8th IAA Planetary Defense Conference – PDC 2023
3-7 April 2023, Vienna, Austria

IAA-PDC-23-04-04

RUBIN OBSERVATORY LSST: STATUS, NEO EXPECTATIONS, AND COMMUNITY READINESS

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Keywords: *NEOs, Surveys, Follow-up, LSST*

Introduction

The Rubin Observatory (Ivezic et al. 2019) is a new U.S. NSF/DOE-funded facility on Cerro Pachón, Chile, housing the 8.4m Simonyi Survey Telescope. The Observatory is expected to be completed and commissioned by early 2025. Over a ten-year period Rubin will execute the Legacy Survey of Space and Time (LSST). Enabled by its 9.6 square degree field of view, a 3.2 Gigapixel camera, and a cadence covering the sky every 3-4 days to median single-exposure depths of r~24mag, the LSST will deliver a large catalog of Solar System objects. Based on simulations, this catalog will include 5M+ new main-belt asteroids, 200,000+ Jupiter Trojans, 40,000+ TNOs, and tens of ISOs (among others).

The LSST will also deliver the most comprehensive survey of NEOs, PHAs, and imminent impactors to date. Simulations indicate yields of over 100,000+ NEAs, O(1-10) imminent impactors per year, O(100) temporarily captured objects, and a census of over 80% of the PHA population by mid 2030s. These discoveries will come with precise astrometry (10mas systematics limited), photometry (<1% systematics limited), understood selection functions, as well as 10-100+ observations per object, all allowing for detailed population studies.

In this extended abstract we give an overview of the Rubin observatory, its construction status, and discuss projections for solar system discovery. We argue that the opportunities for planetary defense will be significant; however, with the jump in discovery rates will also come significant challenges for the world-wide community: from coordination of observations, strained follow-up capacity, to reaction procedures for imminent impactors. We offer thoughts and potential solutions.

Rubin Observatory

Figure 1: The main building of the Rubin Observatory on Cerro Pachon, Chile, as photographed on March 15th, 2023. The observatory houses the 8.4m Simonyi Survey Telescope, and is slated to begin commissioning in late 2024.

The Rubin Observatory is a dedicated optical sky-survey facility presently in final stages of construction at Cerro Pachón, Chile. The observatory, funded jointly by the U.S. National Science Foundation (NSF) and the U.S. Department of Energy (DOE), aims to deliver a comprehensive real-time data stream and plus a static-sky dataset that supports four key research areas: the structure of the Universe, Dark Matter and nature of Dark Energy; understanding the structure and history of the Milky Way; enabling the exploration of time-domain astronomy phenomena and; taking a comprehensive census of small bodies of the Solar System.

The observatory houses a 8.4-m, wide-field telescope, with a 3.2Gpix, fast-readout (2 second) mosaic CCD camera. Observations can be made in six bands – u, g, r, i, z – spanning near-UV, through optical, to near-IR. With typical seeing and airmass, a 30-second exposure is expected to capture ~10deg^2 of the sky to r~24 mag. Once completed in early 2025, Rubin will begin a 10-year automated sky survey – the Legacy Survey of Space and Time (LSST). During a typical night, LSST observations will cover 8,000deg^2 of the sky (4,000deg^2 of unique area), with the entire observable sky covered every 3-4 nights. This pattern will continue through the year, resulting in roughly 80 coverings per year of the main survey area of about 18,000deg^2. Beyond the main survey area, additional 4,000 deg^2 will be covered with lower cadence (~20 coverings). A smaller set of "deep drilling fields" – on order of 100deg^2 total – will be covered at significantly higher cadence (up to ~1,000 coverings/yr).

The collected data will be automatically processed by the Rubin Data Management (DM) system pipelines (Juric et al. 2017). Rubin DM pipelines operate in two main modes: *prompt processing* and *data-release processing*. In the prompt processing mode, images are differenced against a deep template within about a minute of observation, and any variable or moving sources are identified. This capability is meant to enable rapid identification of time-varying phenomena, including moving objects. Data release processing occurs on an annual cadence, and is designed to enhance deep, systematics-limited, static sky science.

