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The population of near-Earth asteroids

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ABSTRACT

We describe a methodology of estimating the size–frequency distribution (SFD) of near-Earth asteroids (NEAs). We estimate the completion versus size of present surveys based on the re-detection ratio, that is, the fraction of all detections over a recent period that are re-detections of already discovered objects rather than new discoveries. The re-detection ratio is a robust measure of completion, but must be corrected for the obvious bias caused by differences in ease of discovery due to specific orbital geometries. We do this with a computer survey simulation using a large set of synthetic orbital elements matching as best possible the distribution of the real NEA population. Once suitably "calibrated" to match re-detections of the real survey, the completion estimate versus size derived from the simulation can be extended both to large size where few if any new detections are recorded, and to small sizes beyond where re-detection numbers are statistically significant, thereby providing an estimate of the population and survey completion over the entire range from the largest NEAs down to the smallest sizes detected (∼3 m diameter). Here we update our previous population estimates and survey progress, using discoveries by surveys from August, 2012 through July, 2014. We estimate that there are 990 ± 20 NEAs larger than 1 km in diameter (absolute magnitude $H \leqslant 17.75$), of which about 90% have been discovered as of August, 2014. We confirm a "dip" in the SFD, in the range from a few tens to a few hundreds of meters diameter, which may be due to the transition from larger "rubble pile" bodies to smaller "monolithic" bodies. We compare our population estimate at the smallest sizes with recent ones based on bolide frequency and find excellent agreement, within estimated errors. The same survey simulation methodology can be used to investigate population and survey completion of various subset populations, for example Earth-Crossing Asteroids (ECAs, with orbits crossing 1 AU heliocentric distance), Potentially Hazardous Asteroids (PHAs, with orbits passing within 0.05 AU of the Earth's orbit), or Interior to Earth Asteroids (IEOs, with orbits entirely interior to the Earth's orbit). Lastly, we have investigated the population and completion of so-called "ARM-target" asteroids, of size ∼10 m diameter in orbits passing within 0.03 AU of the Earth's orbit with very low Earth-encounter velocity, <2.5 km/s. We find current ground-based surveys are remarkably efficient in detecting this subset of NEAs, and are currently about 1% complete, implying a total population of such bodies of only a few thousand.

1. Introduction

Ever since the discovery of objects in orbits that cross the orbit of the Earth, it has been recognized that such objects might collide with the Earth from time to time, and raises the obvious questions, how many of them are there, and how often to they collide with the Earth? Edmund Halley himself speculated on this issue in his 1705 treatise announcing the orbit of the comet that bears his name. Watson (1941), less than 10 years after the discovery of the first asteroid truly crossing the Earth's orbit, (1862) Apollo, speculated, "Close approaches by these flying mountains [1–2 km in diameter] are rare and the Earth probably goes at least 100,000 years between collisions with them." Watson based his speculation on a total of only three discovered "Apollo" asteroids, all of them since lost (but now re-found), and only one, Apollo itself, as large as 1 km in diameter. Yet his estimate was remarkably close, our current estimate is about once in 500,000 years for an impact by an asteroid as large as 1 km in diameter.

Before the general distribution of orbits was known, it was essentially impossible to estimate an absolute population of objects. So early estimates of impact frequency were based on the frequency of objects passing within a given distance of the Earth. Kresak (1978) used 0.1 AU for his distance and estimated, from the rate of discovery of such objects, that 120–170

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Apollo-type asteroids larger than 1 km in diameter pass within that distance per century, from which he could derive an impact rate. As the distribution of orbits became better known, it became possible to estimate the fraction of orbital space that was being searched by the (then photographic) surveys and thereby estimate the fraction of objects of a given size that should have been detected by the surveys to date. Helin and Shoemaker (1979) applied this method to estimate populations based on their photographic survey using the Palomar 18" Schmidt telescope. They estimated $\sim$100 Atens, 700 ± 300 Apollos, and 1000–2000 Amors larger than 1 km in diameter. These numbers now appear to be about a factor of two too high, but were based on only 12 (!) discoveries by that survey.

Some definition of terms is in order. "NEO" stands for "near-Earth object", and includes any object, asteroid or comet, with perihelion distance q less than 1.3 AU. Our analysis is of only the asteroid component of that population, called near-Earth asteroids (NEAs). Comets are only a small fraction of NEOs. We do not attempt our own definitions or determinations of what is an asteroid versus a comet, but rather simply adopt as NEAs all objects cataloged by the Minor Planet Center with asteroid numbers or temporary designations in the asteroid format. Current tables of these objects can be found at http://www.minorplanetcenter.net/iau/lists/MPLists.html, separated under "Amors", "Apollos" and "Atens". The present analysis is of all NEAs, although we can analyze various sub-sets using the same techniques, for example objects in orbits completely interior to the Earth's orbit (sometimes called Atira asteroids), those crossing the Earth's orbit (ECAs), or only Potentially Hazardous Asteroids (PHAs), those with minimum orbital intersection distance (*MOID*) less than 0.05 AU. In the concluding section of this paper, we will present one such sub-set analysis, of the so-called "ARM-target" asteroids, objects in the size range $\sim$10 m diameter in very Earth-similar orbits, with *MOID* < 0.03 AU and velocity relative to the Earth < 2.6 km/s.

