Dust can condense in the stellar winds of evolved asymptotic giant branch (AGB) stars, in the ejecta of supernovae (SNe) and planetary nebulae (PNe), or in situ in the ISM (Draine 2009). While all three are likely contributing the dust content of the Universe, which mechanism dominates is an area of active study and a consensus has yet to be reached. The dust associated with each production mechanisms will vary in size, composition, and structure. Figure 2 shows example spectra of oxygen-rich and carbon-rich AGB stars. Oxygen-rich stars and SNe primarily produce silicates, whereas carbon-rich stars primarily produce carbon dust like PAHs and SiC (e.g., Jones et al. 2012). Interstellar dust has spectral features for both silicate and carbon grains, which indicates that both carbon-rich and oxygen-rich sources are necessary. Nevertheless, anomalous silicates and the abundance of interstellar metals cannot be fully explained without dust accretion directly from the ISM. Roughly 15% of these silicates and most interstellar metals in dust are expected to condense directly within the ISM and not from stars (e.g., Zhukovska et al. 2018).

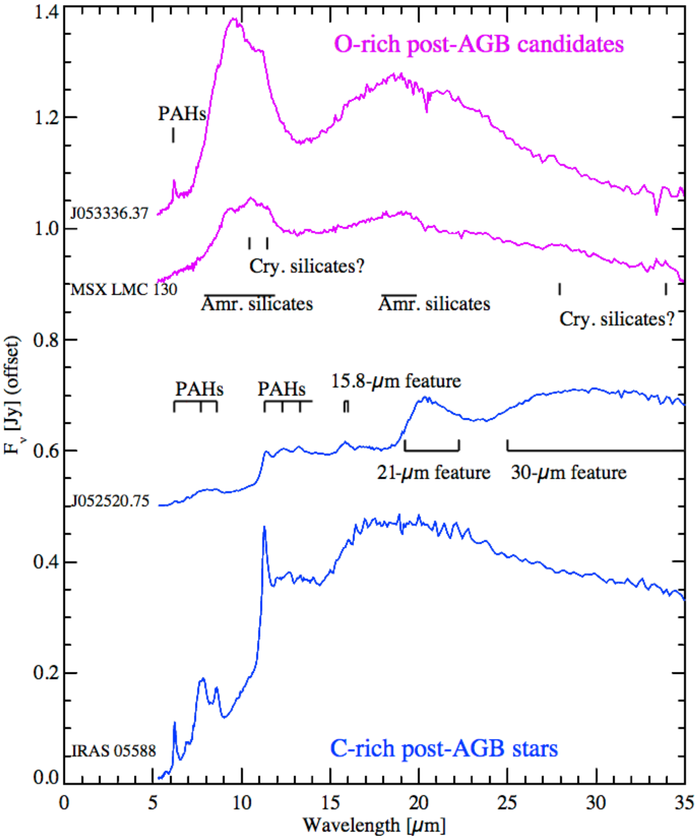

Figure 2: *Spitzer dust spectra for oxygen-rich (purple) and carbon-rich (blue) AGB stars (modified from Matsuura et al. 2014). Key dust spectral features (amorphous silicates, crystalline silicates, and PAHs) are also labeled. Note that the oxygen-rich stars produce mostly silicates, whereas the carbon-rich stars produce mostly carbonaceous dust or PAHs. Unlabeled spectral features at 15.8 μm, 21 μm, and 30 μm are attributed to multiple carbonaceous materials.*

Figure 2 illustrates several key spectral features that can be used to identify the dust produced by the outflows of

AGB stars. These features include silicate bands at ~ 9.8 μm and 18 μm and several bands between 5-15 μm from PAHs. The shape and position of these spectral bands reveal the dust structure and composition. Broad, featureless lines indicate amorphous (disordered) molecular structure, whereas discrete narrow features indicate crystalline (ordered) structures (Henning 2010). In the Milky Way, at least 95% of interstellar silicate dust is amorphous and roughly 15% of interstellar carbon is in PAHs (Draine 2003).