Rubin Observatory Solar System Pipelines

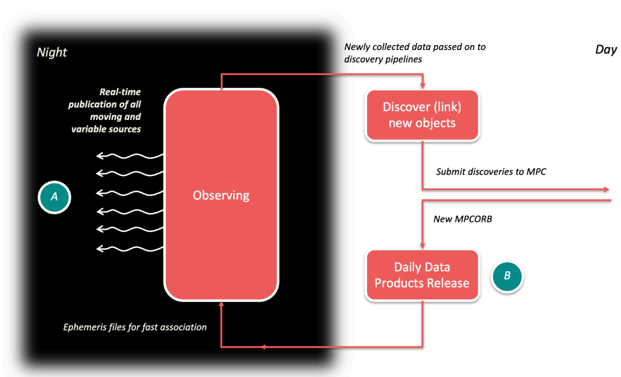

Figure 2: Daily observing/discovery loop.

The majority of Rubin's solar system capability will come from the prompt processing data outputs. A schematic of the daily observation and discovery loop is shown in Figure 2. During the night, Rubin collects images and processes them within 1-2 minutes of observation to identify any objects that have changed position, brightness, or morphology. Information about such objects is immediately (within seconds) transmitted in form of a (public) *alert stream*[1]. The alerts will include solar system objects (known and unknown). If an object is known, it will be tagged with its designation, expected position, and expected magnitude. This makes it possible to monitor known sources for activity. The stream will also contain information about the shape of each detected source, including whether they appear trailed. The latter capability makes it possible to also rapidly identify potential new, fast-moving, objects.

At the end of each night, the collected data are passed to Rubin's Solar System pipelines for discovery of new solar system objects via tracklet construction and linking. Rubin generally re-observes pointings twice each night within 20-90 minutes. This is sufficient to construct tracklets, but insufficient to have confidence a tracklet is real. For example, two unrecognized nearby cosmic-ray artefacts could be misconstrued for a tracklet, or two real asteroids, and so on. Therefore, Rubin does not report individually linked tracklets, but searches for combinations of at least three nights of tracklets in a two-week period whose positions and motion are well fit to a Keplerian orbit. Such combinations are highly unlikely to occur by chance and are high-confidence discovery candidates. The software to perform this linking, based on Holman et al. (2018) HelioLinC algorithm has been prototyped and tested both on present-day survey data and with simulated Rubin data. The code can be found at https://github.com/lsst-dm/heliolinc2 (Heinze et al. 2022).

Following automated linking and after brief human vetting, all discovery candidates will be reported to the Minor Planet Center. Simulations indicate that in the first year of LSST, we expect to discover about 10,000 new objects per night, on average, with occasional peaks to 70,000 or more (particularly good nights with many observations on the ecliptic). This is a significant increase over present-day discovery rates (>20x), presenting some data management challenges. To prepare for this "firehose", Rubin and the Minor Planet Center have been collaborating on upgrading and testing the MPC systems over the past three years[2]. Newly upgraded MPC software has been shown to intake and process data at Rubin the required rates.

Every day, the MPC will independently verify submitted candidates, and assign designations to those that are deemed valid. Rubin will then take the updated database of MPC orbits to compute, on a daily basis, an added-value catalog of quantities not computed by the MPC (e.g., absolute magnitudes computed in individual Rubin bands, and similar). These catalog(s) are used to predict positions of known objects in the next observing night, and the cycle continues.

[1] E.g., see https://www.lsst.org/scientists/alert-brokers for more details.

[2] For example, see https://dmtn-180.lsst.io/ .

With this strategy and software, over the 10 year of LSST Rubin is expected to discover over 5M new main-belt asteroids, 200,000+ Jupiter Trojans, 40,000+ TNOs, and tens of ISOs. Closer to home, the Rubin is expected to uncover over 100,000+ NEAs, O(1-10) imminent impactors per year, O(100) temporarily captured objects, and provide a census of over 80% of the PHA population by mid 2030s (Jones et al. 2018).

