OBJECTS IN MIRROR ARE CLOSER THAN THEY APPEAR: The Roman Space Telescope as a Revolutionary Solar System Survey Machine

Roman Core Community Survey: High Latitude Wide Area Survey

Scientific categories: Solar system astronomy

Additional scientific keywords: Asteroids, Centaurs, Comets, Irregular Satellites, Minor Planets, Small Solar System Bodies, Surface Composition, Trans-Neptunian Objects

Submitting author: Bryan J. Holler (STScI; bholler@stsci.edu)

Contributing authors: Susan Benecchi (PSI), Richard Cosentino (STScI), Richard Cartwright (SETI), Rosemary Pike (SAO/CfA), Mike Alexandersen (SAO/CfA), Nathan Roth (Catholic U.), Teddy Kareta (Lowell Obs.), Max Mutchler (STScI), Stefanie Milam (NASA GSFC), Amy Simon (NASA GSFC)

Abstract: The era of astronomically big data is upon us, with NASA's next space observatory, the Nancy Grace Roman Space Telescope, set to launch in the next few years and operate in parallel with ground-based all-sky surveys. Although primarily designed as an astrophysics observatory, the nature of implementing its Core Community Surveys will produce data sets invaluable to solar system scientists that were once considered impossible. Planetary science has historically made use of smaller survey footprints close to the ecliptic and targeted studies of individual objects, but will benefit immensely from these large astrophysics surveys. Roman will revolutionize the study of solar system minor body populations, including the high-inclination populations of Centaurs, comets, and interstellar objects, as well as the distant trans-Neptunian objects, through observations made as part of its High Latitude Wide Area Survey. To further enhance the yield of new targets and increase the scientific value of the observations for solar system science, we discuss the possibility of extending a thin "spur" to lower ecliptic latitudes, maintaining the notional observing strategy of building tiles into sectors and ultimately passes, and adding imaging with the broad F146 filter for deeper investigations.

Solar system science cases. The solar system's minor bodies, including small asteroids, trans-Neptunian objects (TNOs), Centaurs, comets, and irregular satellites, and occasional interstellar objects (ISOs), are at the frontier of solar system astronomy. These different populations of small bodies record the original composition of the solar nebula (ours and others), the migration of the giant planets, and ongoing physical, chemical, and dynamical processes at work on primordial objects at different heliocentric distances. Basic characterization of these small bodies' orbits and surface colors for statistically significant samples in each of the numerous populations is key to improving our understanding of how the solar system formed and evolved. The Nancy Grace Roman Space Telescope and the Wide Field Instrument (WFI), with its large field of view (FOV), are well-suited to answer these big questions by studying known small bodies and discovering many new objects. In particular, Roman will be highly valuable for time-variable characterization of objects because it will not be subject to the 24-hour aliasing limitation of ground-based facilities. We highlight specific science cases below that would benefit from new discoveries and characterization of objects by Roman.

Asteroids. Asteroids reside in a variety of orbits throughout the inner solar system. They are primarily rocky in nature, but a handful show intermittent cometary activity and those at the furthest reaches show the spectral signatures of H_2O ice, organics, and salts. Many investigations have been performed to characterize this phase space in our solar system, however, Roman will still make significant contributions to object discoveries and characterization since it will be able to explore different regions of the sky compared to ground-based searches, and will observe objects in places where follow-up observations are less frequently made.

Irregular satellites. The origins of the giant planets' irregular satellites are not well understood. These likely captured objects may have originated in distinct heliocentric populations, proximal to each giant planet's sub-nebula. Alternatively, they may have originated from the primordial Kuiper belt at the edge of the solar nebula and were later scattered onto radically different orbits during giant planet migration and subsequently captured. Understanding the origin of irregular satellites is therefore a key piece of the puzzle for determining how the early solar system formed and evolved. Improved spectral color measurements of the irregular satellites, and more sensitive searches for smaller objects with Roman, will allow us to build better population statistics and investigate potential source populations.