Canadians are leaders in investigations of carbon dust in a variety of environments, including PAHs in the outflows of Wolf-Rayet stars (Marchenko & Moffat 2017) and the ISM (Peeters et al. 2017), and fullerenes in the ISM (Cami et al. 2010). Canadians are also key players in the Nearby Evolved Stars Survey (NESS), a large program with the Canada-France-Hawaii Telescope (CFHT) and James Clerk Maxwell Telescope (JCMT) to constrain the dust yields, sizes, and features produced by AGB stars (Dharmawardena et al. 2019; Scicluna et al., in prep). AGB stars are expected to be a large source of carbon necessary for PAHs, an important opacity feature at UV to infrared wavelengths. While PAHs are abundant and widespread, their actual molecular structure is unknown. The first detection of a simple, single aromatic carbon molecule was only possible in the past year (McGuire et al. 2018).

Dust production in a complex, multi-phase ISM is also closely linked to dust destruction. Dust reformation in the ISM will produce primarily amorphous silicates or carbon-based materials that are able to condense and grow under constant UV photoexcitation (Draine 2009). Crystalline silicates are likely produced from thermal processes in stellar sources. For example, AGB winds show silicate crystallinity fractions of $\sim 10\%$ that may correlate with outflow energy and SNe shocks that sputter or shatter grains will preferentially remove metals (Jones et al. 2012; Matsuura et al. 2019), thereby changing dust mineralogy and spectral line features from their constitutions at production. Thus, we must study how stardust and ISM dust each form in different environments within the local universe and how long those grains will last in the ISM.

2.2 Dust as a tracer of star and planet formation

Stars and planets form in cold, densest regions of molecular clouds and disks, respectively, where dust grains are expected to grow from micron sizes seen in clouds and the ISM to planets in $\sim 10^{6-7}$ yr (e.g., Testi et al. 2014). Indeed, dust scattering at mid-infrared (MIR) wavelengths around clouds and at (sub)millimeter wavelengths in protoplanetary disks indicate grains may reach sizes of up to ~ 1 μm and ~ 100 μm, respectively (e.g., Pagani et al. 2010; Kataoka et al. 2015).

Dust growth affects its opacity, a fundamental quantity that is necessary to convert thermal emission into mass. Figure 3 shows how larger dust grains in cores have higher opacities than ISM dust, and these opacities are expected to increase further from grain growth in disks. Measuring accurate dust opacities, however, is a significant challenge. Dust opacity can vary with grain structure, metallicity, and ice content (e.g., Demyk et al. 2017; Ysard et al. 2018), and measurements are complicated by degeneracies with dust temperature (Shetty et al. 2009) or uncertainties from high optical depths, particularly in disks. Due to these challenges, most studies assume a dust opacity value based on models, and these values can vary by factors of a few. Improvements in dust opacity through direct observations are crucial to assess masses, gravitational stabilities and star formation potentials of clouds, cores, and disks.

Canadians are leaders in probing dust sizes and structures in star-forming regions through several key dust continuum and dust polarization surveys using *Herschel*, *Planck*, and the JCMT. The *Herschel* Gould Belt Survey (HGBS) and JCMT Gould Belt Survey (JGBS) sampled over ten nearby clouds in continuum observations between 70 μm and 850 μm, with the goal of identifying star-forming structures via dust emission. As members of both surveys, Canadian astronomers were the first to combine these datasets to also study dust opacities in these clouds (Sadavoy et al. 2013; Chen et al. 2016). More recently, there has been a coordinated effort to combine observations of near-infrared extinction from the CFHT with thermal dust emission from *Herschel* to constrain dust opacities in nearby clouds (Webb et al. 2017) and to use dust polarization measurements to constrain grain alignment efficiencies (Pattle et al. 2019), each of which were led by Canadian astronomers or involve Canadian participation. The POL-2 polarimeter for the JCMT, developed by Pierre Bastien at the Université de Montreal, is a key component of using dust polarization as a constraint for grain growth and shape. Canadians are actively involved in the B-fields of

