PLANETARY ASTRONOMY: MINOR PLANETS AND PLANET FORMATION.

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SUMMARY

Solar system studies of minor body populations provide unique perspectives into planet formation, since only in our Solar System can one explore in detail the physical, dynamical, and chemical evolution of planet formation over several orders of magnitude in scale.

A decade ago, Canadian activity in these topics by permanent researchers was limited to theoretical dynamics. Since the year 2000, the Canadian astronomy and planetary science community has made a long-term investment in people and is supplying those scientists with world-class ground-based and space-based resources to tackle these areas, which are a critical component to building a world-class 'tripod' in the planetary studies that will assuredly be the biggest wave of growth in astronomy over the next decade.

To remain competitive, the minor-planet community within Canada needs continued access to observational facilities that are at the forefront of time-resolved survey astronomy. This access should come either through participation in new facilities (such as the Large Synoptic Survey Telescope, LSST) or via enhancements to existing facilities such as the CFHT 'IMAKA project.

The nascent Canadian planetary science community that is engaged in space-based research programs, relies heavily on collaborations with international research partners. Increased levels of collaboration between the Canadian agencies responsible for Canada's space-based research projects (in particular the Canadian Space Agency) and the our international partners in the US, Europe and Asia, are strongly recommended. The pathways and funding cycles for such partnerships must be clearly and reliably managed.

The Canadian Space Agency, via projects like MOST and NEOSSAT, has established a role for micro-satellite based research in astronomy. The CSA should be encouraged to more formally establish a regularized program of micro-satellite research so that other areas of research within Canadian astronomy can derive greater benefit from specialized access to space based observing platforms.

1. SUMMARY OF RESEARCH ACTIVITIES COVERED BY THIS REPORT.

The minor-body belts of the Solar System provide tracers of the ancient and ongoing dynamical processes that have and are still sculpting the Solar System. These processes have retained imprints of the density and chemical distribution of the Sun's protoplanetary disk, retain memory of the speed and scale of giant-planet migration, tell us about the source of Earth's watery outer skin, provide the path back to the asteroid belt for the impactors like the one that terminated the reign of the dinosaurs, and tell us the stellar number density of stars in the Sun's birth cluster. This rich diversity of processes and observations derives from a field that is intensely multi-disciplinary and relies on a strong coupling between modelling and observations. Studies of the near-Earth objects, main-belt asteroids, trojans, Kuiper belt objects, and our Oort cloud all directly connect to theories and models of planet formation and evolution.

The planetary science community associated with astronomy in Canada has grown from nearly non-existent a decade ago to a major theme of active astronomical research in Canada. The pioneering observational efforts of Campbell, Walker and Yang (1988) opened the astronomical research community to the field of exoplanets. Similarly, the computational dynamics work lead by Duncan, Quinn and Tremmaine in the late 1980s laid out the framework for the new discoveries in the outer solar system. At the start of the previous LRP, few, if any, research faculty in Canada university departments were engaged in 'Planetary Astronomy'. Today, a decade later, Canadian planetary scientist lead projects in mapping the structure of the outer Solar System, detecting extra-solar planets, and mapping of the structure of planetary debris disks.

The study of 'planet formation and evolution' is going to be *the* growth industry in worldwide astronomy over the next decade. Positioning Canada for major role in this area requires a all three components of a 'tripod' of skills:

a. Studies of protoplanetary disks to explore the physical conditions of planet formation, (the subject of separate white paper).

b. an understanding of the evolution of planetary systems provided via small-body populations (developed in the rest of this white paper); this includes debris-disk research (see the protoplanetary disk white paper).

c. the ability to detect exoplanets (discussed in another white paper); characterization of exoplanets in any detail is probably beyond the next decade. These efforts need to be supported by the development of planetary structure theory (especially giant-planet structure) in the Canadian community.

In this report we outline some of the observational and modelling questions that are being investigated by the Canadian astronomers who are pursuing minor-planet science, along with the challenges this growing field is facing. The studies naturally divide into two types of studies: population studies (which provide information on the spatial distribution, dynamics, formation, and collisional processes by which planets are assembled) and physical studies (which focus on the properties of individual objects, aiming to constrain the thermal state and chemical properties that were present when the objects formed).

