HOW MUCH WARNING TIME FOR ASTEROID IMPACTS WILL WE HAVE IN THE VERA RUBIN ERA?

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Introduction: The Vera C. Rubin Observatory, with its Legacy Survey of Space and Time (LSST), will provide unprecedented capabilities for detecting and tracking near-Earth objects (NEOs), including possible discoveries of impacting asteroids. To prepare for potential planetary defense scenarios, understanding the warning time for asteroid impacts is critical. In this context, we investigate how quickly Earth-impacting asteroids are discovered and how their impact probabilities evolve over time.

We focus on quantifying the amount of time required for the impact probability of each asteroid to rise to 1%, which is considered the threshold for initiating mission planning and mitigation efforts. We examine how this time varies with asteroid size, time until impact, and orbital characteristics. By tabulating the distribution of impact probabilities over time, we can characterize the warning time, defined as the period between when the probability surpasses 1% and the predicted impact date. These findings are crucial for enhancing planetary defense strategies, as they underscore the need for early detection and robust follow-up observations to ensure that mitigation strategies are initiated with sufficient lead time. Our analysis provides actionable insights into the timing and discovery rates of potential impactors, directly informing future preparedness efforts in the Rubin era.

Methodology: A synthetic population of 5,000 Earth-impacting asteroids was generated by sampling orbital elements using the Granvik model[1] and enforcing an impact via the method described in Chesley et al. 2024[2]. These orbits were then placed in 6 size bins, with albedos drawn from a bimodal Rayleigh distribution, resulting in a final set of 30,000 synthetic impactors.

These impactors were then run through Sorcha[3], the LSST Solar System survey simulator, which generates ephemerides for each object, filters based on field of view, limiting magnitude, and variable seeing conditions, and applies realistic observational uncertainty. For the observing cadence, we used the pointing database: "baseline_v4.3.1_10yrs.db". For each new night of data, all cumulative observations were fed into Find Orb, an orbit determination program, to calculate the 'best-known' orbit based on the observations available at that time. Find Orb was chosen for its wide use in the NEO community and its open-source availability.

We then used ADAM Core to generate variants of the orbit from its covariance. We propagated the variants using an ASSIST back-end with ADAM Core[4] used to detect the impacts and calculate impact probability. ASSIST was chosen for its speed, proven accuracy relative to JPL[5], and for consistency with Sorcha. Impact probabilities were calculated for all orbits and windows that met a minimum criteria of at least three nights of observations, which is needed to determine an orbit. We considered an object 'discovered' when it met the linking criteria of three 2-observation tracklets over 15 days, consistent with LSST[6].

Results: During the survey, 70.4% of synthetic impactors $\geq 140m$ were discovered at a rate consistent with recovery rates for PHAs as found in Jones et al. 2018 (65.6%)[7]. Of the smaller objects ($< 140m$), less than 50% were discovered. Out of the discovered population, most were recognized immediately to have an impact probability risk of at least 10^{-4}. 83.0% of discovered objects reached an impact probability of $> 90\%$ before the end of the survey. Most of those that did not reach 90% impact probability had impact dates farther into the future. Many objects within the impacting population maintain a low impact probability for a significant period of time, highlighting the importance of follow up to risk list objects.

Of the objects that did reach 1% impact probability, the majority were simply not detected during the ten year survey. Size was the primary factor in detectability, however, we also see some expected trends on the basis of their orbital characteristics. In particular, even for 1km asteroids, the proportion of objects recovered with $a < 1.0AU$ is significantly lower, as in Fig 2. For much of their orbits, these objects are interior to Earth, and suffer from both lower solar incidence angle and visibility only at twilight. An especially difficult population exists at $a \approx 1.0AU$. These objects tend to have large synodic periods relative to Earth, and may simply have no close approach during the survey.