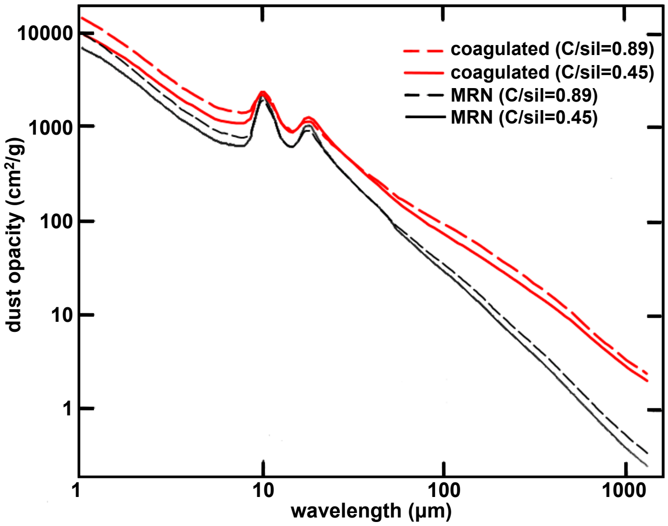

Figure 3: *Models of dust opacity for gas densities typical of dense cores. These curves compare ISM-like dust (MRN) with coagulated dust (after 10^5 yr at a gas density of 10^6 cm^{-3}), and at different ratios of carbonaceous dust (C) to silicate dust (sil). In general, dust opacity is higher for larger dust grains and more carbon-rich dust. This image was modified from Ossenkopf & Henning (1994).*

Star Forming Regions (BISTRO) surveys that use POL-2 to sample dust polarization of nearby clouds (e.g., Coudé et al. 2019). These studies showcase how Canada is a leader in observational studies of dust in nearby clouds.

Grain growth in clouds is only one part of the transition to form a planet. Most dust grain growth occurs within disks around young stars. Canadians are actively involved in observational studies of disks at both early and late stages of their evolution. These studies include the Disc Emission via Bias-free Reconnaissance in the Infrared/Submillimeter (DEBRIS) survey, a *Herschel* key program led by Brenda Matthews at NRC, to participation in surveys of disks with the Atacama Large Millimeter Array (ALMA), where disks are spatially resolved at (sub)millimeter wavelengths (Mann et al. 2014; Eisner et al. 2018; van de Marel et al. 2019). (See the white paper on protoplanetary disks by van der Marel.) Canadian scientists are prominent ALMA users and also provide regional support for ALMA. Canada is also highly involved in connecting disk properties to planet formation. Numerical models of dust coagulation in disks (e.g., Birnstiel et al. 2010) indicate that millimeter-sized dust should form quickly in the inner 10 au, but it is difficult to infer grain sizes in disks from observations due to complex geometries and temperature structures. Instead, theoretical studies have shown that polarized emission from Rayleigh self-scattering processes in disks (Kataoka et al. 2015; Yang et al. 2017) are a promising mechanism to constrain grain sizes. Already, there are ongoing projects within the community to use this new approach to investigate planet formation (Sadavoy et al. 2019).

Canada has a strong presence in studying dust in nearby galaxies as well, including several surveys with *Herschel* (e.g., KINGFISH, H-ATLAS; Maddox et al. 2018) and a number of large programs with the JCMT (JINGLE, JINGLE-2, HASHTAG). Similar to Galactic clouds, Canadians are combining *Herschel* and JCMT data to identify changes in dust grains (Lamperti et al. 2019). There is also the Canadian-led ACS Virgo Cluster Survey with the Hubble Space Telescope, which measured dust in elliptical galaxies of the Virgo cluster (Ferrarese et al. 2006), and a number of infrared projects to study dust composition and PAHs in nearby galaxies (e.g., Maragkoudakis et al. 2018). Observations measured for nearby galaxies are critical to determine how dust varies in different environments so that we can tune theoretical models (e.g., Jones et al. 2013) and to infer the dust properties in the more distant Universe.