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2. POPULATION STUDIES

Our Sun's minor planets are divided into groups based on *dynamical* classification, with further refinement into families and classes on the basis of *spectral* (as a proxy for physical) properties. Both aspects hold information about the processes at work during the formation of the planetary system. The asteroid belt was coeval with terrestrial planet formation, while the Kuiper belt and Oort cloud were sculpted by the formation and dynamical evolution of the giant planets. The Jupiter trojans appear to provide a captured reservoir from the ancient asteroidal region while the Neptune's trojans may provide clues to the source region of the Kuiper belt. The minor planets also provide insights into the processes that are still actively operating in the Solar System. In particular, the short-lived Near-Earth Object (NEO) population, that is constantly re-supplied from the slowly-eroding asteroid belt, is responsible for the crater-recorded impact chronology in plain sight on terrestrial surfaces. In a similar way, the tiny fraction of comets which approach the Sun and become active reveal the dynamics and structure of the Kuiper belt and Oort cloud.

Discovery surveys for minor planet belts require large-format, wide field-of-view cameras to allow the efficient acquisition of samples of objects large enough to make statistically-meaningful statements. Since LRP-2000 the majority of Canadian research in this field has utilized the Canada-France-Hawaii telescope's Megacam facility. Covering one degree of sky and achieving a flux limit of R$\sim$24 in only 60 seconds of exposure, the facility is ideally suited to discovery and tracking of solar system bodies. This capability has led to Megacam being used to search for NEOs, main-belt asteroids, Trojans of several planets, and Kuiper belt objects. In what follows, we proceed outward from the Sun

CFHT-Megacam has been used to conduct surveys for **near-Earth objects** (NEOs) and Earth Trojans, resulting in the discovery of a number of dynamically interesting 'quasi satellites' of the Earth (6) and a number of NEOs with non-zero Earth-collision cross-sections. Due to dedicated ground-based telescopic surveys in the USA, the last decade has seen a dramatic increase in the known NEO population, with over 6,000 now observed including the majority of the population projected to be larger than 1 km in diameter. Albedo and/or spectral data, however, are available for only a small fraction of the discovered population, making size estimates for most objects highly uncertain (a factor of 3 in size, with a corresponding order-of-magnitude uncertainty in mass). The last ten years have resulted in somewhat meaningful NEO size and orbital distributions, but recent population model revisions have included larger than anticipated numbers of Amor-class objects, more objects on high-inclination (and thus high collision velocity) orbits, and a factor of 2 drop in the NEO total population size. During October 2008, the extraordinary detection of a small NEO 2008 TC3, just before the object slammed into Earth's atmosphere, coupled with spectral observations, an accurate fall prediction, and subsequent recovery of fragments as meteorites on the ground, marked a first for asteroid research; meteorite fall recovery and subsequent physical studies are a historical and current strength of the Canadian small-body community, which allows these compositional investigations to be coupled back to the primordial processes in the asteroid-belt region. Returning to space, while over 85% of the D$>$1 km NEO population has now been discovered (based on model estimates), only 10% of the still-hazardous D$>$ 100m population is known. The need for discovery effort for asteroids in this size range was recently assessed by the Space Studies Board of the U.S. National Research Council in a report published January 2010. A variety of ground and space-based mission are recommended as routes to cataloguing this population of objects. The Near Earth Object Surveillance Satellite (NEOSSat, NESS project PI: Hildebrand), being constructed by the Canadian Space Agency, will begin to contribute to this effort after its expected launch in April 2011. The NEOSSat project has sparked a re-invigoration of Canadian NEO research, both in surveys and modelling of the impactor population. Asteroid search projects within Canada include the North Polar Cap survey being conducted at the University of Calgary and the extinct-comet search project at the University of Western Ontario. The U. Western Ontario study made spin-off use of the CFHTLS-VW imaging archive data via the CADC.

The first **Neptune Trojans** were discovered in 2004 and, while the more proximate Jupiter trojan population has been studied in some detail, our understanding of the physical and dynamical properties of the both of these populations would benefit greatly from a deep and wide-field survey; current surveys lack sufficient detail to accurately constrain the accretion history of these populations (35). The currently-favoured mechanisms for populating the trojan swarms is capture by sweeping resonances, or scattering into the resonance during the migration of the gas-giant planets (26; 28; 25). These same mechanisms may also be important for populating the Kuiper belt and Oort Cloud. The similar evolutionary tracts indicate a genetic link between the trojans and most, if not all, of the small body populations of the Solar System. This connection is a poorly understood one (27) and understanding of planetesimal accretion and evolution will remain incomplete unless the similarities and differences in the properties of the trojan and other small body populations can be accounted for.