Searching for NEOs in LSST Data

Rubin will provide the major NEO discovery capability in the late 2020s. Quantitative expectations are summarized in Jones et al. 2018. They show that when LSST discoveries are added, and assuming other present-day programs continue with roughly similar efficiency, we could detect some 81% of the PHA and 73% of the (H<22) NEO population in about a decade (Table 4 in Jones et al. 2018). They also show that with further optimizations Rubin could approach the ~90% threshold for PHA population completeness.

All these discoveries are expected to come through multi-tracklet linking, as described in the previous section. But there's an opportunity to further increase the yield by a few percentage points as well as find objects a few days earlier (of importance for likely imminent impactors).

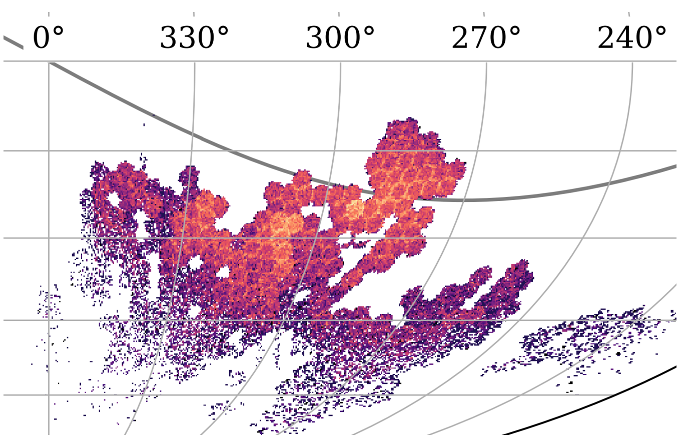

Figure 3: An example of asteroids detected in a single night. This simulated night yielded ~420,000 observations, of which ~1000 were NEOs. Brightness of points indicates the number of asteroids in the pixel. Grey curve indicates the ecliptic plane

Rubin occasionally observes a pointing more than once. Also, as seen in Figure 3, there's a not-insignificant area where adjacent Rubin observations overlap. These can lead to more than two observations per tracklet, presenting an opportunity to identify them immediately. They could then be reported to the MPC, prioritized, and opened to same- or next-night 3rd party follow-up. An upcoming paper by Wagg et al. looks at this option.

NEO candidates are presently found by NEO surveys at a rate of 10-30/night, reported to the Minor Planet Center, and – if they meet certain criteria – announced on the NEOCP for the community to follow-up. Wagg et al. find that Rubin, should they choose to report tracklets with 3+ observations, would vastly increase the rate of reported candidate NEOs. They find that Rubin would contribute between 1000 and 20,000 new objects to the NEOCP each night, 2 to 3 orders of magnitude higher than the current rates (assuming present-day NEOCP admission and prioritization criteria). Such an increase would overwhelm the NEO follow-up system.

Disconcertingly, only between 0.2% - 10% of these candidates would be NEOs; most are main belt asteroids (MBAs) masquerading as NEOs. So, rather interestingly, that the main challenge is not the absolute rate of NEOs, but *the large background of undiscovered 22-24th mag MBAs*. In fact, the same is true today – all NEO searches fish in the sea of MBAs, but fortunately MBA catalogs are mostly complete to typical survey depths.

