The Sensitivity of NEO Surveyor to Low-Perihelion Asteroids

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ABSTRACT

Asteroids with low orbital perihelion distances experience extreme heating from the Sun that can modify their surfaces and trigger non-typical activity mechanisms. These objects are generally difficult to observe from ground-based telescopes due to their frequent proximity to the Sun. The Near Earth Object Surveyor mission, however, will regularly survey down to Solar elongations of 45° and is well-suited for the detection and characterization of low-perihelion asteroids. Here, we use the survey simulation software tools developed for mission verification to explore the expected sensitivity of NEO Surveyor to these objects. We find that NEO Surveyor is expected to be $> 90\%$ complete for near-Sun objects larger than $D \sim 300$ m. Additionally, if the asteroid (3200) Phaethon underwent a disruption event in the past to form the Geminid meteor stream, Surveyor will be $> 90\%$ complete to any fragments larger than $D \sim 200$ m. For probable disruption models, NEO Surveyor would be expected to detect dozens of objects on Phaethon-like orbits, compared to a predicted background population of only a handful of asteroids, setting strong constraints on the likelihood of this scenario.

1. Introduction

Asteroids, as reservoirs of materials from the early inner Solar system (DeMeo *et al.* 2015), allow us to study the mineralogical processes that occurred in the early protosolar disk. The main asteroid belt between Mars and Jupiter is generally stable over the age of the Solar system, meaning most objects found there have been largely unmodified since their formation (Binzel *et al.* 2015). However, some of these objects can drift into resonances that change their orbits so that they approach close to the Earth. These objects, with perihelia less than $q < 1.3$ AU, are known as near-Earth objects (NEOs) and experience very different evolutionary regimes for their ~ 10 Myr dynamical lifetime (Gladman *et al.* 2000).

A very small subset of NEOs evolve onto orbits with extremely low perihelion distances. Currently, only 28 of the $> 33,000$ known near-Earth asteroids, along with comet 96P/Machholz,

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have perihelia of $q < 0.15$ AU.[1] These objects experience subsolar heating that can be in excess of $1,000$ K (MacLennan *et al.* 2021), exposing primitive surface materials to these temperature regimes for the first time. The evolution of the surface materials in this regime, as well as their potential for catastrophic disruption (cf. Granvik *et al.* 2016), provides important clues that help us investigate the global physical properties of these objects.

The poster-child for low-perihelion asteroids is (3200) Phaethon, which will soon be visited by the DESTINY+ mission (Arai & Destiny+ Science Team 2023). Discovered during the infrared sky survey conducted by IRAS (Green *et al.* 1985a), Phaethon was assumed to be an extinct cometary nucleus due to its orbital proximity to the Geminid meteor stream (Green *et al.* 1985b). Although numerous studies of this object were undertaken, detection of any activity was not seen until a small tail was identified by Jewitt *et al.* (2013) in STEREO data during the object's 2009 and 2012 perihelion passes. Multiple theories have been put forth for the driver of observed activity, including thermal fracturing (Ryabova 2018) and volatilization of sodium (Masiero *et al.* 2021; Zhang *et al.* 2023), but all are a result of the extreme temperatures Phaethon experiences at perihelion.

Phaethon's association with the Geminid stream has led to the suggestion that a breakup event thousands of years ago might explain the association between these objects and other nearby asteroids like (155140) 2005 UD (Ohtsuka *et al.* 2006). Given that the currently observed levels of activity are insufficient to populate the Geminid stream (Jewitt & Li 2010), such a breakup event could naturally resolve this discrepancy. Devogèle *et al.* (2020) showed that the physical properties of Phaethon and 2005 UD are consistent, strengthening the proposed link, while dynamical modeling by Jo & Ishiguro (2024) finds an optimal epoch of dust creation ~ 18 kyr ago. A fission event large enough to create the Geminid stream and 2005 UD from a proto-Phaethon body would also be expected to produce a number of intermediate sized objects in the tens-to-hundreds of meter range that would still be present in the NEO population today, based on observed outcomes of rotational (Jewitt *et al.* 2017) and tidal (Sekanina *et al.* 1994) breakups.

