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On the rotation rates and axis ratios of the smallest known near-Earth asteroids—The archetypes of the Asteroid Redirect Mission targets

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ABSTRACT

NASA's Asteroid Redirect Mission (ARM) has been proposed with the aim to capture a small asteroid a few meters in size and redirect it into an orbit around the Moon. There it can be investigated at leisure by astronauts aboard an Orion or other spacecraft. The target for the mission has not yet been selected, and there are very few potential targets currently known. Though sufficiently small near-Earth asteroids (NEAs) are thought to be numerous, they are also difficult to detect and characterize with current observational facilities. Here we collect the most up-to-date information on near-Earth asteroids in this size range to outline the state of understanding of the properties of these small NEAs. Observational biases certainly mean that our sample is not an ideal representation of the true population of small NEAs. However our sample is representative of the eventual target list for the ARM mission, which will be compiled under very similar observational constraints unless dramatic changes are made to the way near-Earth asteroids are searched for and studied.

We collect here information on 88 near-Earth asteroids with diameters less than 60 m and with high quality light curves. We find that the typical rotation period is 40 min. Relatively few axis ratios are available for such small asteroids, so we also considered the 92 smallest NEAs with known axis ratios. This sample includes asteroids with diameters up to 300 m. The mean and median axis ratios were 1.43 and 1.29, respectively.

Rotation rates much faster than the spin barrier are seen, reaching below 30 s, and implying that most of these bodies are monoliths. Non-principal axis rotation is uncommon. Axial ratios often reach values as high as two, though no undisputed results reach above three. We find little correlation of axis ratio with size. The most common spectral type in the sample of small NEAs is S-type (>90%), with only a handful of C and X types known.

1. Introduction

In a detailed study of a hypothetical mission to retrieve a small asteroid and bring it to near-Earth space, the Keck Institute for Space Studies (KISS) report (Brophy et al., 2012)[1] concluded that “one of the most challenging aspects of the mission was the identification and characterization of target NEAs suitable for capture and return” (p. 7). The report also outlines three key mission drivers, one of which is “the size and mass of the target body” (p. 28); the two others are the total delta-v required for capture and return, and the total flight time.

The design of the Asteroid Redirect Mission or a similar mission depends significantly on the properties of the target, namely its mass, size, density, internal cohesiveness, spin state, surface roughness, presence/absence of regolith and so forth. In the ideal case, mission planners will have complete information on the target's characteristics before launch. However, the near-Earth asteroids in the appropriate size range, which we will refer to as Very Small Asteroids or VSAs, are particularly difficult to characterize. They are faint and spend only a short time (typically days) within easy reach of Earth-based telescopes when they are first discovered, often not returning to the Earth's vicinity for several years.

Only relatively few of the already-known near-Earth asteroid population make suitable targets, as most known NEAs are simply too big. The discovery rate of suitable asteroids for the ARM was estimated in the KISS report (Table 2) to be five asteroids per year if a low-cost ground-based telescopic campaign was begun specifically

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[1] Available at http://kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf (retrieved 2014 July 24).

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to search for such asteroids; however, such a dedicated program is not yet in place. The total known sample of potential targets as of June 2014 is only nine[2] and what is known of their properties is scattered throughout the literature and internet. By collecting information on the smallest known NEAs, we hope to make the discussion of relevant design issues simpler.

The heliocentric orbit of an asteroid can be relatively easily determined, requiring only a handful of astrometric measurements from short imaging exposures, and the orbit provides enough information for the mission to be launched and to arrive at its destination successfully. Not that a high-precision orbit can necessarily be determined from the few-day apparition of a newly discovered small asteroid, but orbits are typically easier to measure than an asteroid's physical and internal properties and this may limit how accurately the density, spin state, taxonomy, etc. of the target is known before the mission proper is launched. Though there is always the option to study the target intensively when it makes a subsequent passage near the Earth, these opportunities may occur only at intervals of years, decades or even longer, and waiting for them could delay the mission significantly.

Furthermore, even careful study may not reveal all the properties of interest of a particular target. Hergenrother and Whiteley (2011) and Kwiatkowski et al. (2010b) examined the light curves of many small asteroids, and they point out that these are not always conclusive. Non-detections of asteroid brightness variations could indicate a non-rotating body, but could also be the result of asteroid shapes that are close to spherical, viewed pole-on and/or with rapid rotation periods that are not properly sampled by the exposure times used. Since smaller asteroids have a tendency to rotate rather quickly compared to large ones (Pravec and Harris, 2000), issues of this sort complicate the picture. Studies such as the present paper of the properties of the ARM target population as a whole can shed light on the probable characteristics of individual targets for which some properties cannot be measured prior to launch.