2.3 Dust grain properties across cosmic time

Canada has a rich history in investigating the high redshift ($z > 1$) Universe (Lilly et al. 1996). Dust is an important tracer of the high redshift Universe, since the bulk of emission from these galaxies is produced by dust. These dust grains, however, may be vastly different from what we see in the local Universe. High-redshift galaxies have different environments than local galaxies and vastly different timescales for dust processing. The dust life cycle in the Milky Way has been active for $\sim$ 10 Gyr, whereas galaxies at $z > 5$ have had less time ($\lesssim$ 1 Gyr) to enrich their ISMs with metals from stellar evolution and allow for grain regrowth. Nevertheless, some high-redshift galaxies have substantial dust emission (e.g., Vieira et al. 2013; Scoville et al. 2016) and inferred dust reservoirs that are larger than the Milky Way's ($> 10^8$ $M_\odot$; e.g., Marrone et al. 2018). Although these inferred dust masses are unreliable due to incomplete knowledge of high-redshift dust (Imara et al. 2018), the presence of large quantities of dust in galaxies at $z > 5$ indicates that star formation and dust production must occur very quickly.

The origin and growth of high-redshift dust is an open question, but the processes must occur on relatively short timescales (Draine 2009). Figure 4 shows a model for how early galaxies could obtain their dust masses. There is significant debate about the contribution of AGB stars at high redshifts, with some studies saying that core-collapse SNe should dominate (e.g., Galliano et al. 2008; Nozawa et al. 2009) with others finding that AGB stars could be significant if early galaxies have high star formation rates (> 1000 $M_\odot$ yr^{-1}) and top-heavy initial mass functions (Valiante et al. 2009; Dwek & Cherchneff 2011). AGB stars are important for the production of carbon dust (e.g., PAHs), as these grains are necessary for UV absorption in the spectra of high redshift galaxies (Casey et al. 2014).

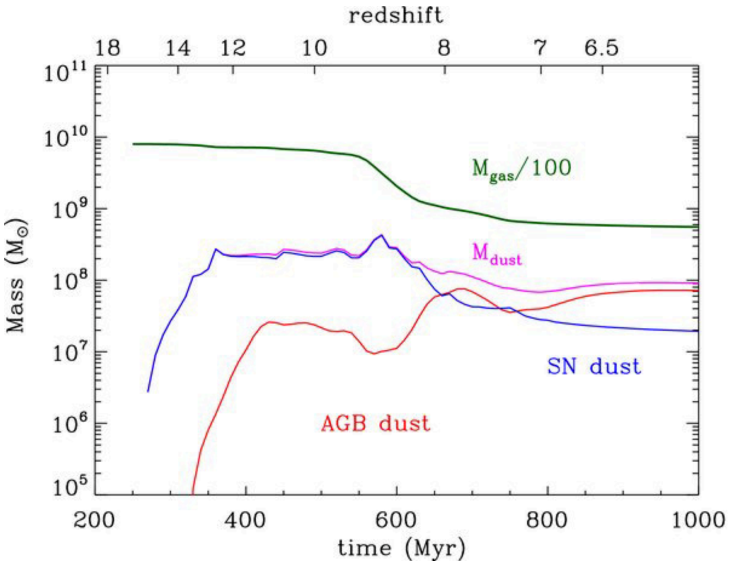

Figure 4: *Evolution of dust mass at early epochs for a starburst galaxy assuming a specific star formation law (from Dwek & Cherchneff 2011). The curves show the total dust mass (purple) and the relative contributions from AGB dust (red) and SN dust (blue). The gas mass in the model is shown in green. Note that several exceptionally dusty high-redshift* ($z > 6$) *galaxies have inferred dust masses of* 10^{8-9} $M_\odot$ *(Bertoldi et al. 2003; Beelen et al. 2006; Marrone et al. 2018).*

