Asteroids Observed by The Sloan Digital Sky Survey

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ABSTRACT

We announce the first public release of the SDSS Moving Object Catalog, with SDSS observations for 58,117 asteroids. The catalog lists astrometric and photometric data for moving objects observed prior to Dec 15, 2001, and also includes orbital elements for 10,592 previously known objects. We analyze the correlation between the orbital parameters and optical colors for the known objects, and confirm that asteroid dynamical families, defined as clusters in orbital parameter space, also strongly segregate in color space. Their distinctive optical colors indicate that the variations in chemical composition within a family are much smaller than the compositional differences between families, and strongly support earlier suggestions that asteroids belonging to a particular family have a common origin.

Keywords: Solar System, asteroids, photometry

1. INTRODUCTION

SDSS is a digital photometric and spectroscopic survey which will cover 10,000 deg^2 of the Celestial Sphere in the North Galactic cap and produce a smaller ($\sim$ 225 deg^2) but much deeper survey in the Southern Galactic hemisphere.[1] The survey sky coverage will result in photometric measurements for about 50 million stars and a similar number of galaxies. About 30% of the Survey is currently finished. The flux densities of detected objects are measured almost simultaneously in five bands[2] (u, g, r, i, and z) with effective wavelengths of 3551 rA, 4686 rA, 6166 rA, 7480 rA, and 8932 rA, 95% complete for point sources to limiting magnitudes of 22.0, 22.2, 22.2, 21.3, and 20.5 in the North Galactic cap. Astrometric positions are accurate[3] to about 0.1 arcsec per coordinate (rms) for sources brighter than 20.5^m, and the morphological information from the images allows robust star-galaxy separation[4] to $\sim 21.5^m$.

1.1. SDSS Observations of Moving Objects

SDSS, although primarily designed for observations of extragalactic objects, is significantly contributing to studies of the solar system objects, because asteroids in the imaging survey must be explicitly detected to avoid contamination of the samples of extragalactic objects selected for spectroscopy. Preliminary analysis of SDSS commissioning data[5] showed that SDSS will increase the number of asteroids with accurate five-color photometry by more than two orders of magnitude (to about 100,000), and to a limit about five magnitudes fainter (seven magnitudes when the completeness limits are compared) than previous multi-color surveys (e.g. The Eight Color Asteroid Survey[6]). The main results derived from these early SDSS observations are

1. A measurement of the main-belt asteroid size distribution to a significantly smaller size limit (< 1 km) than possible before. The size distribution resembles a broken power-law, independent of the heliocentric distance: $D^{-2.3}$ for 0.4 km $< D <$ 5 km, and D^{-4} for 5 km $< D <$ 40 km.

2. A smaller number of asteroids compared to previous work. In particular, the number of asteroids with diameters larger than 1 km is about 7×10^5.

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3. The distribution of main-belt asteroids in 4-dimensional SDSS color space is strongly bimodal, and the two groups can be associated with S (rocky) and C (carbonaceous) type asteroids, in agreement with previous studies based on smaller samples.[7] A strong bimodality is also seen in the heliocentric distribution of asteroids: the inner belt is dominated by S type asteroids centered at $R \sim 2.8$ AU, while C type asteroids, centered at $R \sim 3.2$ AU, dominate the outer belt.

The preliminary analysis of SDSS commissioning data was based on a sample of about 10,000 objects. Here we describe the first public catalog of SDSS asteroid observations that includes about 60,000 objects, and show an example of analysis made possible by such a large, accurate and homogeneous database.

2. THE SDSS MOVING OBJECT CATALOG

The purpose of this catalog (the Sloan Digital Sky Survey Moving Object Catalog, hereafter SDSSMOC) is to promptly distribute data for moving objects detected by SDSS. Some of these data have already been released as a part of the SDSS Early Data Release (EDR). While EDR, and all future releases, will be accessible from the SDSS Data Archive, it is probably more convenient for many users to have the relevant data in a simple text file. In addition, the proposed selection cuts have been tested in practice, and corresponding estimates of the sample completeness and contamination are available.[5,8] Of course, one can design own selection criteria and start from scratch.

The first release of SDSSMOC* includes all data obtained up to Dec 15, 2001. The catalog includes data for 58,117 moving objects from 87 observing runs that roughly cover the area included in the upcoming SDSS Data Release 1 scheduled for January 6, 2003. SDSSMOC will be updated about once a month (i.e. once per every dark run), with a time delay of about 1-3 weeks between the observations and public release. This time delay is mandated by the minimum time needed for data processing and quality assurance procedures.