Considering as well the long flight time for the ARM (six to ten years), it is conceivable that an incompletely characterized asteroid with a particularly favorable orbit (i.e. one that would result in a shorter travel time or a lower delta-v, and hence a lower cost for the mission) might be more enticing as a candidate than a better-studied small asteroid whose orbit is less favorable. As a result, a statistical study of the properties of small asteroids in general provides helpful insight as to the likely or worst-case properties of a potential target that is not yet fully characterized.

In the following sections, we collect the information available on VSAs in an attempt to paint a picture of a typical asteroid within the size range suitable to be an ARM target. This picture will include the most likely spin-state, shape, and composition of such an asteroid. In addition, we will also discuss the "worst-case" scenario for an ARM target in terms of extremes of rotation rate and the likelihood of a tumbler or non-principal axis (NPA) rotator.

2. Methods

The body of results on asteroids within the desired size range is small. A large portion of the information presented here was gathered from the Light Curve Database (LCDB, Warner et al., 2009). Additional information was collected from published asteroid surveys presented by Whiteley et al. (2002), Kwiatkowski et al. (2010a,b), Hergenrother and Whiteley (2011), Hergenrother et al. (2012), Polishook et al. (2012) and Statler et al. (2013).

In obtaining data from the LCDB and the other surveys, we selected two samples. One contained the smallest asteroids with known rotation periods, and the other one the smallest asteroids with known axis ratios, as unfortunately not all small asteroids have measurements of both of these quantities.

The first sample was selected on two criteria. Firstly, given the scarcity of data on asteroids with diameters of ten meters and under, we chose a sample of asteroids with estimated diameters of 60 meters and under as a proxy. The choice of 60 meters as our upper-boundary is arbitrary, but it gave us a sizable amount of data without straying too far from the intended diameter. It also allows some consideration of the alternative ARM scenario nicknamed *Pick Up A Rock*, where instead of retrieving an asteroid whole (the *Get a Whole One* scenario), a boulder or other material would be recovered from the surface of a larger body. Secondly, for data that came directly from the LCDB, asteroids with a quality rating U lower than $2-$ were not included in the study. (The LCDB quality rating runs from 1 (low) through $1+$, $2-$, 2, $2+$, $3-$ to 3 (high).) This first sample we will refer to as the $D \leq 60$ m sample, and contains 88 objects. We note that the diameter measurement is an equivalent diameter computed from the absolute magnitude and an assumed albedo. Such measurements invariably contain some uncertainty but this is not quoted in the LCDB and we do not discuss it here. For more information on the methods by which these quantities are deduced the reader is directed to Warner et al. (2009).

It proves difficult to find derived axial ratios (or a/b ratios) in the literature, and most members of our first sample do not have reported axis ratios. So a second sample was selected to increase the number of axis ratios available. Since the LCDB does not quote the necessary data, these asteroids are selected from the papers referenced in paragraph 1 of this section. We had to increase the size limit of the second sample to $\sim$300 m in order to obtain a sizable sample of known axial ratios (92 asteroids in total). We call this second sample the a/b ratio sample.

We note that asteroid shape – specifically its a/b ratio, assuming a simplified triaxial ellipsoid shape where the axis lengths are $a \geq b \geq c$ – is not typically a parameter that is calculated in most light curve studies. To overcome this, a formula presented by Kwiatkowski et al. (2010a) was used in order to determine the minimum a/b ratio from two parameters that are usually found in most surveys; the light curve amplitude A and the phase angle α (Eq. (1)). We calculate the minimum axis ratio here (that is, we assume equality in Eq. (1)) which thus is a lower limit.

$$\frac{a}{b} \geq 10^{0.4A(\alpha)/(1+0.03\alpha)} \quad (1)$$

Non-principal axis (NPA) rotators (or tumbling asteroids) are also taken into account here. NPA rotation is unstable rotation that occurs when an asteroid is not spinning around its principal axis of maximum inertia, a state which may be caused by an impact with a meteoroid or another asteroid. During NPA rotation, energy is slowly dissipated from the asteroid until the body returns to stable principal-axis rotation. Information on whether an asteroid was a suspected tumbler is often recorded in the LCDB or the various surveys, though it should be noted that these asteroids have not all been confirmed to be tumblers. Some of these asteroids have been deemed possible tumblers simply because of the irregularity of their light curves, and further study is necessary to confirm NPA rotation. For the purposes of this study, if an asteroid is either a confirmed or possible tumbler, it has been designated as a tumbler in our samples. It is noted in Warner et al. (2009) that there may be selection biases against small fast-rotating tumblers due to the additional data required to properly analyze a light curve with tumbling characteristics, therefore there is a possibility that our study underestimates the true fraction of tumblers in the general VSA population.

[2] NASA Announces Latest Progress in Hunt for Asteroids, http://www.jpl.nasa.gov/news/news.php?release=2014-195 (retrieved 2014 November 9).