High-redshift galaxies primarily emit radiation at (sub)millimeter wavelengths, e.g., they are often called submillimeter galaxies or SMGs. Canadians are leading or involved in a number of SMG surveys with both single-dish telescopes and interferometers. Key programs like HERMES and H-GOODS with *Herschel* and S2CLS with the JCMT (e.g., Geach et al. 2013) were vital programs to identify SMGs that could be followed-up with higher resolution observations from interferometers to determine their true dust content and star formation histories (e.g. Hill et al. 2018). More recently, there are several ongoing JCMT large programs (STUDIES, S2-COSMOS) led by Scott Chapman at Dalhousie using the SCUBA-2 instrument to observe SMGs and there are Canadian contributions to large ALMA surveys of SMGs in the GOODS, COSMOS and Hubble Ultra Deep Field (e.g., Dunlop et al. 2017). In spite of these large surveys, very high redshift galaxies $z > 6$ are still rare. Larger samples are necessary to trace dust properties best over cosmic time.

The dust composition in these early galaxies must also be probed, something that is difficult with current instrumentation. Questions about the composition of dust at high redshifts can be addressed by comparing those systems with more nearby galaxies, which exhibit a range of properties from low-metallicities to starbursts (e.g., Galliano et al. 2018). Moreover, observations of a variety of environments within the Milky Way (e.g., Galactic center, high latitude clouds) offer the chance to resolve spatially dusty structures and determine the conditions surrounding the formation of the first stars. At present, such observations of local dust are piecemeal or incomplete. For example, there are limited observational studies of dust produced by SNe in low-metallicity environments to compare with dust composition studies at high redshifts. Key spectral features are shifted to mid-infrared (MIR) and FIR wavelengths and require highly sensitive detectors to identify spectral signatures.

3 Canadian Participation

Investigation of the life cycle of dust must combine laboratory measurements and models with multi-wavelength observations that constrain dust scattering, extinction, emission, and polarization signatures. Laboratories provide the necessary templates to identify dust compositions and can trace how grain properties under different conditions affect dust opacities (e.g., Demyk et al. 2017) and models test dust extinction, polarization, and scattering processes (e.g., Ysard et al. 2018). Large, unbiased, statistical studies of dust throughout the ISM in different environments within the Milky Way and out to high redshifts are still needed to understand the dust life cycle fully.

Canadian researchers are already leading a number of research initiatives that explore dust locally and out to high redshifts. For this white paper, we describe how Canada can continue to hold key roles in studies of dust properties by building on our current expertise and looking ahead to the next generation of instruments. Access to these next generation facilities is paramount to our continued success in dust characterization. We refer the LRP panel to the specific facility white papers for their details and instead highlight what science is possible with them.

1. Dust production in the local universe: As highlighted in Section 2.1, dust can form from stars (stardust) or in situ from the ISM. The composition and structure of the resulting grains can differ considerably, and there are no strong constraints regarding which mechanism dominates or how well the dust is mixed in the ISM. Key questions to answer are: (1) How much dust is produced by stars compared to the ISM? (2) Can stardust explain the dust content in the Milky Way or other galaxies or is most dust ISM generated? (3) What are the dust signatures from each source? (4) What fraction of metals are locked up in dust? (5) How does dust composition vary in different environments (e.g., dwarf galaxies versus the Galactic Center)?

