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The need for speed in Near-Earth Asteroid characterization

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ABSTRACT

We have used Minor Planet Center (MPC) data and tools to explore the discovery circumstances and properties of the currently known population of over 10,000 NEAs, and to quantify the challenges for follow-up from ground-based optical telescopes. The increasing rate of discovery has grown to ~1000/year as surveys have become more sensitive, by 1 mag every ~7.5 years. However, discoveries of large ($H \leq 22$) NEAs have remained stable at ~365/year over the past decade, at which rate the 2005 Congressional mandate to find 90% of 140 m NEAs will not be met before 2030 (at least a decade late). Meanwhile, characterization is falling farther behind: Fewer than 10% of NEAs are well characterized in terms of size, rotation periods, and spectral composition, and at the current rates of follow-up it will take about a century to determine them even for the known population. Over 60% of NEAs have an orbital uncertainty parameter, $U \geq 4$, making reacquisition more than a year following discovery difficult; for $H > 22$ this fraction is over 90%. We argue that rapid follow-up will be essential to characterize newly discovered NEAs. Most new NEAs are found within 0.5 mag of their peak brightness and fade quickly, typically by 0.5/3.5/5 mag after 1/4/6 weeks. About 80% have synodic periods of <3 years that would bring them close to Earth several times per decade. However follow-up observations on subsequent apparitions will be difficult or impossible for the bulk of new discoveries, as these will be smaller ($H > 22$) NEAs that tend to return $100\times$ fainter. We show that for characterization to keep pace with discovery would require: quick (within days) visible spectroscopy with a dedicated ≥2 m telescope; long-arc (months) astrometry, to be used also for phase curves, with a ≥4 m telescope; and fast-cadence (< min) light curves obtained rapidly (within days) with a ≥4 m telescope. For the already-known large ($H \leq 22$) NEAs that tend to return to similar brightness, subsequent-apparition spectroscopy, astrometry, and photometry could be done with 1–2 m telescopes.

1. Introduction

Near-Earth Asteroids (NEAs) are asteroids that have been brought into the inner Solar System mainly through gravitational interactions with Jupiter and Saturn, placing them in orbits with perihelia $q \leq 1.3$ AU that intersect or come close to Earth's orbit (Shoemaker et al., 1979; Bottke et al., 2002; Greenstreet et al., 2012). This population is of interest to science as it provides a probe into the dynamical and compositional evolution of our Solar System and, not least, as a source of objects that have shaped Earth's history, geologically and biologically, through numerous impacts over many millions of years. And they may yet do so again (Shoemaker, 1983).

NEAs have attracted public interest in recent times due to the unexpected 2013 February 15 event when a ~17 m meteor exploded with 500 kt TNT of energy over the city of Chelyabinsk, Russia, and injured over 1000 people (Emel'yanenko et al., 2013; Borovička et al., 2013). The start-up of two private companies aiming to mine valuable resources from NEAs in the near future has rekindled interest in the scientific and for-profit exploration of asteroids (e.g., Elvis, 2014). In addition, the 44th U.S. president, Barack Obama, has made NEAs the prime targets for human space exploration.[1]

In 2005 the U.S. Congress issued a mandate to NASA to find at least 90% of the NEAs larger than 140 m (corresponding to an

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[1] http://www.nasa.gov/news/media/trans/obama_ksc_trans.html

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absolute magnitude[2] of $H \le 22$) by 2020 (Brown Jr., 2005). There are an estimated $13,200 \pm 1900$ in this size range, and $20,500 \pm 2000$ larger than 100 m, or $H \lesssim 23$ (Mainzer et al., 2011). Some argue that follow-up efforts aimed at characterization should concentrate only on the subset of NEAs that come close to Earth (Minimum Orbit Intersection Distance,[3] MOID ≤ 0.05 AU) *and* are larger than ~140 m; these are formally classified as Potentially Hazardous Asteroids (PHAs).[4] However, there are good reasons to design follow-up programs that are broader than that. In terms of hazard assessment, we know that the much more numerous objects smaller than 140 m can pose significant risks (Brown et al., 2013), as we were reminded by the Chelyabinsk event. A large majority (~67%) of the >4900 known NEAs with $H > 22$ have MOID ≤ 0.05 AU. In addition, because PHAs (irrespective of size) are, as far as we know, drawn from the same general population as other NEAs, characterizing the general population will allow us to calibrate the relationships needed to infer physical and orbital evolution properties of the PHA subset. Finally, from the technological standpoint, NASA's proposed Asteroid Redirect Mission[5] requires an 8 m NEA in a favorable orbit be found. A second option for ARM is the retrieval of a 1–5 m boulder from a larger NEA (Abell et al., 2014).

As we argue below, most kinds of follow-up that would help to quantify an object's threat or usefulness must be done within a short window of time, before some of the properties are well-enough known to judge whether it is an "important" object for follow-up or not. Thus we concentrate our discussion on the NEA population as a whole.