The outermost **irregular satellites** of the giant planets were a great success story for Canadian planetary astronomy, again enabled by wide-field optical capabilities of the CFH12k and Megacam mosaic cameras. These objects were captured into orbit around the giant planets late in their evolution, and thus constrain the dynamical environment (number of planetesimals, orbital distribution, planetary locations) and probably the circumplanetary gas environment during the capture phase. Large-area surveys (11; 12; 17; 20). around the giant planets detected these irregular-moon populations, leading to colour studies via broad-band photometry and low-resolution spectroscopy. The combined dynamical and surface properties show that the smaller moons are the collisional fragments of a smaller number of large moons captured by the giants long ago.

The **Kuiper Belt**'s minor planets were the subject of the biggest telescopic investment in Canadian planetary astronomy of the last decade. The Canada-France-Ecliptic Plane Survey (CFEPS) project, the science driver for the Very Wide component of the CFHT Legacy Survey, begun in 2003, represents both one of the great successes and failures within this research community. The wide field of the camera coupled with the ability of queue scheduling to implement the critical time cadence needed for the orbit determination of $>$1000 objects made this the best platform in the world for this multi-year science. Unfortunately the impact was blunted when discovery operations ceased in 2005 (see the CFHT white paper). CFEPS still discovered and tracked 215 new Kuiper belt objects and provides the first detailed measurement of the size and structure of the main Kuiper belt components

(21). The CFEPS project is continuing with PI-program extensions to high to mid-latitudes, attempting to map out the more sparsely populated 'scattering disk' which appears to be the source of Jupiter-family comets. Totally unexpected orbits for Kuiper Belt objects have been found, ranging from the most distant nearly-circular ($e < 0.1$) orbit (1) to a stunning retrograde trans-neptunian orbit (14). The availability of a wide field imager on the CFHT platform enabled Canadian research astronomers to become world-class competitors in the field of outer Solar System surveys (in fact, all other search programs shut down in face of this competition). As a side benefit, >10,000 observations of asteroid positions were measured using the CFHTLS-VW observations and submitted to the IAU's Minor Planet Centre (the clearing house responsible for the orbits of minor bodies), helping to complete the inventory of our Solar System and study its compositional gradients (32).

The possibility of a partnership with the Large Synoptic Survey Telescope (LSST, 8m telescope with 10-degree FOV + IQ=0.8" FWHM at 600nm, first light expected in 2015?) is desirous, as among its other scientific output, the project will catalog virtually every moving object in the Solar system brighter than m(R)$\sim$ 24.5. Combined partnerships in both the LSST and Hyper-Suprime-Camera on the Subaru telescope (8m telescope with 2-degree FOV + IQ=0.35" FWHM at 600nm, first light expected in 2011) or perhaps the implementation of CFHT 'IMAKA would enable Canadian astronomers to achieve continued excellence in wide-field surveys of the Solar system's planetesimal populations (12; 9; 21).

Surveys for members of the **Oort Cloud**, the region of the Solar System extending from beyond 1000 to >10,000 AU is stymied by the faintness of the population, resulting from the D^4 brightness fall-off for sources seen in reflected light. Sedna, the only putative member of the Inner Oort cloud known today, was discovered in a survey of some 20,000 square degrees to to a depth of R$\sim$21. In the 1000 or so square degrees of sky imaged to depths of R$\sim$24, CFHT has found no members of the Oort cloud, only slightly in conflict with the population estimates scaled from Sedna's detection. Deeper surveys covering wider sky areas will be needed before members of the inner edge of the Oort cloud can be detected and this population characterized. Based on theoretical models produced since the 2003 discovery of Sedna, the existence of the so-called inner Oort Cloud is a strong constraint on the structure of the Sun's birth cluster.

Occultation studies are likely the only viable method to allow direct detection of members of the Oort cloud. At this time a number of international teams are pursuing projects to construct space based observatories capable of detecting the Oort cloud and Kuiper belt via serendipitous stellar occultation. Probing this population via a space-based occultation experiment was funded by a CSA pre-phase A study (the OCLE-DOCLE experiment). Unfortunately, there is no programmatic/regularized program in place to continue development of this project within Canada.

2.1. *Physical Properties*

The minor body belts of the solar system also provide accessible and relatively unprocessed samples of the primordial nebula. The degree of processing depends on the size of the object (due to self gravity) and the distance from the Sun (irradiation and space weathering). Interpretation of reflectance spectra is complicated by the poorly understood ice sublimation and surface chemistries driven by solar and cosmic ray irradiation (see for example 4; 18). The amount of surface modification a body has undergone depends heavily on its orbit. For example, Kuiper belt objects appear icy with some organic products (2; 29), centaurs - objects that have emerged from the Kuiper belt into the gas-giant region - appear spectroscopy similar to, but detectably different than the KBOs (30), and the Jupiter trojans and asteroids, whose surfaces have been completely de-volatised by solar irradiation, have little to no detectable ice on their surfaces (33; 5). See Fig. 1.