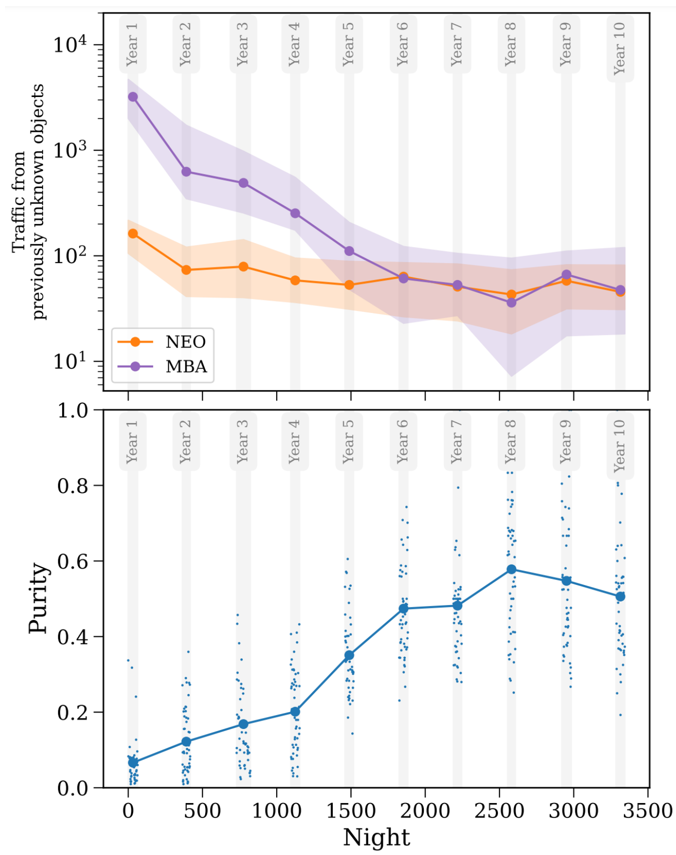

Figure 4: Top: Median number of NEOCP-admissible previously undiscovered NEOs and MBAs. Shaded areas indicate interquartile ranges. Bottom: Percentage of NEOs in the NEOCP-admissible sample.

To mitigate, Wagg et al. propose to deprioritize follow-up of objects that are likely to be "self followed-up" by Rubin itself (and provide an algorithm to identify these). They further argue for strong cuts on ecliptic latitude to mitigate against unknown MBAs, and yield a cleaner NEO candidate sample. As time goes on, and Rubin maps the MBA background, the purity of the NEO candidate sample will continue to rise. As shown in Figure 4., by year 4 of observing, nearly 40% single-tracklets with high digest scores will be true NEOs, at which point such mitigations will become unnecessary. Alternatively, this argues for prioritizing MBA discovery early on, to reduce the backgrounds for NEOs.

Summary and Conclusions

Rubin Observatory is a major new astronomical facility being built on Cerro Pachon, Chile. It is expected to enter commissioning in about a year, and begin regular survey operations in less than two years, building up the Legacy Survey of Space and Time (LSST).

Once operational, Rubin will rapidly become the most prolific discoverer of solar system objects to date. Using a novel tracklet-linking implementation based on the HelioLinC algorithm, Rubin will discover over 100,000+ NEAs, O(1-10) imminent impactors per year, O(100) temporarily captured objects, and more. Its contributions to the planetary defense community can lead to a census of over 80% of the PHA population by mid 2030s.

Importantly, key data of intrest to planetary defense will be made public and broadly shared. Both astrometric and photometric data for Rubin discoveries will all be submitted to the Minor Planet Center within hours of observation. Image cutouts will also be publicly available through Rubin's alert streams.

With operations less than two years away, it's an excellent time to learn more about this upcoming resource. We are looking toward to help the community get ready to take advantage of Rubin's capabilities in the area of NEO discovery and planetary defense.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Cooperative Agreement 1258333 managed by the Association of Universities for Research in Astronomy (AURA), and the Department of Energy under Contract No. DE-AC02-76SF00515 with the SLAC National Accelerator Laboratory. Additional funding for Rubin Observatory comes from private donations, grants to universities, and in-kind support from LSSTC Institutional Members.

The authors further acknowledge the support from the University of Washington College of Arts and Sciences, Department of Astronomy, and the DiRAC Institute. The DiRAC Institute is supported through generous gifts from the Charles and Lisa Simonyi Fund for Arts and Sciences and the Washington Research Foundation. M. Juric wishes to acknowledge the support of the Washington Research Foundation Data Science Term Chair fund, and the University of Washington Provost's Initiative in Data-Intensive Discovery.

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