The NEO Surveyor mission (Mainzer *et al.* 2023) will conduct a census of asteroids and comets near the Earth's orbit, in order to determine the risk posed to our planet from any potential impactors. The mission makes use of a single instrument consisting of a two-channel thermal infrared camera, and will conduct a dedicated survey optimized for the detection of near-Earth objects. NEO Surveyor is expected to increase the catalog of known NEOs by more than an order of magnitude, detecting two-thirds of all potentially hazardous asteroids larger than 140 m in diameter after 5 years and 90% after 12 years. As part of its survey, NEO Surveyor will regularly observe down to Solar elongations of $45°$ covering a region of space where low-perihelion asteroids spend a significant fraction of time. In this work, we investigate the potential of NEO Surveyor for discovering and characterizing low-perihelion asteroids, and we use these simulations to give

[1] We do not consider sun-grazing comets; while the SOHO mission has discovered well over 1000, they are generally thought to have a different formation history (originating mostly from the Oort Cloud as opposed to the inner solar system), and many of them are destroyed shortly after discovery.

predictions on the number of Phaethon-like objects that will be detected. We can also set constraints on the mission's sensitivity to any asteroids created if Phaethon previously underwent a breakup event.

2. Population Model

Our work makes use of the recently developed survey simulation tools for the NEO Surveyor mission (Mainzer *et al.* 2023). These tools have been demonstrated by Masiero *et al.* (2023) to successfully reproduce predicted observations of near-Earth asteroids through comparison with data from the NEOWISE mission (Mainzer *et al.* 2011a, 2014a, 2019). Validation of the predicted positions, fluxes, and detectabilities ensures that survey simulation outputs match the expectations for performance of the mission system in flight.

To build our input population, we take all known asteroids with perihelia less than $q < 0.15$ AU that have detections over multiple orbital epochs from the Minor Planet Center (MPC) orbit catalog[2]. At the time this work was carried out this subset included 28 objects. Although a relatively small sample, the distribution of orbital elements for these objects showed:

- Perihelion distance q was consistent with a flat distribution from ~ 0.075 AU to the cutoff at 0.15 AU,
- Eccentricity e is approximately a Gaussian that peaks at ~ 0.92 and is truncated at 0.97 AU (with two outliers at $0.7 < e < 0.8$),
- Inclination i is roughly flat below $\sim 35°$ (with one outlier above $i > 50°$),
- The argument of perihelion and longitude of the ascending node are consistent with flat distributions across all angles,
- No significant correlations exist between $q - e$, $q - i$, or $e - i$.

In order to perform a statistically significant simulation, we take these observed trends and synthesize a population of 10,000 objects to run through our survey simulator. Time of perihelion for each object is chosen from a flat distribution within 4000 days of the start of survey (the approximate period of our most extreme object with $q = 0.15$ and $e = 0.97$). Figure 1 shows the real objects from the MPC catalog in orange, and the synthetic population in blue. The synthetic population is broadly consistent with the real objects (neglecting the few outliers), and sufficient to allow us to estimate the sensitivity of NEO Surveyor to unknown near-Sun objects.

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[2] *https://minorplanetcenter.net/iau/MPCORB.html*