A new class of object, **main belt comets** appear to be cometary-like objects that have become lodged in the asteroid belt. These objects may represent the tail end of a population of outer solar system material that was scattered through the asteroid belt late in the formation of the giant planets. Following a report in 2006 of these unexpected comet-like objects being observed in the main asteroid belt (16), Canadian astronomers used the CFHTLS-VW data to undertake the first observational survey for these objects (10). This survey relied solely on the archival imaging data of the CFHTLS-VW project, accessed via the CADC.

Low resolution spectroscopy in the optical and infrared ($0.5-2.5\mu$m) is one of the few types of observations that can provide detailed compositional information about specific objects surfaces (see Fig. 1). Such techniques have been successfully applied to the Jupiter trojans, revealing them as iceless, heavily-processed bodies resembling the main-belt asteroid population (33). Spectral confirmation/detection of main belt comets requires significant access to 4-meter size telescopes with Near IR spectroscopic capability, something which is completely absent in the Canadian community.

In the outer solar system, all but the brightest Neptune trojans and Kuiper belt objects are too faint for the spectroscopic capabilities of existing telescope facilities. The James-Webb Space Telescope and the TMT are the obvious solutions; both will have superior image quality and aperture, enabling these observations. These future facilities will have sufficient sensitivity to detect the signatures of the various chemical processes (primarily organic hydrocarbons) which are the consequence of surface irradiation processing. Canadians should take advantage of their future access to these facilities and direct their efforts to this area of research currently not performed by the Canadian community.

Spectroscopy of Oort cloud objects is possible when they appear in the sky as long-period comets. Such observations provide an excellent probe of the primitive (unprocessed) material in the forming Solar System, especially H_2O. Of particular interest has been the measurement of the D/H ratio in these primitive waters as that ratio is indicative of the temperature/density conditions in the disk. Currently only three long period comets (Hale Bopp, Hyakutake and Halley) have had their D/H ratios measured via spectroscopic analysis. Observations of the required line ratios (at 400-500 GHz) are currently feasible using the JCMT and CSO for only the brightest cometary sources. Access to these frequency bands using a larger collecting area, perhaps through the 'total power' configuration of ALMA will be critically important for the field of cometary chemistry.

2.2. *Size distributions*

The signatures of planetesimal accretion and collisions is recorded in the size distribution of the minor-body belts. In the NEO population we can read the size distribution from recent collision events, which then inform strength and collision modelling. The asteroid belt collisional families are continuing to evolve dynamically and measures of the Size Distribution Function (SDF) of the asteroids is an excellent probe of the properties of collisions today. In the Kuiper belt, the large object (D > 100km) SDF appears to retain the signature of the accretion process, while indicating that some dynamical process(es) caused a rapid depletion in the number density of minor planets of the outer Solar System, effectively terminating collisional evolution among the largest members. Recently-detected members of the 'dwarf planet' class of objects appear to follow a SDF that is decoupled from the smaller (1000km < D < 100km) size range.

The CFHT Megacam has been an indispensable tool for such surveys. With dedicated observing efforts, depths as faint as $m(R) \sim 26$ have been achieved in moving object surveys (9). However, progress in each of these belts and discovery of the clues to planet formation contained in their size distributions require surveys of many square degrees to depths of R>28 to enable detection of a sample significant enough to enable the measurements of the SDF. No currently operating facility provides this capability. The access of Suprime-cam granted to Canadians through the Gemini-Subaru time-exchange has proved fruitful for Canadian moving object surveys (see for example 8; 14). With Hyper-Suprime-cam soon to be commissioned, the Gemini-Subaru partnership is all the more paramount; Hyper-Suprime-cam will easily be the most efficient deep (m(R)$\sim$ 27) survey tool available in the next decade. Looking beyond the next decade, access to space based wide-field imaging capability will be needed.

3. FUTURE REQUIREMENTS

The health of the Canadian research community in this area has largely depending on access to the CFHT Megacam camera and its wide field imaging capability. The CFHT Megacam camera now has some direct competitors and, over the next decade, the current configuration will no longer provide a strategic advantage to the community. Facilities like SUBARU Hyper-Suprime-Cam (8m telescope with 2-degree FOV + IQ=0.35" FWHM at 600nm, first light expected in 2011), LSST (8m telescope with 10-degree FOV + IQ=0.8" FWHM at 600nm, first light expected in 2015?) will dramatically alter the landscape for minor-planet surveys, creating factors of 10 to 100 increases in the samples sizes of the known populations. If the CFHT 'IMAKA project were to reach fruition with currently-targeted performance levels, this platform would be competitive with Hyper-Suprime-Cam for planetary astronomy science. Canadian competitivity can be retained via access to these facilities and/or the data they produce.

