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Spectral properties of near-Earth and Mars-crossing asteroids using Sloan photometry

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ABSTRACT

The nature and origin of the asteroids orbiting in near-Earth space, including those on a potentially hazardous trajectory, is of both scientific interest and practical importance. We aim here at determining the taxonomy of a large sample of near-Earth and Mars-crosser asteroids and analyze the distribution of these classes with orbit. We use this distribution to identify the source regions of near-Earth objects and to study the strength of planetary encounters to refresh asteroid surfaces. We measure the photometry of these asteroids over four filters at visible wavelengths on images taken by the Sloan Digital Sky Survey (SDSS). These colors are used to classify the asteroids into a taxonomy consistent with the widely used Bus-DeMeo taxonomy (DeMeo et al. [2009]. Icarus 202, 160–180) based on visible and near-infrared spectroscopy. We report here on the taxonomic classification of 206 near-Earth and 776 Mars-crosser asteroids determined from SDSS photometry, representing an increase of 40% and 663% of known taxonomy classifications in these populations. Using the source region mapper by Greenstreet et al. (Greenstreet, S., Ngo, H., Gladman, B. [2012]. Icarus, 217, 355–366), we compare for the first time the taxonomic distribution among near-Earth and main-belt asteroids of similar diameters. Both distributions agree at the few percent level for the inner part of the main belt and we confirm this region as a main source of near-Earth objects. The effect of planetary encounters on asteroid surfaces are also studied by developing a simple model of forces acting on a surface grain during planetary encounter, which provides the minimum distance at which a close approach should occur to trigger resurfacing events. By integrating numerically the orbit of the 519 S-type and 46 Q-type asteroids in our sample back in time for 500,000 years and monitoring their encounter distance with Venus, Earth, Mars, and Jupiter, we seek to understand the conditions for resurfacing events. The population of Q-type is found to present statistically more encounters with Venus and the Earth than S-types, although both S- and Q-types present the same amount of encounters with Mars.

1. Introduction

Asteroids are the leftovers of the building blocks that accreted to form the planets in the early Solar System. They are also the progenitors of the constant influx of meteorites falling on the planets, including the Earth. Apart from the tiny sample of rock from asteroid (25,143) Itokawa brought back by the Hayabusa spacecraft (Nakamura et al., 2011), these meteorites represent our sole possibility to study in details the composition of asteroids. Identifying their source regions is crucial to determine the physical conditions and abundances in elements that reigned in the protoplanetary nebula around the young Sun (see, e.g., McSween et al., 2006). From the analysis of a bolide trajectory, it is possible to reconstruct its heliocentric orbit and to find its parent body (e.g., Gounelle et al., 2006), but such determinations have been limited to a few objects only (Rudawska et al., 2012).

Among the different dynamical classes of asteroids, the near-Earth and Mars-crosser asteroids (NEAs and MCs), whose orbits cross that of the telluric planets, form a transient population. Their typical lifetime is of a few million years only (Bottke et al., 2002;

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Morbidelli et al., 2002) before being ejected from the Solar System, falling into the Sun, or impacting a planet. These populations are therefore constantly replenished by asteroids from the main asteroid belt, the largest reservoir of known small bodies, between Mars and Jupiter.

The resonances between the orbits of asteroids and that of Jupiter have been long thought (Wetherill, 1979; Wisdom, 1983) to provide the kick in eccentricity necessary to place asteroids on planet-crossing orbits. It was later found that the secular resonance ν_6, delimiting the inner edge of the main belt, and the 3:1 mean-motion resonance (MMR) with Jupiter, separating the inner from the middle belt, were the most effective, compared to the 5:2 resonance, for instance, which tends to eject asteroids from the Solar System (see Morbidelli et al., 2002 for a review). The major role played by the ν_6 resonance was confirmed by the comparison between the reflectance spectra of the most common meteorites, the ordinary chondrites (OCs, 80% of all meteorite falls), the dominant class in the near-Earth space, the S-type asteroids (about 65% of the observed population, Binzel et al., 2004), and the dynamical family of S-types asteroids linked with (8) Flora in the inner belt (Vernazza et al., 2008).

The NEAs also represent ideal targets for space exploration owing to their close distance from Earth. This proximity is quantified by the energy required to set a spacecraft on a rendezvous trajectory and is often expressed as Δv (in km/s), the required change in speed. This is the reason why the first mission to an asteroid targeted the Amor (433) Eros (Veverka et al., 2000), why all the targets of sample-return missions were selected among NEAs: (25,143) Itokawa for JAXA Hayabusa (Fujiwara et al., 2006), (101,955) Bennu for NASA OSIRIS-REx (Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer, Lauretta et al., 2011), (162,173) Ryugu for JAXA Hayabusa2 (Yano et al., 2010), and (175,706) 1996 FG3 and (341,843) 2008 EV5 for the former ESA M3/M4 candidate MarcoPolo-R (Barucci et al., 2012) and ARM (Asteroid Redirect Mission, Abell et al., 2015), and why the recent proposition for a demonstration project of an asteroid deflection by ESA, AIDA (Asteroid Impact & Deflection Assessment, Murdoch et al., 2012), targets the NEA (65,803) Didymos. This latter point, the protection from asteroid hazard, is certainly the most famous aspect of the asteroid research known to the general public, and has triggered many initiatives leading to breakthroughs in NEA discovery and characterization of their surface and physical properties (see, e.g., Binzel, 2000; Stokes et al., 2000; Ostro et al., 2002; Binzel et al., 2004; Jedicke et al., 2007; Mainzer et al., 2011a; Mueller et al., 2011 among others).