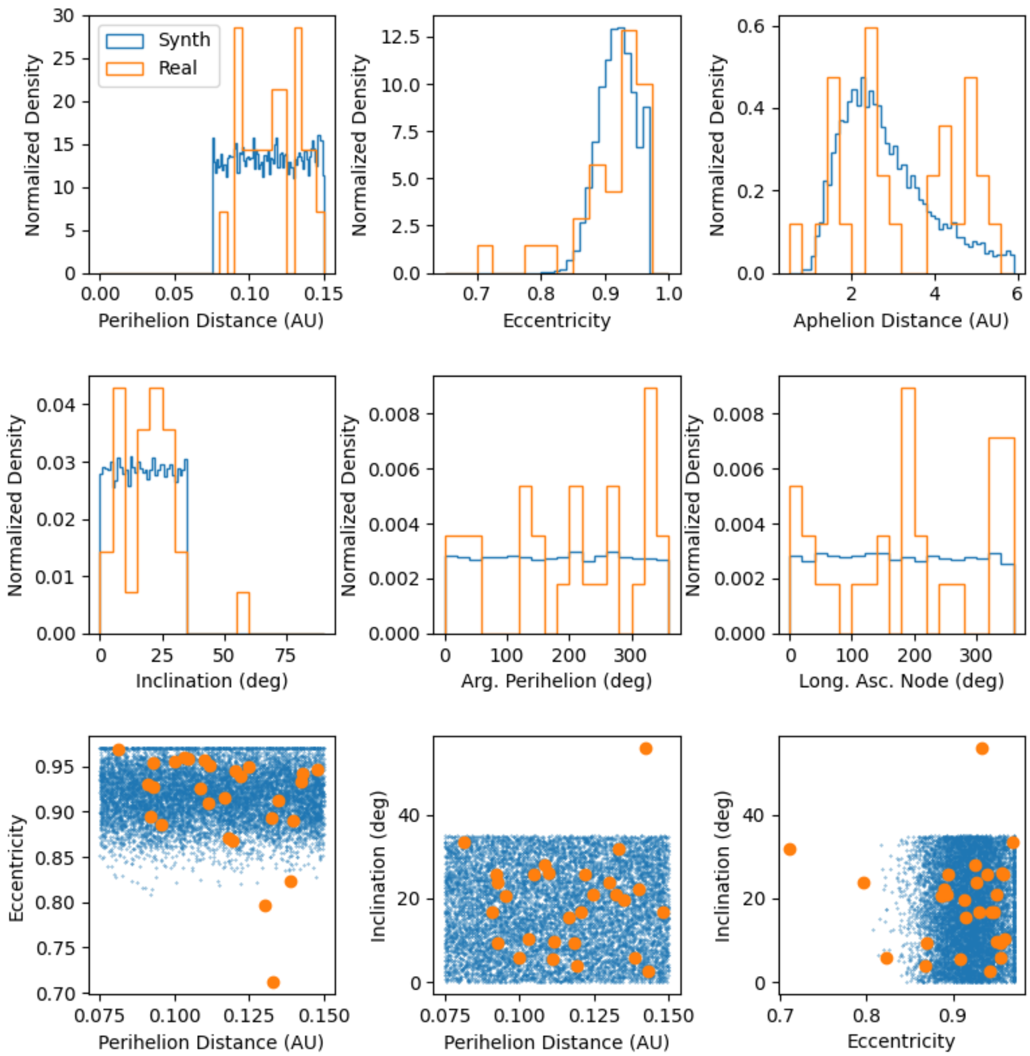

Fig. 1.— Comparison of the currently known population of near-Sun asteroids (orange) to the synthetic population used for our completeness determinations (blue). Histograms of orbital parameters (top left: perihelion distance; top middle: eccentricity; top right: aphelion distance; middle left: orbital inclination; center: argument of perihelion; middle right: longitude of the ascending node) and scatter plots of orbital elements (bottom left: perihelion distance vs eccentricity; bottom middle: perihelion distance vs inclination; bottom right: eccentricity vs inclination) demonstrate that the synthesized population sufficiently samples the phase space occupied by the real objects.

Our choice of synthetic orbital parameters restricts our input population to having aphelion outside of Q$\sim$ 0.7 AU. This is coincident with the known population, however the known objects are almost certainly biased against low aphelia by the difficulty in observing these objects from ground- or space-based facilities. Due to the design of the spacecraft sunshade, NEO Surveyor is restricted to observing objects with heliocentric distances larger than $R_h > 0.7$ AU, and thus objects with Q$<$ 0.7 AU can never be detected. Although a population of such objects may well be present in the inner Solar system, it neither poses a hazard to Earth nor will be observable by NEO Surveyor, and so we do not consider it further in this analysis.