4. RECOMMENDATIONS

- Access to LSST as a partner will be critically important to the minor-planet community. Not having access to this dataset and not participating in the acquisition of that data will leave the minor-planet community in Canada trailing very far behind the leading edge, although if 'IMAKA is available Canadians will be well place to exploit LSST data.
- Increased integration between the various 'planetary astronomy' research communities (the tripod mentioned in the introduction, along with planetary geology and geophysics links) in Canada will be critical to our future success. This integration may be achieved by establishing a regular series of 'planetary science' themed meetings, much like the theory/modelling communities 'Kingston meetings'.
- Improved access to low-resolution spectroscopy in the 1-3um region on 4m-8m telescopes is needed for surface property studies of Trojans and objects that appear to be extinct comets lodged in the asteroid belt during the late stages of planet formation.
- The involvement of the Canadian Space Agency is important to the future of this field, as space-based platforms like MOST and NEOSSat show that microsatellites can address forefront science issues. However, a more reliable programmatic path needs to exist that results in science projects chosen via scientific priorities (established by the community) that then proceed through a regular and repeatable selection program.
- Increased access to wide-field imaging, in the optical with Hyper-Suprime-Cam or perhaps 'IMAKA in the optical, and in the NIR with GLAO are essential if Canadian minor-planet astronomers are to remain competitive in the field of Luminosity Function science, which we have pioneered. While projects like the LSST will go a long ways to mapping the skies, the depth is not sufficient to characterize the small members of the outer solar system.
- Access to ALMA (particularly Band-8) to enable cometary molecular spectroscopy.

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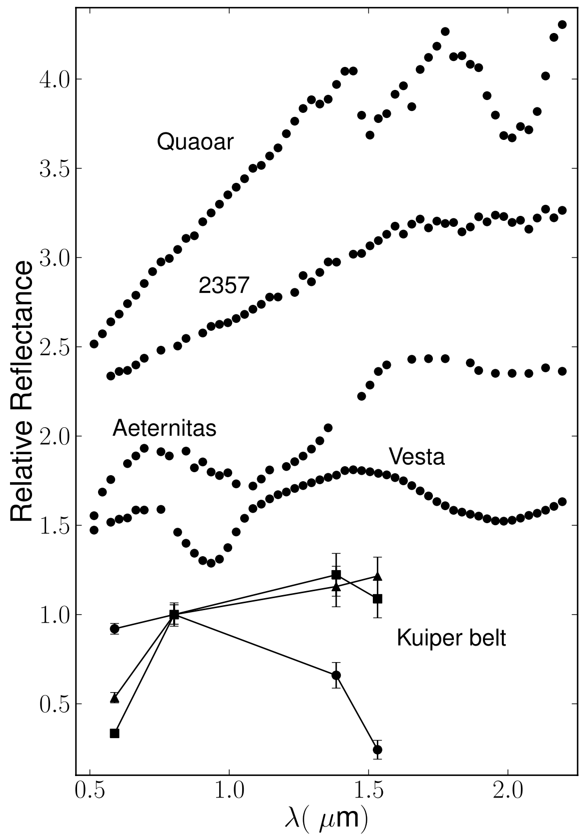

FIG. 1.— Relative reflectance of various typical small bodies of the Solar system, normalized at 0.8 μm. From top to bottom, offset in units of 0.5 for clarity: large icy Kuiper belt object Quaoar (Jewitt 2004), Jupiter trojan 2357 (Dotto et al. 2006), asteroid 446 Aeternitas (Golubeva 2001), Asteroid 2 Vesta (Book Asteroids 1), and typical Kuiper belt objects in decreasing water-ice content for circles, squares, and triangles. Large primordial Kuiper belt objects for which spectra can be obtained exhibit flat optical spectra, and ice absorption features such as the 1.5 μm water-ice feature detected on Quaoar. Jupiter trojans whose ice has been baked away exhibit carbon and tholin rich surfaces. From broad-band colours such as those shown for the Kuiper belt, compositional information such as water-ice content - from the spectral slope at 1.4-1.5 μm - can be determined. For reference, asteroid spectra are shown which exhibit common silicate spectral features at 1 and 1.2 μm. These silicate features are expected to occur on small, but icy Neptune trojans, and could also be identified with appropriate filter selection.