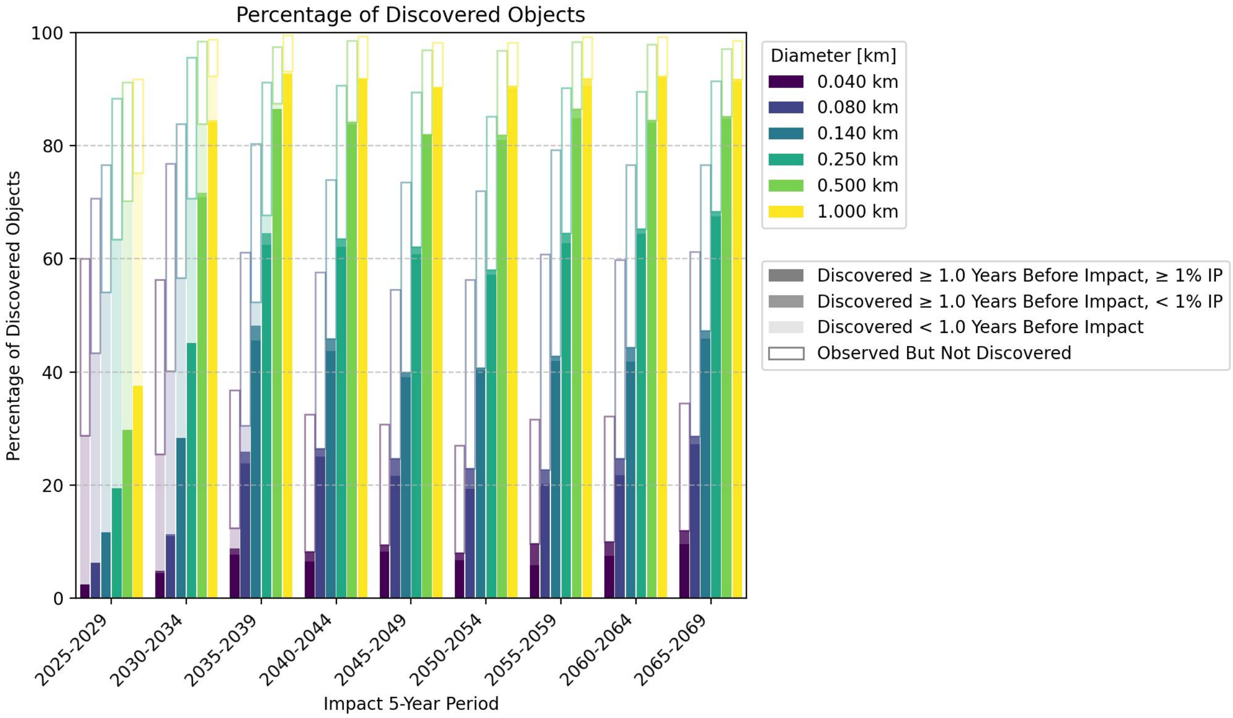

Figure 1: **Percentages of each object diameter in five year bins and their recovery status. The hollow region represents the proportion that were imaged in LSST but did not meet the discovery criteria and the different shaded regions indicate the proportions that were discovered before or after 1 year prior to impact.**

Finally, we see that for smaller objects, past about a = 1.4, higher semi-major axis corresponds to lower detection rates. The same trend is not seen for our larger impactor sample, which LSST would be able to successfully image at further distances.

The 1% threshold is significant as the notification threshold for the International Asteroid Warning Network (IAWN). The warning time, the duration of time from reaching 1% impact probability to impact date, is primarily a function of the discovery rate for LSST. The median value of the impact probability at discovery time is 7%. 4.5% of the discovered objects never reach an impact probability of 1%. For objects with an impact probability below 1% at discovery time and then later surpass the 1% threshold, the median time to reach 1% is 45 days (mean 326 days).

As seen in Figure 1, there are a large number of objects that are observed by LSST but not discovered based on the criteria of three 2-observation tracklets over 15 nights. Additionally, many objects that are discovered have a large number of prior observations that could not be included in this linking set, pushing the date of discovery later than it might be with more generous criteria. This demonstrates the sensitivity of discovery to the linking algorithm. By defining a minimum realistic discovery criteria of any 6 observations within a maximum of 30 days, which span at least 2 nights, we are able to find an additional 2355 out of 6102 of the observed but not discovered objects (38.5%). Additionally, for discovered objects, adopting these criteria would increase median warning times by 7 days, and would increase the mean warning time by 240 days. This represents the population of objects that could be discovered by novel linking algorithms, including those that are able to link singleton observations, such as the Tracklet-less Heliocentric Orbit Recovery algorithm[8].