For tests of sensitivity to objects that might have been formed from a breakup event of a proto-Phaethon object, we generate a more focused synthetic population of 1,000 objects around Phaethon's current orbital parameters to better test our sensitivity to this region of phase space. Here we use flat distributions in a narrow range around Phaethon's orbit: $q = 0.14 \pm 0.01$, $e = 0.890 \pm 0.015$, $i = 22 \pm 5$, $0 \leq \omega \leq 360$, and $0 \leq \Omega \leq 360$. Time of perihelion is chosen from a flat distribution with 523 days of the survey start, consistent with the period of Phaethon. This population of Phaethon-like objects provided improved statistics for sensitivity as a function of diameter, as discussed below.

3. Survey Simulation Results

We use the NEO Surveyor Survey Simulator (NSS) software tools (Mainzer *et al.* 2023) to propagate our synthetic orbits over the 5 year nominal mission survey lifetime and calculate their expected fluxes with respect to the instrument sensitivity. The NSS then determines if the objects are detectable a sufficient number of times to report tracklets (sequences of position-time measurements) to the MPC that would all for the orbit to be constrained. State vector propagation is carried out using an N-body simulator; instrument sensitivity uses the Current Best Estimate for the hardware that will be implemented for the mission; tracklet generation efficiency is based on on-going tests of the NEO Surveyor Science Data System at IPAC; estimations for the capability of the MPC to link tracklets into measurable orbits are based on historic performance from the NEOWISE mission as well as on-going testing between NEO Surveyor and the MPC. Mainzer *et al.* (2023) provide the specific values used for these parameters in the NSS and the method of their derivation. The output of the NSS is a list of observations of each input object that passes detection and tracklet-building requirements; this is used to determine overall completeness as a function of both size and orbit, described in detail below.

3.1. Size Effects

The larger an object is, the more flux it will emit for a given orbital position and observing geometry, and so the easier it will be to detect. Since larger objects have more opportunities to be detected, it also increases the chance that they will be cataloged following our survey rules. In this analysis we take our synthetic orbital population, assign all objects the same diameter, and run the survey simulator to determine completeness at the end of five years. By sweeping through a range of diameters we can constrain the completeness as a function of size. We show these results in Figure 2.

The general behavior of the full synthetic population shows that while 50 m objects will have low completeness fractions, this rises rapidly with size and surpasses 90% for sizes of a few hundred meters. Restricting our analysis to the synthetic objects that come closest to Earth's orbit, those with Earth Minimum Orbit Intersection Distance (MOID) less then 0.05 AU, we see that the completeness fraction is generally a few percent higher at all sizes until reaching the same saturation point at a few hundred meters. Objects with Phaethon like orbits follow a comparable trend, though have a steeper change in completeness with size and reach $> 90\%$ completeness at smaller sizes of $D \sim 200$ m. This improvement compared to the general synthetic population is primarily due to the relatively lower eccentricity of the Phaethon-like set of objects which increases the overall likelihood of detection.