Current instrumentation has touched on dust composition from evolved stars and the ISM, but larger studies probing a range of environments are still necessary. Multi-epoch observations will also be key to identify differences in dust compositions and sizes following destructive events. Current facilities are able to touch on these elements (CFHT, Green Bank Telescope, GBT), but future facilities across a wide spectrum of wavelengths will enhance this work. Canadians are involved in and co-leading a large James Webb Space Telescope (JWST) program on Radiative Feedback from Massive Stars (ID 1288) that will investigate the processing and formation (in the ISM) of carbonaceous molecules and dust in the photodissociation region of the Orion Bar. We also need access to wavelengths at UV and mid-infrared to capture spectral features from a wide range of dust particles. The proposed, Canadian-led CASTOR mission will provide critical UV wavelength coverage to probe key carbonaceous and PAH spectral features. Also, the proposed SPICA and *Origins* missions are space telescopes at MIR and FIR wavelengths that will enable us to target key silicate and carbonaceous features which are less confused at longer wavelengths. The proposed facilities have instrument designs that will benefit greatly from Canadian expertise and include Canadian participation in the mission designs. For PAH identification, we also require access to sensitive low frequency observations to identify these large molecules. The proposed ngVLA and SKA interferometers, both of which have strong Canadian presence, will enable the identification of these elusive molecules with much higher sensitivity than the single-dish GBT. Finally, we require continuum detectors at FIR and submillimeter wavelengths to trace larger dust grains and to quantify the amount of dust produced. Proposed upgrades to the instrumentation for the JCMT and the proposed development of the large single-dish submillimeter telescopes (e.g., CCAT-p) will be powerful survey instruments to measure the total dust produced by AGB stars, SNe, and PNe events.

2. Dust composition and growth in star-forming clouds: Canada has been a leader in studies of dust grain growth in nearby clouds (Galactic and extragalactic), but these studies are still mostly piecemeal. We require larger samples that can produce statistically significant conclusions about the conditions under which grains are able to grow in size. In addition to grain sizes, we must also investigate grain composition to disentangle changes in dust opacity from dust composition and dust size. Key questions are: (1) What types of dust grains are generally found in clouds? (2) How to do these grains evolve as they move from the lower density environment of the diffuse cloud to a gravitationally unstable star-forming core? (3) When do we see ices? (4) How does dust grain growth affect opacities, reddening, and polarization? (5) How does dust grain growth vary with environment?

Dust in nearby clouds requires observations across a wide range of wavelengths in emission, extinction, scattering, spectral line, and polarization studies to constrain dust grain sizes, shapes, compositions, and structures. Current Canadian-led studies that combine *Herschel* and JCMT observations show variations in opacities in nearby clouds, but the full extent of these variations requires further exploration and much larger, more complete surveys. For continuum emission studies, we need access to cameras operating between MIR and (sub)millimeter wavelengths to constrain grain sizes in clouds. We require facilities like SPICA and *Origins*, which can trace both diffuse and dense dust material in nearby clouds, and higher resolution observations from single-dish facilities (e.g., JCMT and CCAT-p) or interferometers (ALMA) to extend these observations out to more distant clouds and nearby galaxies. For dust extinction and scattering, we need access to deep, NIR observations over large areas and multiple wavelengths (e.g., Dragonfly, LSST, WFIRST). Such observations will allow Canadian astronomers to constrain dust opacity laws and grain sizes in clouds, and better develop an overall model of dust. Spectral line capabilities are necessary to constrain dust composition prior to star and planet formation, and we need access to telescopes that can probe spectral line studies at NIR to FIR wavelengths. For example, the confirmed and proposed JWST, SPICA, and *Origins* mission have spectroscopic capabilities to detect a wide range of dust and ice features from ~ 1 μm to ~ 100 μm. Finally, we need access to multi-wavelength polarization studies at MIR to (sub)millimeter polarization to investigate dust polarization and grain evolution. Continued Canadian involvement in the JCMT, *Planck*, and in balloon-born polarimeters (e.g., previous BLAST-POL, upcoming BLAST-TNG) are a key element of our success in measuring dust polarization in nearby clouds (e.g., Fissel et al. 2016), and access to proposed polarimeters (SPICA, *Origins*, CCAT-p) will enable us to span wavelengths from 20 μm to 850 μm.