Improvements & Future Work:

We make a number of assumptions in this study, most notably perfect linking (based on the LSST linking criteria) and perfect precovery (post-discovery linking of all prior observations of this object in the survey). Both of these assumptions are worth examining for their impact on the total rates of discovery and warning time. There is also a potential to test additional novel linking algorithms, such as THOR, or even less generous

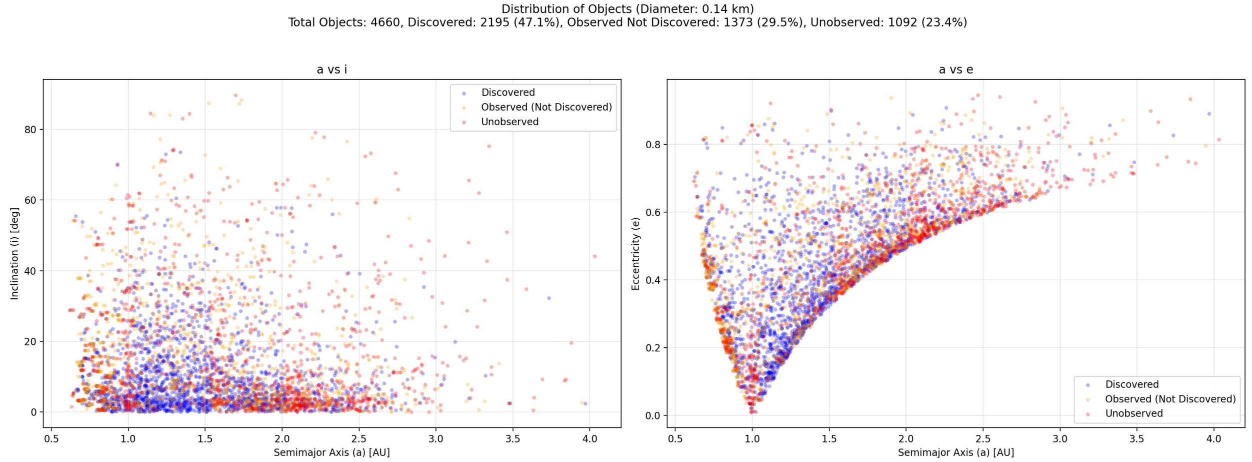

Figure 2: Figure 2 shows the orbital elements for unobserved, observed but not discovered, and discovered 140-meter asteroids, highlighting any systematic survey blind spots. We see that objects with semi-major axes around 1 AU or orbits interior to Earth's orbit have significantly lower detection rates due to the challenging observational geometries and high synodic periods. Such orbital configurations often result in minimal or no close Earth approaches within Rubin's nominal 10-year survey duration, limiting discovery opportunities.

criteria to represent a 'worst-case' scenario for HelioLinC.

The same pipeline could also be used to test different pointing databases that represent different iterations of the survey, such as an extended LSST operating window or the inclusion of a Twilight study. Another potential extension would be to run a similar study on different telescopes or surveys, such as NEO Surveyor, either in tandem with LSST or alone.

Finally, this study considered only objects that had an eventual impact. A follow-up of near-miss objects, or a full NEO realistic population, could give greater insight into how Impact Probabilities evolve over time for objects that do not impact (such as 2024 YR4), to better understand how the rate of these 'greater than 1% IP' non-impact objects is likely to change in the Rubin era, and whether the current risk-list pipelines are robust to these changes.

Conclusion: While LSST was able to find the majority of the most dangerous simulated impactors, there are still significant gaps, especially in the 140m and below range. Extending the survey duration, incorporating dedicated twilight observations, and employing space-based infrared observatories like NEOSurveyor could substantially reduce these observational gaps. Additionally, advanced linking algorithms offer potential improvements in the effective discovery rate by better associating sparse observations over extended periods.

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