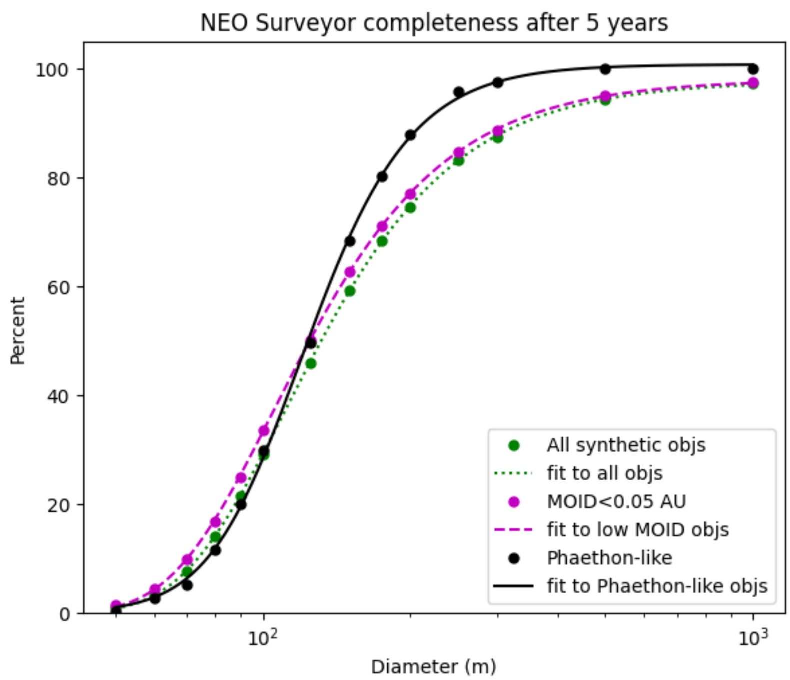

Fig. 2.— Fraction of synthetic objects recovered by NEO Surveyor after 5 years as a function of object size. Green points show all synthetic objects, magenta shows those objects with Earth MOIDs less that 0.05 AU, and black shows a subset of objects close in orbital space to (3200) Phaethon. The lines for each color show the best fit to the calculated completeness points using Eq 1.

We can analytically describe the completeness vs size by fitting a generalized logistic function to each of our results, of the form:

$$F = L\left(1 + e^{-k(s-s_0)}\right)^{\beta} \tag{1}$$

where F is the completeness fraction, L is the maximum fraction, s is the log of the size (in meters), s_0 is the pivot point of the function (in $log(m)$), k is the steepness of growth, and β dictates the asymmetry of the growth. The best fit values for each parameter are given in Table 1. We note that the best-fit maximum fraction for Phaethon-like objects settles to slightly above 100%; this is due to the incomplete sampling of the size range at very large sizes. Artificially constraining this to an upper limit of 100% produced a worse fit to the data, and so we choose to leave it as is, with the caveat that it is simply a fitting artifact.

Table 1: Parameters of the best-fit logistic functions to the survey completeness

Synthetic Population	k	s_0 (log(m))	β	L
All near-sun	5.19	1.60	-10.08	97.8
Low MOID	5.12	1.51	-13.97	98.1
Phaethon-like	8.50	2.02	-1.67	100.8

3.2. Orbital Element Dependencies

For objects in near-Earth space, geometry can conspire to cause some classes of orbits to only approach Earth's orbit when the planet is far from the close-approach point. NEO Surveyor will have improved sensitivity to these objects through searching the sky at low Solar elongations, scanning down to 45° ahead and behind the Earth along its orbit. Even with this survey strategy, however, some very high eccentricity asteroids can require many years of survey before falling into one of these fields of regard.

This is particularly true for low-perihelion objects with high eccentricities which can spend large fractions of their orbit too close to the Sun to be observable or too far from the Sun to be detectable. Surveyor's five-year nominal mission survey provides opportunities to sample the full orbit for objects with semimajor axes $a < 3$ AU, increasing the likelihood of detection. The majority of our synthetic sample is within this orbital range, though longer survey periods would be expected to improve completeness by recovering objects on near-resonant orbits with Earth's orbit.

In Figure 3 we show the fraction of objects that would be detected and cataloged by NEO Surveyor after five years as a function of their orbital elements. Bins showing eccentricities of $e < 0.85$ have few objects in them based on our input population, and in some cases are not shown where no objects were implanted. A semimajor axis of 1 AU approximately traces the edge of the highest completeness bins in the plot of perihelion distance vs eccentricity in Figure 3.