Lastly, we should note that optical surveys measure objects in terms of their intrinsic brightness, not their diameter. But most results are stated in terms of diameter, so some conversion is needed. The brightness is given in absolute magnitude, H, which is the sky brightness the object would have, in the visual (V) color band, 1 AU from the Earth and 1 AU from the Sun, at zero solar phase angle. In order to relate H to diameter D, an albedo needs to be assumed. The fundamental relation between H, D, and albedo, p_V, is (Bowell et al., 1989):

$$D = \frac{1329\ \text{km}}{\sqrt{p_V}} 10^{-H/5} \tag{1}$$

The primary method we will use to estimate population is an extension of that of D'Abramo et al. (2001). In that method, one tabulates for a "test period" (say the most recent 2 years) the number of objects newly discovered by a survey, and the number of like objects (same size range, PHAs or all NEAs) already known that are re-detected by the same survey in the same time interval. If all objects were equally detectable, then the fraction of objects not yet discovered is simply the ratio of new detections to the sum of new detections plus re-detections. However, not all NEAs are equally detectable. The most obvious bias is simply orbital period. Many NEAs in short-period orbit can be seen all around their orbit and in any event come to favorable geometry more frequently than longer period NEAs that are simply too faint to be seen near aphelion and do not come to perihelion very often. In order to correct the population estimates from the D'Abramo et al. method, one must estimate this effect of unequal discovery probability. The way we will do this is to model survey completion versus time by computer simulation, using a model population of NEAs (or PHAs or ECAs) and matching current survey performance as closely as possible. From this, we can match the current survey re-detection versus discovery rate to the computer model, but in the case of the computer model, we know the model population and thus we know the model completion that corresponds to the model re-detection ratio in question. Once we match the model re-detection ratio to the actual survey re-detection ratio over the size range where the re-detection ratio is well determined, we can actually extrapolate the inferred survey completion model outside of that range, and thus estimate completion at the very large end, where not even one new object was detected in the test interval, and to very small sizes where no previously known objects were re-detected.

The outline of this paper is as follows. In Section 2 we collect and present the statistics of discovered NEAs and PHAs as of August, 2014. This file of objects will serve as our baseline for the population estimates to follow. In Section 3, we use the file of discoveries of the last 2 years to evaluate the performance of current surveys in terms of limiting magnitude versus rate of motion of actual discoveries. In Section 4, we describe how we arrive at the distribution of synthetic orbital elements that were used for the survey modeling starting from the elements of the largest actually discovered objects to estimate the complete distribution of elements. In Section 5 we describe the methodology of the computer survey simulation and calibration to the real survey via the "re-detection ratio". In Section 6 we present the results of our analysis, the estimated completion of current surveys, and the inferred total population, size frequency distribution, over the entire range of size of discovered NEAs. In Section 7, we evaluate as best we can the various errors and uncertainties, both random and systematic, that affect our analysis. In Section 8, we digress a bit to show how the survey simulation model can be used for analysis of special populations, in this case the so-called "ARM-target" NEAs with orbits very close to the Earth's and Earth encounter velocities less than $\sim$2.5 km/s. In Section 9, we summarize our main results, especially noting our model improvements which now bring our population estimate at the small end into close agreement with estimates from bolide frequency, within uncertainties of either estimate.

2. Current discovery status

In the sections that follow, we need a standardized list of NEAs and PHAs with absolute magnitudes, since the final output is a size–frequency distribution, number versus H magnitude (or equivalently, diameter). We adopt the files given on the Minor Planet Center web site, which lists all discovered NEAs, with orbital elements, *MOID*, H magnitudes, and date of discovery. In this study, we will take a diameter of 1.0 km to be equivalent to an absolute magnitude $H = 17.75$ (Stuart and Binzel, 2004; Stokes et al., 2003). This corresponds to a mean albedo for NEAs of $p_V = 0.14$. Recent results from the NEOWISE IR survey (Mainzer et al., 2011) confirm this choice since their estimate of NEA population $D > 1$ km is almost identical to ours based on H, and the thermal IR measures D fairly directly, rather than H. It should be noted, however, that there appears to exist a systematic error in H magnitude in the Minor Planet Center orbit file, MPCORB, of as much as 0.4 magnitudes in the range of $H > 14$ (Pravec et al., 2012). Pravec et al. based this determination on a sample of all asteroids, not just NEAs, for which we have precise photometric H values. It may be that the offset is different for NEAs than for other asteroids, but in any case, there could be an average offset for most NEAs of as much as 0.3 magnitudes at $H \sim 17$–18, in the sense that the tabulated magnitudes are too bright. This does not mean that the estimate of the number of NEAs larger than 1 km is "wrong", but rather that the actual mean albedo is higher by $\sim$30%, to offset the systematic bias in H magnitudes.