Icarus 226 (2013) 723–741

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The taxonomic distribution of asteroids from multi-filter all-sky photometric surveys

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ARTICLE INFO

Article history:
Received 6 April 2013
Revised 4 June 2013
Accepted 24 June 2013
Available online 4 July 2013

Keywords:
Asteroids, Surfaces
Asteroids, Composition
Spectrophotometry

ABSTRACT

The distribution of asteroids across the main belt has been studied for decades to understand the current compositional distribution and what that tells us about the formation and evolution of our Solar System. All-sky surveys now provide orders of magnitude more data than targeted surveys. We present a method to bias-correct the asteroid population observed in the Sloan Digital Sky Survey (SDSS) according to size, distance, and albedo. We taxonomically classify this dataset consistent with the Bus and Binzel (Bus, S.J., Binzel, R.P. [2002]. Icarus 158, 146–177) and Bus–DeMeo et al. (DeMeo, F.E., Binzel, R.P., Slivan, S.M., Bus, S.J. [2009]. Icarus 202(July), 160–180) systems and present the resulting taxonomic distribution. The dataset includes asteroids as small as 5 km, a factor of three in diameter smaller than in previous work such as by Mothé-Diniz et al. (Mothé-Diniz, T., Carvano, J.M.Á., Lazzaro, D. [2003]. Icarus 162(March), 10–21). Because of the wide range of sizes in our sample, we present the distribution by number, surface area, volume, and mass whereas previous work was exclusively by number. While the distribution by number is a useful quantity and has been used for decades, these additional quantities provide new insights into the distribution of total material. We find evidence for D-types in the inner main belt where they are unexpected according to dynamical models of implantation of bodies from the outer Solar System into the inner Solar System during planetary migration (Levison, H.F., Bottke, W.F., Gounelle, M., Morbidelli, A., Nesvorný, D., Tsiganis, K. [2009]. Nature 460(July), 364–366). We find no evidence of S-types or other unexpected classes among Trojans and Hildas, albeit a bias favoring such a detection. Finally, we estimate for the first time the total amount of material of each class in the inner Solar System. The main belt's most massive classes are C, B, P, V and S in decreasing order. Excluding the four most massive asteroids, (1) Ceres, (2) Pallas, (4) Vesta and (10) Hygiea that heavily skew the values, primitive material (C-, P-types) account for more than half main-belt and Trojan asteroids by mass, most of the remaining mass being in the S-types. All the other classes are minor contributors to the material between Mars and Jupiter.

1. Introduction

The current compositional makeup and distribution of bodies in the asteroid belt is both a remnant of our early Solar System's primordial composition and temperature gradient and its subsequent physical and dynamical evolution. The distribution of material of different compositions has been studied based on photometric color and spectroscopic studies of ~2,000 bodies in visible and near-infrared wavelengths (Chapman et al., 1971, 1975; Gradie and Tedesco, 1982; Gradie et al., 1989; Bus, 1999; Bus and Binzel, 2002a; Mothé-Diniz et al., 2003). These data were based on all available spectral data at the time the work was performed including spectral surveys such as Tholen (1984), Zellner et al. (1985), Barucci et al. (1987), Xu et al. (1995), Bus and Binzel (2002a), Lazzaro et al. (2004).

The first in-depth study showing the significance of global trends across the belt looked at surface reflectivity (albedo) and spectrometric measurements of 110 asteroids. It was then that the dominant trend in the belt was found: S-types are more abundant in the part of the belt closer to the Sun and the C-types further out (Chapman et al., 1975). Later work by Gradie and Tedesco (1982) and Gradie et al. (1989) revealed clear trends for each of the major classes of asteroids, concluding that each group formed close to its current location.

The Small Main-belt Asteroid Spectroscopic Survey (SMASSII, Bus and Binzel, 2002b) measured visible spectra for 1447 asteroids and the Small Solar System Objects Spectroscopic Survey (S3OS2) observed 820 asteroids (Lazzaro et al., 2004). The conclusion of

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0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.06.027

these major spectral surveys brought new discoveries and views of the main belt. Bus and Binzel (2002b) found the distribution to be largely consistent with Gradie and Tedesco (1982), however they noted more finer detail within the S and C complex distributions, particularly a secondary peak for C-types at 2.6 AU and for S-types at 2.85 AU. Mothé-Diniz et al. (2003) combined data from multiple spectral surveys looking at over 2000 asteroids with H magnitudes smaller than 13 (D $\sim$ 15 km for the lowest albedo objects). Their work differed from early surveys finding that S-types continued to be abundant at further distances, particularly at the smaller size range covered in their work rather than the steep dropoff other surveys noted.

Only in the past decade have large surveys at visible and mid-infrared wavelengths been available allowing us to tap into the compositional detail of the million or so asteroids greater than 1 km that are expected to exist in the belt (Bottke et al., 2005). The results of these surveys (including discovery surveys), however, are heavily biased toward the closest, largest, and brightest of asteroids. This distorts our overall picture of the belt and affects subsequent interpretation.

