RoSET
Roman Survey for Extreme TNOs

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Q: Do you support the selection of a Roman Early-Definition Astrophysics Survey?
A: Yes, this would provide a valuable opportunity for the astronomical community to fill knowledge gaps not covered by the three Core Community Surveys. It would specifically address the lack of surveys for the detection and study of solar system minor bodies, such as trans-Neptunian objects (TNOs), which are rapidly emerging as crucial to our understanding of solar system formation, evolution, and current structure. It would also provide significant legacy value for those interested in, e.g., foreground solar system objects, faint galaxies, and astrophysical transients. Such a survey would therefore engage a larger portion of the scientific community and general public, and significantly increase the visibility of the Roman mission.

Science investigations. The purpose of the Roman Survey for Extreme TNOs (RoSET) is to discover and compute orbits for the most distant observable objects in the solar system, specifically those currently found beyond 100 au. There are two main dynamical classes in this region, with the division based on perihelion distance, indicating whether or not the objects are interacting gravitationally with Neptune. Only two objects are known to be in the class of TNOs interacting with Neptune and currently beyond 100 au: 2018 VG_{18} and 2018 AG_{37}. Although these two objects are currently considered to be curiosities, their existence hints at a larger population of bodies, which Roman should be able to detect.

The second class of distant objects, referred to as extreme TNOs (ETNOs), have perihelia large enough that their orbits cannot be easily explained through interaction with Neptune [1]. The approximately two dozen known ETNOs exhibit clustering of their longitudes of perihelion (Fig. 1), potentially due to a distant, previously (and heretofore) undetected planet orbiting hundreds of au from the Sun [2-4]. However, because of their faint magnitudes (as a result of their distant location) all ETNOs have been detected close to their perihelia, which results in a significant observational bias. ***The major goal of RoSET is to meaningfully increase the sample size of known ETNOs, specifically those further from perihelion, in order to remove any observational biases in the distribution of ETNO orbital parameters and re-evaluate the possibility of a distant planet.***

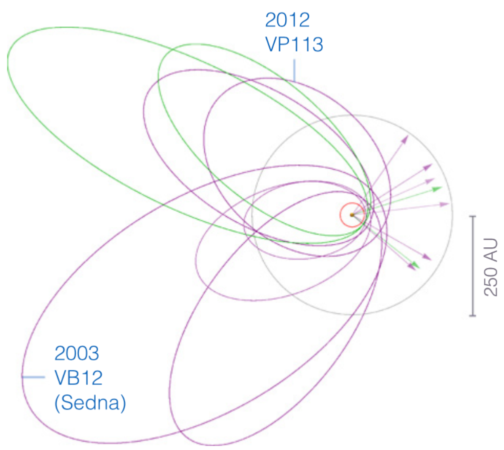

Figure 1: Clustering of extreme TNO (ETNO) longitudes of perihelion (purple and green arrows), possibly pointing to the existence of a distant giant planet. The orbits of two objects with perihelia greater than 75 au (Sedna and 2012 VP_{113}) are marked. Purple corresponds to stable orbits, while green corresponds to unstable orbits. (Image from [4].)

A secondary goal of RoSET is to detect objects on even more distant orbits than the ETNOs. A relatively small fraction of all TNOs are known to orbit beyond the so-called "Kuiper cliff," roughly corresponding to objects beyond the 2:1 mean motion resonance with Neptune (~48 au) [e.g.: 5,6]. It is unclear if this is a hard limit or just a gap before the number of objects increases again; this is a crucial piece of information for understanding solar system formation and present day dynamical structure of the outer solar system. At larger distances, long-period comets provide evidence for a spherical repository of objects (the Oort cloud) [7] in heliocentric orbit at extreme distances of thousands of au, but none have been directly observed at these distances. A transition region called the Hills cloud is theorized to connect the Kuiper belt to the Oort cloud at hundreds of au [8]. It is worth noting that extended debris discs have been observed around other stars [e.g.: 9,10] and with increasing detail using ALMA [e.g., 11]. The first step to resolving the Kuiper cliff question and discovering the extent of our own "debris disc" could start with Roman.

To achieve both the primary and secondary goals, we propose that RoSET target fields far from the galactic plane and near the ecliptic (Fig. 2). Meeting these criteria will decrease confusion from background stars, while also increasing the chance for serendipitous observations of foreground minor bodies. These data would therefore be useful to those who study asteroids, Centaurs, and comets in our own solar system; positioning the fields away from the galactic plane will also result in useful data for those interested in faint galaxies and astrophysical transients such as supernovae. The legacy value of these data is expected to be very high.

Synergies with the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) could also be leveraged by targeting regions within the LSST patrol field, which covers the entire southern sky up to 10° north of the ecliptic [12]. The possibility to overlap a deeper LSST field with a RoSET field would help optimize discovery and characterization of minor bodies detected in both surveys. In this way, RoSET would complement the premier ground-based survey of the next decade, the Rubin LSST.