High-inclination Centaurs. The Centaurs, a population of outer solar system objects on chaotic planet-crossing orbits, are thought to be derived from the dynamically-excited parts of the trans-Neptunian belt (Levison & Duncan 1997; Volk & Malhotra 2008), and are in turn the primary source of the Jupiter Family Comets (JFCs) in the inner solar system. However, Brasser et al. (2012) recognized that this cannot be the case for the high-inclination ($i \geq 30°$) and retrograde ($i \geq 90°$) Centaurs, which are more likely originate from the Oort cloud like the Halley-type comets (HTCs; Fig. 1). It is not clear how easily the high-inclination Centaurs can move into the inner solar system as JFCs, but some fraction of the low-inclination Centaurs should be Oort Cloud-derived as well. At present, the census of the high-inclination Centaurs is woefully incomplete and significantly biased to closer distances and larger sizes (only 192 known objects spanning a wide range of sizes and orbital distances). It has been estimated that there are ≤200 high-inclination

Centaurs with diameters >165 km, assuming a 5% albedo (Brasser et al., 2012). In other words, there could be >100 objects larger than 100 km across hidden on high-inclination, high-perihelion orbits in the outer solar system, or there could be just a handful. A well-characterized and deep survey could unravel how many objects there are and the unbiased inclination distribution. Typical ground-based surveys have been biased towards low orbital inclinations (i.e., towards the ecliptic), but Roman's High Latitude Wide Area Survey would allow for serendipitous detection of these objects, as well as being sensitive to objects of smaller sizes than current ground-based surveys permit.

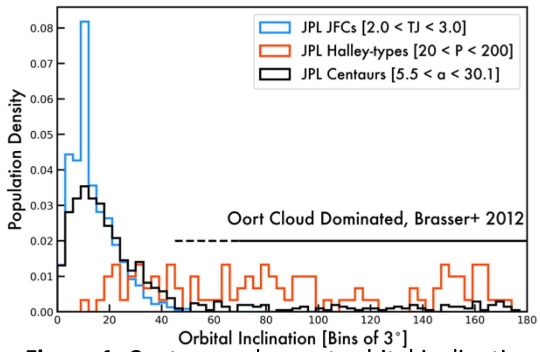

Figure 1: Centaur and comet orbital inclination distributions.

Comets and interstellar objects. During the era of planet formation, comets were assembled in the cold disk midplane and scattered into their present-day dynamical reservoirs in the Kuiper disk and the Oort cloud. Entombed in a deep-freeze for the last ~4.5 Gyr, they remain relatively unaltered, having suffered minimal thermal or radiative processing. As comets enter the inner solar system, solar insolation triggers volatile sublimation and forms an expanding atmosphere (the coma). Studies demonstrate that the cometary formation region was likely quite complex, with significant radial mixing and other processes leading to the accretion of cometary nuclei incorporating material from across the disk, both spatially and temporally (Willacy et al., 2022). Disentangling these signatures preserved in cometary nuclei requires comprehensive compositional information from a statistically significant sample. Furthermore, the recent discovery of the first active interstellar object (ISO), 2I/Borisov, and its remarkable composition compared to comets from our own solar system (Cordiner et al., 2020), has opened an entirely new window by enabling direct sampling of the midplane material in primitive stellar systems beyond our own. Roman's capabilities for identifying new non-sidereal objects within its large FOV will represent a giant leap forward in our ability to discover new comets and active ISOs for follow-up with facilities optimized for spectroscopy. Furthermore, its sensitivity will enable (1) the discovery of comets at larger heliocentric distances, before they begin significantly outgassing, and (2) the identification of ISOs with sufficient time to coordinate studies when they are at the brightest points in their perihelion passage, in contrast to the circumstances for the first ISO, 1I/'Oumuamua. Each new comet and ISO discovered by Roman will mark an opportunity for paradigm-challenging science.

Time-variable studies of small bodies. Surveys of small bodies have primarily focused on studies of objects at single snapshots in time providing information about the object dynamics, but less about object physical characteristics. Follow-on studies make sub-selections to learn about color, size, surface texture, shape, rotation, and binarity, among other properties. Earth-based studies suffer aliasing around the Earth's 24-hour rotation period. Space-based observations like Roman transcend this limitation and open an exciting phase space for de-biasing Earth-based observations. Studies of the K2 dataset (Szabó et al. 2020; Kecskeméthy 2023) have revealed far more long-period rotators among the small bodies than previously anticipated. Roman will be able to continue and enhance this work for small bodies at all heliocentric distances for both a larger sample and broader size range than previously achievable.

Trans-Neptunian objects (TNOs). The trans-Neptunian objects (TNOs; also known as Kuiper belt objects) preserve information relating to planet building processes in their orbital and physical properties. The trans-Neptunian region consists of many sub-populations and the orbital structure within these populations and ratios between populations provide constraints on the dynamical evolution of the solar system, both in physical space and in time. The orbit distribution seen among the >4000 known TNOs reveals that the giant planets did not form where they are today, but have migrated (e.g., Levison et al. 2004). This migration scattered and swept the TNOs outward, with the exact details (speed, granularity, etc.) determining the final distribution of TNOs (e.g., Li et al. 2014; Nesvorný & Vokrouhlický 2016). Further mapping of the distribution of TNOs through the discovery of additional objects would facilitate detailed testing of models of how the solar system formed and evolved. The Roman surveys will cover regions of the sky which are typically not searched for TNOs, such as off-ecliptic regions, the galactic bulge, and portions of the sky not accessible to the Rubin Legacy Survey of Space and Time (LSST; i.e., the northern hemisphere), so the vast majority of identifications will be new. The depth of these datasets will be beyond the typical wide-field, ground-based surveys providing for a more complete investigation of the full extent of the Kuiper belt disk (i.e., how far it extends). Of particular interest are the high-pericenter objects (Fig. 2), which probe the distant solar system and constrain the presence of possible additional planets through their on-sky angular distribution (Sheppard & Trujillo 2016) and inclination distribution (Kaib et al. 2019).