We see that overall, NEO Surveyor will have very high completeness for most of our synthetic population, with low completenesses seen only for the highest eccentricity and highest perihelion distance objects. This class of objects benefits most from longer duration surveys, and so would be expected to grow in completeness as survey continues toward the twelve-year mission goal. Orbital inclination does not show a significant effect on completeness, at least in the parameter range probed by our synthetic population. For different object diameters, completeness in each bin follows the same trend as discussed above, growing with size until completeness reaches 100%. This completeness 'front' tends to follow lines of constant semimajor axis in the perihelion-eccentricity plot.

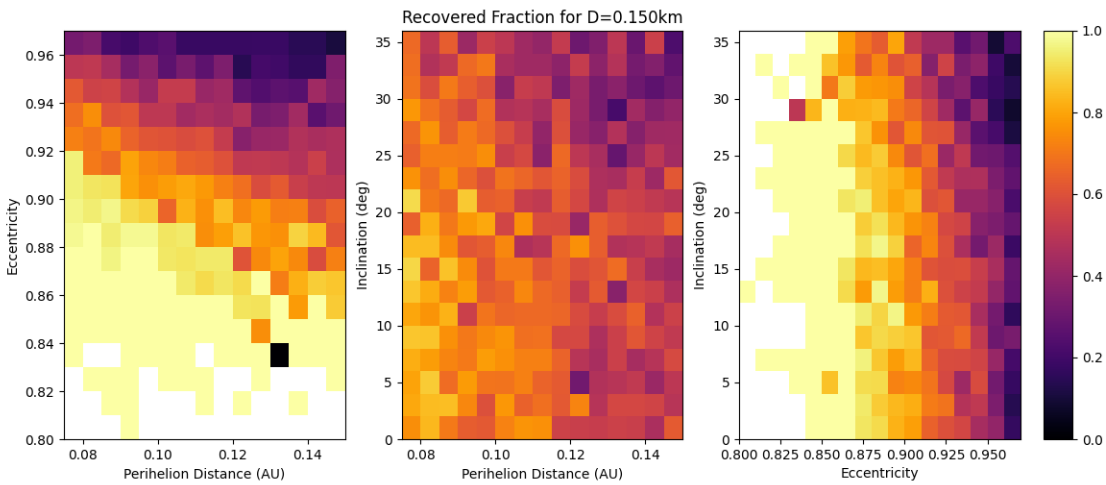

Fig. 3.— Fraction of synthetic objects recovered by NEO Surveyor after 5 years (colorbar) as a function of orbital elements assuming all objects have diameters of D= 150 m. Eccentricity vs perihelion distance (left) shows a strong correlation with recovery fraction; inclination vs perihelion distance (middle) shows only a weak trend; inclination vs eccentricity (right) shows that eccentricity dominates the recoverability.

4. Discussion

Phaethon's current level of activity is insufficient to sustain the Geminid meteor population that we observe today, however it has been postulated to have undergone a major breakup event in the last million years that would have created the Phaethon-Geminid Complex including (potentially) the asteroids (155140) 2005 UD and (225416) 1999 YC (Ohtsuka *et al.* 2006, 2009). If such an event happened, we would expect the population of objects created to follow a size-frequency distribution similar to other observed breakup events, leaving the 6.12-by-4.14 km diameter Phaethon as the largest remnant (Yoshida *et al.* 2023).

Using 2005 UD as the largest fragment (with a diameter of 1.2 km Masiero *et al.* 2019), we constructed a cumulative size frequency distribution (SFD) of cometary fragments larger than $\sim$ 50 m in diameter. The result with a power-law index q is shown in Figure 4. The best estimate and error indicate the median and standard deviation from the literature, respectively. A trend line in this size regime is determined by using three literature studies that provide approximate size ranges: (1) An SFD of stria-forming chunks from Comet West, likely fragmented by water-ice sublimation from Steckloff & Jacobson (2016); (2) an SFD of major fragments of comet 73P/Schwassmann-Wachmann 3 observed by Spitzer Space Telescope from Reach *et al.* (2009), whose upper-limit size is estimated from the flux at 24 μm using an approximate equation; and (3) an SFD of fragments of C/1999 S4 (LINEAR) observed by SWAN telescope from Mäkinen *et al.* (2001). The trend lines and data points in shown are scaled arbitrarily once 2005 UD is set at (size=1.2 km, N=1) as a hard reference point, enabling the high-confidence portion of the data set's size regime to align with the trend line. Based on the estimates, we anticipate that there will be $\sim$140 near-Earth objects besides 2005 UD with a diameter between $\sim$50 m and $\sim$1.2 km.