3. Dust as the building blocks for planets and life: Dust is a key tracer of disks around stars, from young protostellar disks to older debris disks. Dust grain growth and composition are both critical to planet formation and the origin of life. A number of important disk studies investigated either dust growth or dust composition in older disks, without combining them. In part, it is difficult to measure dust composition at early stages. When the disks are enshrouded by their host cloud, they are harder to detect. Future facilities will improve upon both. Key questions are: (1) What are the time scales for dust growth in disks? (2) How does dust grain growth vary with stellar properties or environmental properties? (3) What are the composition and structure of dust in disks? (4) How does dust composition vary with grain growth or disk mass? (5) How do dust grains affect astrochemistry and the formation of organic molecules?

Timescales for dust grain growth and dust compositions in disks are still open questions that require high resolution, multi-wavelength observations to disentangle competing factors from geometry, optical depth, and temperature. While ALMA has produced groundbreaking results on disks, many disks show evidence of high optical depths at 3 mm, the longest ALMA wavelength at present. We require access to interferometers that probe longer wavelengths. Such facilities will enable our community to detect larger grains in disks and trace optically thin material. The proposed development of a Band 1 receiver at ALMA (recall Canadian expertise for the Band 3 receivers) and Canadian participation in ngVLA and SKA will enable us to detect disks at > 7 mm and probe the growth of millimeter-sized and centimeter-sized grains in the inner radii of disks and detect planets in the process of forming. In addition, ALMA has demonstrated the power of using polarized dust emission as an additional constraint on grain sizes from self-scattering signatures. Polarization detections with the current VLA are limited to observing only the brightest disks at ~ 7 mm. The ngVLA will have substantially higher sensitivity to detect polarized dust scattering at longer wavelengths and constrain dust grain sizes of > 1 mm in high mass disks. We also require access to facilities that can detect dust composition and structure in disks, a cornerstone of planet formation. Meteorites have crystalline fractions of $\sim 20\%$, which is substantially higher than the ISM fraction of $< 5\%$ (Draine 2009), indicating that a lot of processing occurs between the ISM and the disk. NIR to FIR spectroscopic telescopes like JWST, SPICA, and *Origins* and radio instruments such as ngVLA and SKA will allow our community to constrain dust composition and PAHs using large samples of disks over different evolutionary stages, to determine when and how this processing occurs.

4. Dust in galaxies across cosmic time: There is a lot of debate about the dust content in the early Universe. Some observations show very dust-rich galaxies within the first 1 Gyr, but how such galaxies form is still unknown. Dust remains our best probe of high redshift galaxies, but we lack large samples of galaxies at very high redshift and knowledge of the composition of dust in those galaxies. Key questions are: (1) What is the dust content at the early universe? (2) What types of stars must have formed first to produce early dust? (3) How much dust is produced by the first stars? (4) Are dust opacities and extinction different between the early Universe and local Universe?

Previous studies of high redshift galaxies focus on dust continuum measurements at FIR to millimeter wavelengths, where the spectral energy distribution peaks. At high redshifts of $z > 1$, key spectral line features also move from UV, optical, and NIR wavelengths to MIR and FIR wavelengths. We need access to MIR to radio wavelengths to probe dust in the high redshift Universe. The *JWST* will have the sensitivity to enable dust composition studies in more extreme environments at $z \lesssim 3$ and toward the centers of starburst galaxies; the SPICA and *Origins* missions will offer high sensitivity studies of dust composition for $z \gtrsim 1$; and the ngVLA and SKA interferometers will capture dust at the highest redshifts ($z > 6$), where current samples of galaxies are limited. Canadian participation in these projects will be invaluable to exploring dust across cosmic time and build on Canadian expertise from deep continuum studies with the JCMT, *Herschel*, and ALMA. Both these single-dish and interferometric instruments will be used by the broader international community to study high redshift galaxies. Canadian leadership in these facilities will enable us to initiate large projects and characterize dust across a wide range of redshifts to trace the evolution of dust for different star formation histories and different galaxies.