In this paper, we use the discovery circumstances and properties of the currently known population of NEAs to quantify some of the challenges that ground-based observers face in making follow-up observations. Our goal is to define the optimal follow-up strategies for NEAs that would allow the bulk of the discovered population to be characterized on a one-decade timescale. This is desirable from a planetary defence perspective because the bulk of the impact hazard resides with the smaller ($H \le 22$), and thus more numerous objects, which are also the least characterized. Gathering these data (composition, structure, size, etc.) for a significant proportion of this size population would allow for better estimates of potential damage due to impact, and more optimistically, better designed missions to deflect or destroy them. For example, if we knew that most 25 m NEAs are monolithic, we would produce different impact damage estimates and deflection mission requirements than if we discovered most of them are rubble piles. Scientifically, knowing the spectral class and spin distributions of a significant portion of a given size population will enable tests of current dynamical evolution models of the inner Solar System as well as possible insights into the collisional history of asteroids and the effect of Solar radiation pressure on spin axis evolution.

We describe our data sources in Section 2, and present current discovery and characterization trends in Section 3. We then describe the known NEA population in terms of brightness behavior (Section 4), positional uncertainties (Section 5), sky motions (Section 6), and hemisphere bias (Section 7). In Section 8, we discuss the implications for follow-up astrometric, photometric, and spectroscopic observations. Finally, in Section 9 we summarize by laying out strategies for increasing the rate of characterization.

In this paper, we use the discovery circumstances and properties of the currently known population of NEAs to quantify some of the challenges that ground-based observers face in performing follow-up observations. Our goals are to define the optimal follow-up strategies for NEAs so the bulk of the discovered population can be characterized on a one-decade timescale, and to provide a centralized source of NEA discovery properties useful for observers planning follow-up programs.

2. Method

The IAU Minor Planet Center[6] (MPC) serves as the world's clearinghouse for NEA observations and orbital data, and provides web-based tools for generating lists of objects that are currently observable, and providing NEA ephemerides. We have written a series of Python programs making use of modules `Mechanize`[7] and `BeautifulSoup4`,[8] to extract data from the MPC webpages and files. We used the following MPC resources.

Data:

- `NEA.txt`[9] provides orbital elements at a nominal epoch, along with absolute magnitude *H*, slope parameter *G*,[10] number of observations, number of oppositions, arc length (for single opposition objects) or years of first and last observations (for multiple opposition objects), and orbital uncertainty parameter *U* (see Section 5.1 for an explanation of this parameter).
- The lists of Atens,[11] Apollos,[12] and Amors[13] provide much of the same data but also include discovery date and site, and Earth MOID, but exclude *U*.

Tools:

- `MPEph`[14] is used to generate a table of ephemerides for user-selected NEAs for a range of dates and times. The data returned include *V* magnitude estimates.
- `NEAobs`[15] is used to generate a list of NEAs suitable for observation according to user-specified criteria including observing location, NEA magnitude, sky motion, solar elongation, RA, Dec, and orbital uncertainty.

We have also made use of the web services of NEODyS-2,[16] which provides convenient text tables of observations for each NEA taken from the MPC's database.

To quantify the various observational follow-up challenges, we use these resources to look at the properties of all NEAs discovered as of 2013 March as described in the sections below. For some of the analysis we also make use of a subsample consisting of the 6763 NEAs discovered during the 10 years spanning January 1, 2002 to December 31, 2011. We call this the "Decade Sample." For

[2] For asteroids, the absolute magnitude *H* is given by the apparent *V* magnitude that the asteroid would have if it could be observed from 1 AU away, at zero phase angle, while it was 1 AU from the Sun.

[3] The Earth MOID is the shortest distance separating the orbit of an asteroid from that of Earth. A small MOID value does not necessarily imply a risk of impact as both Earth and the asteroid are rarely at the points of their orbits closest to each other at the same time.

[4] http://www.minorplanetcenter.net/iau/lists/Dangerous.html

[5] http://www.kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf

[6] http://www.minorplanetcenter.net

[7] http://wwwsearch.sourceforge.net/mechanize/download.html

[8] http://pypi.python.org/pypi/beautifulsoup4/

[9] http://www.minorplanetcenter.net/iau/MPCORB/NEA.txt

[10] The Slope Parameter, *G*, is a measure of how an object's brightness surges when it nears opposition, the so-called *opposition effect*. It is believed to be an interplay of shadowing and coherent-backscattering mechanisms (e.g., Muinonen et al., 2002).

[11] http://www.minorplanetcenter.net/iau/lists/Atens.html

[12] http://www.minorplanetcenter.net/iau/lists/Apollos.html

[13] http://www.minorplanetcenter.net/iau/lists/Amors.html

[14] http://www.minorplanetcenter.net/iau/MPEph/MPEph.html

[15] http://scully.cfa.harvard.edu/cgi-bin/neaobs.cgi

[16] http://newton.dm.unipi.it/neodys/