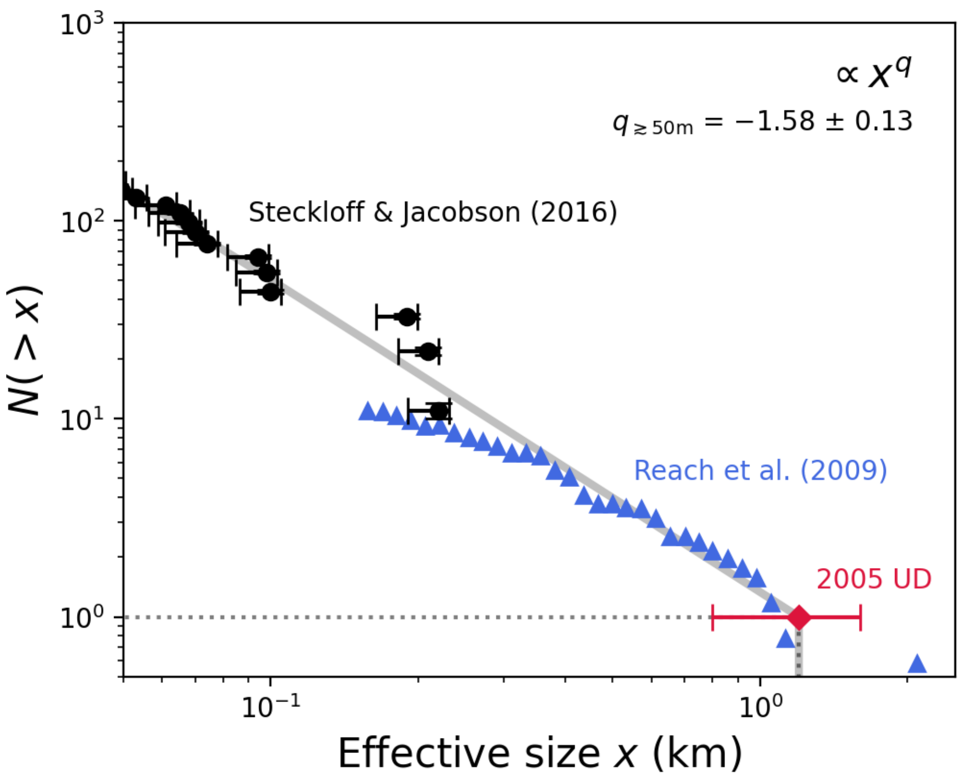

Fig. 4.— Cumulative size frequency distribution (q, grey line) of expected breakup distribution resulting in 2005 UD as the largest fragment (red diamond). Over-plotted are cometary fragment distributions determined by Reach *et al.* (2009) (blue triangles) and Steckloff & Jacobson (2016) (black circles) for analogous situations.

We take this size frequency distribution, and apply our survey completeness parameters for objects on Phaethon-like orbits (Table 1) to determine the expected number of objects that NEO Surveyor will detect from the hypothesized Phaethon-Geminid Complex, which we show in Figure 5. Following the diameter-completeness plots above, the five-year survey carried out by NEO Surveyor would be effectively complete to ~ 200 m for this population.