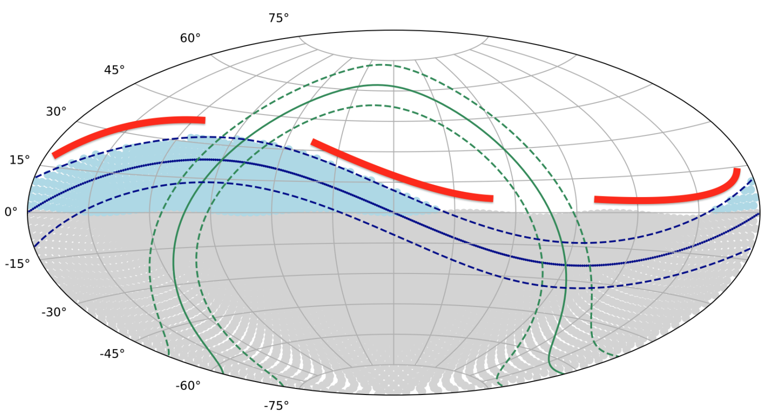

Figure 2: Patrol area of the Rubin LSST (grey region). The blue region denotes the "North ecliptic spur" enhancement for solar system observations. The solid blue line is the ecliptic and the solid green line marks the galactic plane (dashed green and blue lines mark +/-10°). The lengths of the thick red lines mark the approximate RAs for potential RoSET fields, roughly +/-20° from the galactic plane. (Image taken from [12].)

Observational outline. The strategy for this survey is straightforward: stack 4 WFI FOVs parallel to the short axis (can be any orientation on the sky); obtain 10 individual exposures in the F146 filter at each pointing, with dithers to cover chip gaps; then return to the same sky position twice over subsequent days. This will ultimately result in three separate co-added images at each pointing over a full square degree of sky, enabling a search for movement between visits. (Three detections separated in time are the absolute minimum for orbit determination.) Based on recommendations for the James Webb Space Telescope (JWST), the individual exposures would be kept to a maximum of 1000 seconds as a compromise between depth and mitigating cosmic ray strikes. Using version 1.6.2 of the Roman ETC, we calculate a SNR of 1.6 in each 1000-s image for a solar spectrum normalized to r = 28.5. (This provides a conservative estimate for NIR imaging, since TNOs are redder than solar to varying degrees [e.g., 13, 14].) Co-adding 10 such images, for a total depth of 10 ks, results in a SNR of 5. With 4 mosaic tiles, each visit would consist of 40 ks of science time. For comparison, the Outer Solar System Origins Survey (OSSOS) reached a depth of r = 25, with no positive detections of objects beyond 300 au [15] and the LSST is expected to reach a depth of r = 24.5, albeit over a very large area [16].

Covering the same area of sky, to the same depth, as one Roman WFI field (~0.25 sq. deg.) with both modules of NIRCam on JWST would require ~100 mosaic tiles and multiple days worth of exposure time. This hypothetical JWST program would have an efficiency of only 50% when taking the ratio of science time to total time. Making use of the technical resources available on the NASA/GSFC website, we conservatively estimate 2200 s for overheads (1800-s slew tax for each 4-tile mosaic and 400 s for dithers, slews between tiles, and readout time). Overheads make up only 5% of the total time of each visit, an order of magnitude less than for JWST. Each 4-tile mosaic is 11.7 hr, and 60 such mosaics fill 700 hr. With three visits per sky position, this leads to 20 unique sky positions, covering a total of ~20 sq. deg., over Roman's first two years of operations. At a depth of r = 28.5, we expect to identify >100 new ETNOs based on the absolute magnitude distribution of cold classical Kuiper belt objects from [17] and assuming a uniform distribution of targets within 5° of the ecliptic.

Preparatory activities. We describe potential preparatory activities from our current vantage point, with the expectation that additional investigations would be devised and carried out in the lead up to execution of the survey. Three key activities that would be undertaken to optimize RoSET:

1. Perform simulations to determine the effects of residual cosmic rays in the co-added images. The expected number of cosmic rays in a 1000-s exposure is likely to be significant, and while the co-addition of 10 images should remove the majority of cosmic rays, it will not remove all of them. Outputs from this investigation would be fed into the next investigation to help tune the parameters of the automated search.
2. Develop automated software to detect believable moving objects in each set of image trios. The software currently being developed for the LSST [18] could be used as a starting point and adapted for use with Roman. Additionally, advancements in AI, neural networks, and pattern recognition algorithms will be leveraged to efficiently and accurately detect ETNOs in the image sets, as well as to determine the limits of the survey through implantation of synthetic objects.
3. Optimize the sky positions for the 20 unique pointings based on ongoing ground-based surveys of the far outer solar system. The unique pointings should avoid regions of the sky within 20° of the galactic plane, to reduce confusion with background stars. However, it is the ecliptic latitude that is most important to optimize. Observations closer to the ecliptic could increase the yield of ETNOs, as well as faster, closer minor bodies, thus increasing the legacy value of the data for other minor body populations. Additional information on the typical orbital parameters (especially inclination and eccentricity) from deep ground-based surveys will feed directly into determination of the optimal ecliptic latitude to target with RoSET.

Summary. As described in this white paper, RoSET will lead to greater than a factor of five increase in the number of currently known ETNOs, enabling definitive tests of the longitude of perihelion clustering first reported by [2] and the existence of a distant giant planet proposed by [4]. The survey as laid out would exceed the imaging depth provided by OSSOS and the upcoming LSST by a few magnitudes, leading to the deepest probe of the outer solar system ever undertaken. RoSET would meaningfully benefit from pre-selection through community involvement in the identification of optimal target fields and the development of cutting-edge automated target detection software.

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