Conclusions: Tackling dust requires combining data and expertise over many wavelengths. Canada has such expertise, from stars and stellar evolution, nearby star-forming clouds and planet-forming disks, and high redshifts out to the distant Universe. Those working on dust from these different angles will benefit from a vehicle to promote collaborations within in our community and continued access to world-class multi-wavelength ground-based and space-based telescopes. The Canadian community has demonstrated that when we have access to world-class telescopes, we are leaders in studies of dust. Canadian participation in the next generation of telescopes, such as SPICA, *Origins*, ngVLA, and the SKA, will enable us to not only lead timely, large, and statistically significant studies of dust in each discipline, but to also combine the information between disciplines and paint a complete picture of dust. In combination with ongoing laboratory work and dust modeling, we can uncover dust properties in the Milky Way, nearby galaxies, and the early Universe, and investigate not only how dust grains are produced, but also the timescales for them to grow and evolve in different environments.

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

The proposed initiative seeks to understand dust in different conditions so that we can more robustly use dust as a direct probe of physical properties (e.g., masses of high redshift galaxies, stellar ejecta, star-forming clouds, planet-forming disks) or correct for dust obscuration to obtain true measurements (e.g., quantifying the stellar content or star formation rates in dusty galaxies). Accurate dust parameters will yield better measurements of the fundamental quantities used to probe the Universe.

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

To achieve a collective science initiative into data, we must maintain direct access to new data (observational, theoretical, laboratory). We should maintain participation in current facilities and also look ahead to the next generation of technologies (e.g., SPICA, *Origins*, ngVLA, SKA). We also aim to start a dust community that can self-organize a splinter session within larger, national meetings (e.g., CASCA).

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

Canada is a world leader in multi-wavelength studies of dust from stellar, Galactic, and extragalactic research.

The Canadian community are recognized experts in utilizing existing facilities to conduct research in dust extinction, dust emission, and dust polarization, and in developing the technologies necessary for this research. We will continue to lead new science initiatives that probe the full dust life cycle.

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

There is tremendous support from the Canadian community for new instrumentation as evidenced by the instrument-specific white papers that can champion studies of interstellar dust. There is wide-spread interest in future space-based missions (e.g., SPICA, *Origins*) and future ground-based missions (CCAT-p, ngVLA), as well as upcoming projects (e.g., JWST) and new instrumentation at existing facilities (e.g., CFHT, JCMT) which are all valuable to studies of dust. In particular, the polarimeter design for SPICA will open up a completely new observation space in the FIR for dust studies, as this instrument will give polarization maps that are equivalent in terms of S/N to the continuum maps of *Herschel* at 250 μm.

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

This research program highlights research opportunities from current, upcoming, and far-future facilities that span the present and continue beyond 2030.

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

Not applicable

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

Not applicable

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?

The dust life cycle is very interdisciplinary. Dust combines laboratory measurements, theoretical models, and observational astronomers from a wide range of research areas, which will help support EDI within the astronomical community in Canada. Studies that investigate dust require large surveys to gather statistics for different conditions, and such datasets are highly valuable for HQP training and education. Many recent PhD theses have utilized current technologies to study various aspects of dust (e.g., Coudé et al. 2016, 2019; Hill et al. 2018; White et al. 2018), and the data output from the next generation facilities and the timely science questions about the nature of dust will continue to drive numerous thesis projects. Finally, dust is inherently linked to stellar explosions, planet formation, and the onset of star formation at the beginning of time, which will excite the public for outreach and education.

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