In total, 43 objects from a breakup event would be expected to be detected over the course of the 5-year survey. This is a significantly larger than the 3 objects that would be expected to be detected in this orbital element phase space from the population present in the NEO Surveyor Reference Small Body Population Model (RSBPM Mainzer *et al.* 2023). Currently in this region of orbital element space there is only 1 object known besides Phaethon: 2007 PR10, which is an insufficient sample to differentiate a breakup complex from the background population. NEO Surveyor will thus provide sufficient data to confirm or refute the existence of a breakup-created Phaethon-Geminid Complex. In the event that our assumption that 2005 UD is the largest breakup fragment is incorrect, and instead a smaller object such as the ~ 600 m (504181) 2006 TC is the largest remnant, NEO Surveyor would still be expected to detect 13 objects over the 5-year survey in this region of orbital element phase space, a statistically significant excess above the background.

5. Conclusions

Using the new software tools developed to validate mission requirements for NEO Surveyor, we have studied the mission's sensitivity to near-Sun asteroids, including objects with orbital elements similar to (3200) Phaethon. We find that NEO Surveyor is highly sensitive to this population, with 50% completeness reached for objects of size D$\sim$ 125 m after 5 years and 90% completeness for objects with D$>$ 400 m for a wide range of near-Sun orbits. Objects on Phaethon-like orbits would be expected to have completenesses of 90% for sizes of D$>$ 200 m. If the Geminid meteor stream formed from a breakup event of a proto-Phaethon object, NEO Surveyor would detect and catalog dozens of members of such a group, allowing us to test this formation theory. This contrasts with the handful of background NEOs in this orbital element space that would be expected to be detected from the nominal RSBPM used for survey evaluation. The data that will be obtained from NEO Surveyor will significantly improve our understanding of objects on near-Sun orbits.

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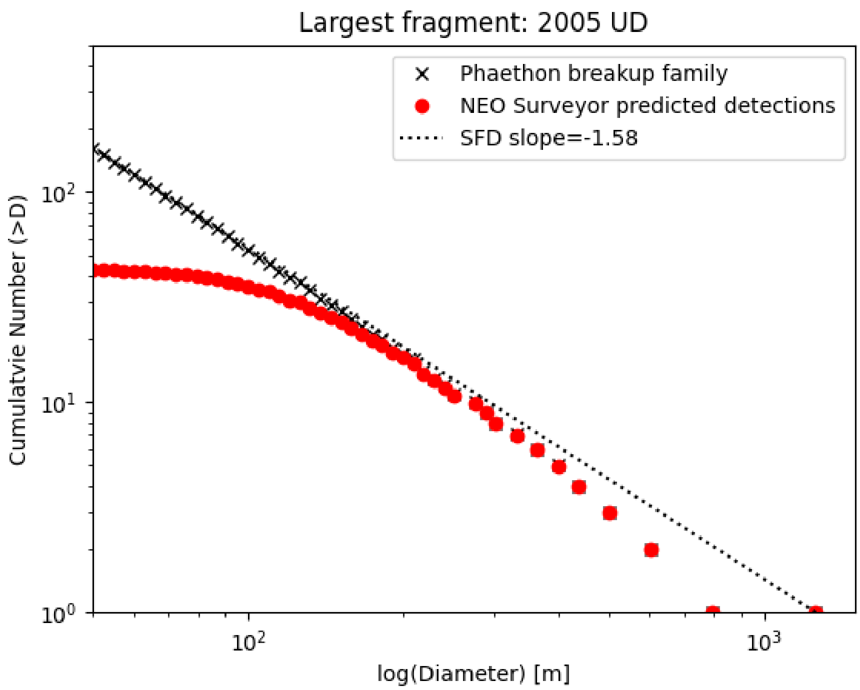

Fig. 5.— Cumulative size frequency distribution of the objects present today in the hypothesized Phaethon-Geminid Complex formed from the breakup of a proto-Phaethon object (black x's) and the subpopulation that would be expected to be detected and cataloged by NEO Surveyor (red circles), under the assumption that the largest fragment of the breakup is (155140) 2005 UD. NEO Surveyor will be approximately complete to D$\sim$ 200 m, and would detect $\sim$ 40 members of this population.

has made use of NASA's Astrophysics Data System Bibliographic Services. This research has made use of the *numpy*, *scipy*, *astropy*, and *matplotlib* Python packages.

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