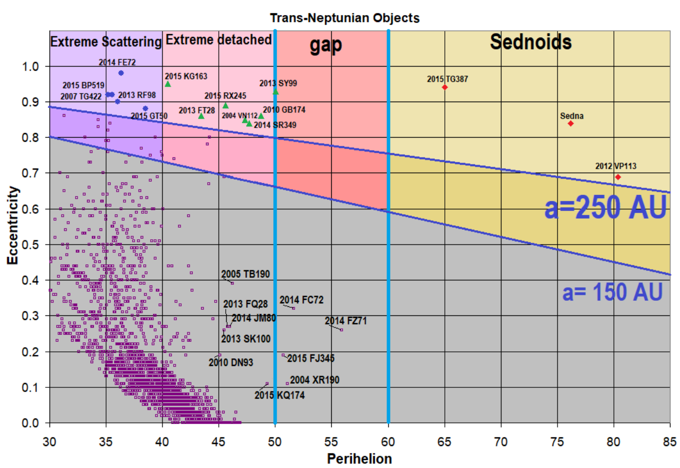

Figure 2: Eccentricity vs. pericenter/perihelion distance for known TNOs. (wikipedia.org)

Optimizing the High Latitude Wide Area Survey for solar system science. Discovery of new objects across the full range of dynamical classes, including those discussed above, is expected in both the Core Community Surveys (CCSs) and the PI-led Astrophysics Surveys. Small tweaks to the notional plan for the High Latitude Wide Area Survey (HLWAS), as well as maintaining other existing aspects, would further increase the survey's yield and significantly expand the impact for solar system science:

<u>*Placement and shape of the survey field.*</u> The reasoning for the "high ecliptic latitude" aspect of the HLWAS is well-justified: observations of distant galaxies require fields with lower foreground contamination from solar system minor bodies. However, it is exactly this "contamination" that we wish to study. We do not expect the high-latitude fields to be completely devoid of targets, as discussed above in the case of high-inclination Centaurs, comets, and ISOs, but given current statistics, we expect the yields of these objects to be relatively small, on the order of a few hundred total objects. Identifying new high-inclination objects is crucial to understanding the

formation and dynamical history of the solar system, but a higher-yield of new objects across all dynamical classes requires observations closer to the ecliptic. As such, we propose the idea of a thin “spur” extending away from the main survey field, perpendicular to the ecliptic, with an end no more than 20° from the ecliptic plane. Such a spur could be only 2 tiles wide and would significantly increase the yield of minor body discoveries. This would yield a “continuum” of sorts to connect Roman results with large-scale ground-based surveys, fully sampling the phase space. In addition, and perhaps more powerfully, an uninterrupted field extending from near the ecliptic pole to 20° in ecliptic latitude would provide a unique cross-section of inclinations across the full range of dynamical classes, leading to statistically meaningful inferences, that can be properly debiased, about the inclination distribution of the solar system’s minor body populations.

The location of the spur would have the largest solar system science gain if placed along the expected trajectory of the New Horizons (NH) spacecraft currently journeying through the Kupier belt. Currently, NH is searching for a second close encounter target. The observations of Arrokoth, the first TNO to be studied in-situ, revealed complex surface morphology. Its binary, pancake-like structure implies that planetesimal formation, in at least the low-inclination, low-eccentricity region of Kuiper belt, resulted from gravitational collapse of a cloud of pebbles rather than hierarchical accretion of collisional fragments (McKinnon et al. 2020; Nesvorný et al. 2021). NH is capable of supporting Roman observations along the proposed spur by looking at the same objects from high phase angles which can never be obtained from inner solar system geometries. Observations of small bodies at multiple phases allows thermal modeling to investigate surface and sub-surface inertia, roughness and regolith studies, and in some cases infer composition (Verbiscer et al. 2019, 2022). In short, Roman’s FOV and sensitivity allow for greater chances of finding another encounter object for NH, and in doing so it would also characterize the phase space in the Kuiper belt to a previously unprecedented level.