In this work we focus on the data from the Sloan Digital Sky Survey Moving Object Catalog (SDSS, MOC, Ivezić et al., 2001, 2002) that observed over 100,000 unique asteroids in five photometric bands over visible wavelengths. These bands provide enough information to broadly classify these objects taxonomically (e.g., Carvano et al., 2011). In this work we refer to the SDSS MOC as SDSS for simplicity. We classify the SDSS data and determine the distribution of asteroids in the main belt. We present a method to correct for the survey's bias against the dimmest, furthest bodies.

Traditionally, the asteroid compositional distribution has been shown as the number objects of each taxonomic type as function of distance. While the number distribution is important for size–frequency distributions and understanding the collisional environment in the asteroid belt, the concern with this method is that objects of very different sizes are weighted equally. For example, objects with diameters ranging from 15 km to greater than 500 km were assigned equal importance in previous works. This is particularly troublesome for SDSS and other large surveys because the distribution by number further misrepresents the amount of material of each class by equally weighting objects that differ by two orders of magnitude in diameter and by six orders of magnitude in volume. To create a more realistic and comprehensive view of the asteroid belt we provide the taxonomic distribution according to number, surface area, volume, and mass. New challenges are presented when attempting to create these distributions including the inability to account for the smallest objects (below the efficiency limit of SDSS), the incompleteness of SDSS even at size ranges where the survey is efficient, and incomplete knowledge of the exact diameters, albedos and densities of each object. We attempt to correct for as many of these issues as possible in the present study.

The distribution according to surface area is perhaps the most technically correct result because only the surfaces of these bodies are measured. We only have indirect information about asteroid interiors, mainly derived from the comparison of their bulk density with that of their surface material, suggesting differentiation in some cases, and presence of voids in others (e.g., Consolmagno et al., 2008; Carry, 2012). The homogeneity in surface reflectance and albedo of asteroids pertaining to dynamical families (e.g., Ivezić et al., 2002; Cellino et al., 2002; Parker et al., 2008; Carruba et al., 2013) however suggest that most asteroids have an interior composition similar to their surface composition. Nevertheless, recent models find that large bodies even though masked with fairly primitive surfaces could actually have differentiated interiors (Elkins-Tanton et al., 2011; Weiss et al., 2012). The distribution of surface area is relevant for dust creation from non-catastrophic collisions (e.g. Nesvorný et al., 2006, 2008) and from a resource standpoint such as for mining materials on asteroid surfaces. The volume of material provides context for the total amount of material in the asteroid belt with surfaces of a given taxonomic class. While we do not know the actual composition or properties of the interiors we can at least account for the material that exists.

The most ideal case is to determine the distribution of *mass*. This view accounts for all of the material in the belt, corrects for composition and porosity of the interior and properly weights the relative importance of each asteroid according to size and density. While the field is a long way away from having perfectly detailed shape and density measurements for every asteroid, by applying estimated sizes and average densities per taxonomic class to a large, statistical sample, we provide in this work the first look at the distribution of classes in the asteroid belt according to mass, and estimate the total amount of material each class represents in the inner Solar System.

Section 2 introduces the data used for this work. We overview observing biases and our correction method in Sections 3 and 4. We describe our classification method for our sample in Section 5. We then explain in Section 6 our method for building the compositional distribution and application of our dataset to all asteroids in the main belt. Finally, we present in Section 7 the bias-corrected taxonomic distribution of asteroid material across the main belt according to number, surface area, volume, and mass, and discuss the results in Section 8.

2. The dataset

2.1. Selection of high quality measurements from SDSS

The Sloan Digital Sky Survey (SDSS) is an imaging and spectroscopy survey dedicated to observing galaxies and quasars (Ivezić et al., 2001). The images are taken in five filters, u′, g′, r′, i′, and z′, from 0.3 to 1.0 μm. The survey also observed over 400,000 moving objects in our Solar System of which over 100,000 are unique objects linked to known asteroids. The current release of the Moving Object Catalogue (SDSS MOC 4, Ivezić et al., 2002) includes observations through March 2007.

We restrict our sample from the SDSS MOC database according to the following criteria. First, we keep only objects assigned a number or a provisional designation, i.e., those for which we can retrieve the orbital elements. We then remove observations that are deemed unreliable: with any apparent magnitudes greater than 22.0, 22.2, 22.2, 21.3, 20.5 for each filter (5.9% of the SDSS MOC4), which are the limiting magnitudes for 95% completeness (Ivezić et al., 2001), or any photometric uncertainty greater than 0.05 (excluding the u′ filter, explained below). These constraints remove a very large portion of the SDSS dataset (about 87% of all observations), largely due to the greater typical error for the z′ filter. While there is only a small subset of the sample remaining (Fig. 1), we are assured of the quality of the data. Additionally, for higher errors, the ambiguity among taxonomic classes possible for an object becomes so great that any classification becomes essentially meaningless. We exclude the u′ filter from this work primarily because of the significantly higher errors in this filter compared to the others (Fig. 2), and secondarily because neither the Bus nor Bus–DeMeo taxonomies (that we use as reference for classification consistency, Bus and Binzel, 2002a; DeMeo et al., 2009) covered that wavelength range.

The fourth release of the MOC contains non-photometric nights in the dataset. The SDSS provides data checks that indicate