In both attempting to link NEAs and MCs transient populations with their source regions and meteorites and designing a protection strategy, the study of their composition is key. Indeed, dynamical studies allows to determine relative probabilities of the origin of asteroids belonging to those populations (e.g., Bottke et al., 2002; Greenstreet et al., 2012). These links are however not sufficient, and must be ascertained by compositional similarities (Vernazza et al., 2008; Binzel et al., 2015; Reddy et al., 2015). Moreover, different compositions yield different densities and internal structure/cohesion (Carry, 2012), and an asteroid on a impact trajectory with Earth of a given size will require a different energy to be deflected or destroyed according to its nature (Jutzi and Michel, 2014).

Here, we aim at classifying a large number of near-Earth and Mars-crosser asteroids into broad compositional groups by using imaging archival data. We present in Section 2 the procedure we used to retrieve the photometry at visible wavelengths from the publicly available images of the Sloan Digital Sky Survey (SDSS). We describe in Section 3 how we use the SDSS photometry to classify the objects into the commonly-used Bus-DeMeo taxonomy of asteroids (DeMeo et al., 2009), following the work by DeMeo and Carry (2013). We present the results of the classification in Section 4 before discussing their implications for source regions in Section 5 and for surface rejuvenation processes in Section 6.

2. Visible photometry for the Sloan Digital Sky Survey

2.1. The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS) is a wide-field imaging survey dedicated to observing galaxies and quasars at different wavelengths. From 1998 to 2009, the survey covered over 14,500 square degrees in 5 filters: u', g', r', i', z' (centered on 355.1, 468.6, 616.5, 748.1 and 893.1 nm), with estimated limiting magnitude of 22.0, 22.2, 22.2, 21.3, and 20.5 for 95% completeness (Ivezić et al., 2001).

2.2. The Moving Object Catalog

In the course of the survey, 471,569 moving objects were identified in the images and listed in the Moving Object Catalogue (SDSS MOC, currently in its 4th release, including observations through March 2007). Among these, 220,101 were successfully linked to 104,449 unique objects corresponding to known asteroids (Ivezić et al., 2001). The remaining 251,468 moving objects listed in the MOC corresponded to unknown asteroids at the time of the release (August 2008).

First, we keep objects assigned a number or a provisional designation only, i.e., those for which we can retrieve the orbital elements. Among these, we select the near-Earth and Mars-crossers asteroids according to the limits on their semi-major axis, perihelion, and aphelion listed in Table 1, resulting in 2071 observations of 1315 unique objects. We then remove observations that are deemed unreliable: with any apparent magnitudes greater than the limiting magnitudes reported above (Section 2.1), or any photometric uncertainty greater than 0.05. These constraints remove a large portion of the dataset (about 75%), primarily due to the larger typical error for the z' filter. While there is only a small subset of the sample remaining, we are assured of the quality of the data (see DeMeo and Carry, 2013 for additional information on the definition of photometric cuts). Additionally, for higher errors, the ambiguity among taxonomic classes possible for an object becomes so large that the classification (Section 3) becomes essentially meaningless. In this selection process, we kept 588 observations of 353 individual asteroids from the SDSS MOC4, as listed in Table 1.

2.3. Identifying unknown objects in the MOC4

As mentioned above, more than half of the MOC4 entries had not been linked with known asteroids. At the time of the release (August 2008), about 460,000 asteroids had been discovered and 350,000 were numbered (i.e., had well-constrained orbits allowing easy cross-matching with SDSS detected sources). The current number of discovered asteroids has now risen above 700,000, with more than 370,000 numbered objects. We therefore use the improved current knowledge on the asteroid population to link unknown MOC sources to known objects.

We use the Virtual Observatory (VO) SkyBoT cone-search service (Berthier et al., 2006), hosted at IMCCE,[1] for that purpose. SkyBoT pre-computes weekly the ephemeris of all known Solar System objects for the period 1889–2060, and stores their heliocentric positions with a time step of 10 days, allowing fast computation of positions at any time. The cone-search tool allows to request the list of known objects within a field of view at any given epoch as seen from

[1] http://vo.imcce.fr/webservices/skybot/.