Maintain the tile/sector/pass concept. As described in the notional design of the HLWAS individual tiles will be composed of either 2, 3, or 4 dithers, with 32 tiles making up a sector, and 155 sectors composing the entirety of the survey field. To reduce filter wheel movements and thereby extend the lifetime of the mechanism, all 32 tiles of a sector would be observed in a single filter before switching to the next filter (or grism). This design would be extremely advantageous for identifying moving targets in WFI images because it would require multiple hours between observations of the same tile in different filters. If we assume 300 seconds per dither and a 3-point dither, this would require 8 hours of exposure time just to cover a single 32-tile sector. Assuming 2 hours of overheads, or 10 hours between observations of the same tile, we could detect 1 pixel’s worth (0.11”) of movement for an object at ~565 au and 10 pixels’ worth of movement for an object at ~120 au. The most distant solar system object yet discovered (2018 AG_{37}) was at ~132 au, so single image detections representative of known objects would move far enough with respect to the background stars between visits to be easily identified. However, Roman also provides a critical sensitivity to slower moving objects, which are challenging to identify, link, and track using ground-based surveys. We note that significant changes to the notional design could be detrimental to such exciting discovery possibilities. Shrinking the time-spacing between visits to the same tile by a factor of 2 would likewise limit the distance sensitivity of the survey by a factor of ~1.6, limiting detectable single-pixel movement to objects at ~75 au, a distance regime that can be, and has been, explored using ground-based facilities.

Add observations with the F146 filter. A crucial enhancement to the HLWAS would be the inclusion of the broadest filter to the cycle of filters and grisms. The F146 filter covers ~0.9 – 2.0 µm and thus would provide the deepest possible imaging in a given exposure time, nearly 1 AB magnitude fainter than the most sensitive filters included in the notional design (F106, F129, F158, and F184). This increased imaging depth translates to the detection of more distant and smaller objects at a particular distance, thus reducing observation bias towards brighter, larger objects. At a minimum, it would be advantageous to add the F146 filter to sectors included in the proposed spur and extending in an uninterrupted line to the northernmost ecliptic latitude of the survey field, producing a stripe of deep F146 images across 10s of degrees of ecliptic latitude.

References

Brasser, R., et al., 2012. An Oort cloud origin for the high-inclination, high-perihelion Centaurs. MNRAS 420, 3396-3402.

Cordiner, M. A., et al., 2020. Unusually high CO abundance of the first active interstellar comet. Nature Astronomy 4, 861-866.

Kaib, N. A., et al., 2019. OSSOS. XV. Probing the distant solar system with observed scattering TNOs. AJ 158, 43.

Kecskeméthy, V., et al., 2023. Light curves of trans-Neptunian objects from the K2 mission of the Kepler Space Telescope. ApJS 264, 18.

Levison, H. F., Duncan, M. J., 1997. From the Kuiper belt to Jupiter-family comets: The spatial distribution of ecliptic comets. Icarus 127, 13-32.

Levison, H. F., et al., 2004. Sculpting the Kuiper belt by a stellar encounter: Constraints from the Oort cloud and scattered disk. AJ 128, 2553-2563.

Li, J., et al., 2014. A study of the high-inclination population in the Kuiper belt – I. The Plutinos. MNRAS 437, 215-226.

McKinnon, W. B., et al., 2020. The solar nebula origin of (486958) Arrokoth, a primordial contact binary in the Kuiper belt. Science 367, aay6620.

Nesvorný, D., Vokrouhlický, D., 2016. Neptune's orbital migration was grainy, not smooth. ApJ 825, 94.

Nesvorný, D., et al., 2021. Binary planetesimal formation from gravitationally collapsing pebble clouds. PSJ 2, 27.

Sheppard, S. S., Trujillo, C., 2016. New extreme trans-Neptunian objects: Toward a super-Earth in the outer solar system. AJ 152, 221.

Szabó, G. M., et al., 2020. Rotational properties of Hilda asteroids observed by the K2 mission. ApJS 247, 34.

Verbiscer, A. J., et al., 2019. Phase curves from the Kuiper belt: Photometric properties of distant Kuiper belt objects observed by New Horizons. AJ 158, 123.

Verbiscer, A. J., et al., 2022. The diverse shapes of dwarf planet and large KBO phase curves observed from New Horizons. PSJ 3, 95.

Volk, K., Malhotra, R., 2008. The scattered disk as the source of the Jupiter family comets. ApJ 687, 714-725.

Willacy, K., et al., 2022. Comets in context: Comparing comet compositions with protosolar nebula models. ApJ 931, 164.