The SDSSMOC includes various identification parameters, SDSS astrometric measurements (position and velocity, with errors), SDSS photometric measurements (five SDSS magnitudes and their errors), and orbital information for previously cataloged asteroids.

2.1. Data Selection

For methods of accessing SDSS data products, and detailed product description, please see SDSS EDR paper[9] (also available as http://archive.stsci.edu/sdss/paper.html). The moving object catalog contains all the objects that satisfy the following SXQL query:

```
WHERE (
   (objFlags & (OBJECT_SATUR | OBJECT_BRIGHT)) == 0
      &&
   (objFlags & OBJECT_DEBLENDED_AS_MOVING) > 0
      &&
   (objc_type == 6)
      &&
   (psfCounts[2] > 14.5) && (psfCounts[2] < 21.5)
      &&
   (rowv*rowv + colv*colv > 0.0025)
      &&
   (rowv*rowv + colv*colv < 0.25)
)
```

The first line excludes all saturated and bright objects (the latter are always duplicate objects), and the second line requires that the object was recognized as a moving object by SDSS photometric pipeline.[4,5] The latter requirement selects objects closer than about 10 AU. The third and fourth lines require that the object is

*Available from http://www.sdss.org/science/index.html unresolved and brighter than r=21.5, and the last condition requires that the magnitude of the object's velocity vector is larger than 0.05 deg/day. Note that some of these entries are multiple observations of the same objects.

The completeness[8] (number of moving objects detected by the software that are included in the catalog, divided by the total number of moving objects recorded in the images) of this catalog is about 90%, and its contamination rate[5] is about 3% (the number of entries that are not moving objects, but rather instrumental artifacts). That is, about 6,000 observed moving objects were missed by the processing software, and about 2,000 catalog entries are instrumental and software artifacts.

2.2. Post Processing

We matched 58,117 moving objects to known objects listed in the ASTORB file,[10] and found 12,602 matches (for 10,592 unique objects). The osculating orbital elements from ASTORB file for these objects are also listed in the catalog, as well as proper orbital elements,[11] when available.

2.3. The Catalog Format

The catalog is distributed as uncompressed ASCII file (30 MB), and a gzip compressed file (6.5 MB), with one record (line) per object observation. Detailed documentation and catalog are available at http://www.sdss.org. To ease the use of a SDSSMOC file, we also provide a sample C program, which can be used as a template when developing your own processing tools.

2.4. Referencing

We would greatly appreciate if you reference this paper, and add the following acknowledgement to your papers based on this catalog:

The Sloan Digital Sky Survey (SDSS) is a joint project of The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Max-Planck-Institute for Astronomy, the Max-Planck-Institute for Astrophysics, New Mexico State University, Princeton University, the United States Naval Observatory, and the University of Washington. Apache Point Observatory, site of the SDSS telescopes, is operated by the Astrophysical Research Consortium (ARC).

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3. THE SDSS COLORS OF ASTEROID FAMILIES

Most of the asteroids observed by the SDSS are new detections, because the SDSS finds moving objects to a fainter limit ($V \sim 21.5$) than the completeness limit of currently available asteroid catalogs ($V \sim 18$). This improvement allows the determination of the size distribution[5] to a smaller size limit (0.4 km) than possible before. On the other hand, SDSS observations, which are obtained with a baseline of only 5 minutes, are insufficient to determine accurate orbits. Accurate orbital parameters are required to study the colors of asteroid dynamical families.[12] To overcome this shortcoming, we have matched[8] SDSS observations to a catalog of orbital parameters for known asteroids.[10] Here we show an example of how the resulting database can be used to study the physical properties of asteroids and constrain their origins.

We analyze SDSS colors of 10,592 previously known objects from the SDSS MOC discussed in the previous Section.[12] This sample is about an order of magnitude larger than used in previous studies of the colors of asteroids, and also benefits from the wide wavelength range spanned by SDSS filters.[13] SDSS colors can distinguish asteroids of at least three different color types.[5,8] Using four of the five SDSS bands, we construct the color-color diagram shown in the top right panel in Figure 1. The two chosen colors are the principal axes for the asteroid distribution in the SDSS photometric system,[5] with the horizontal axis defined as

$$a^* \equiv 0.89\,(g-r) + 0.45\,(r-i) - 0.57. \qquad (1)$$

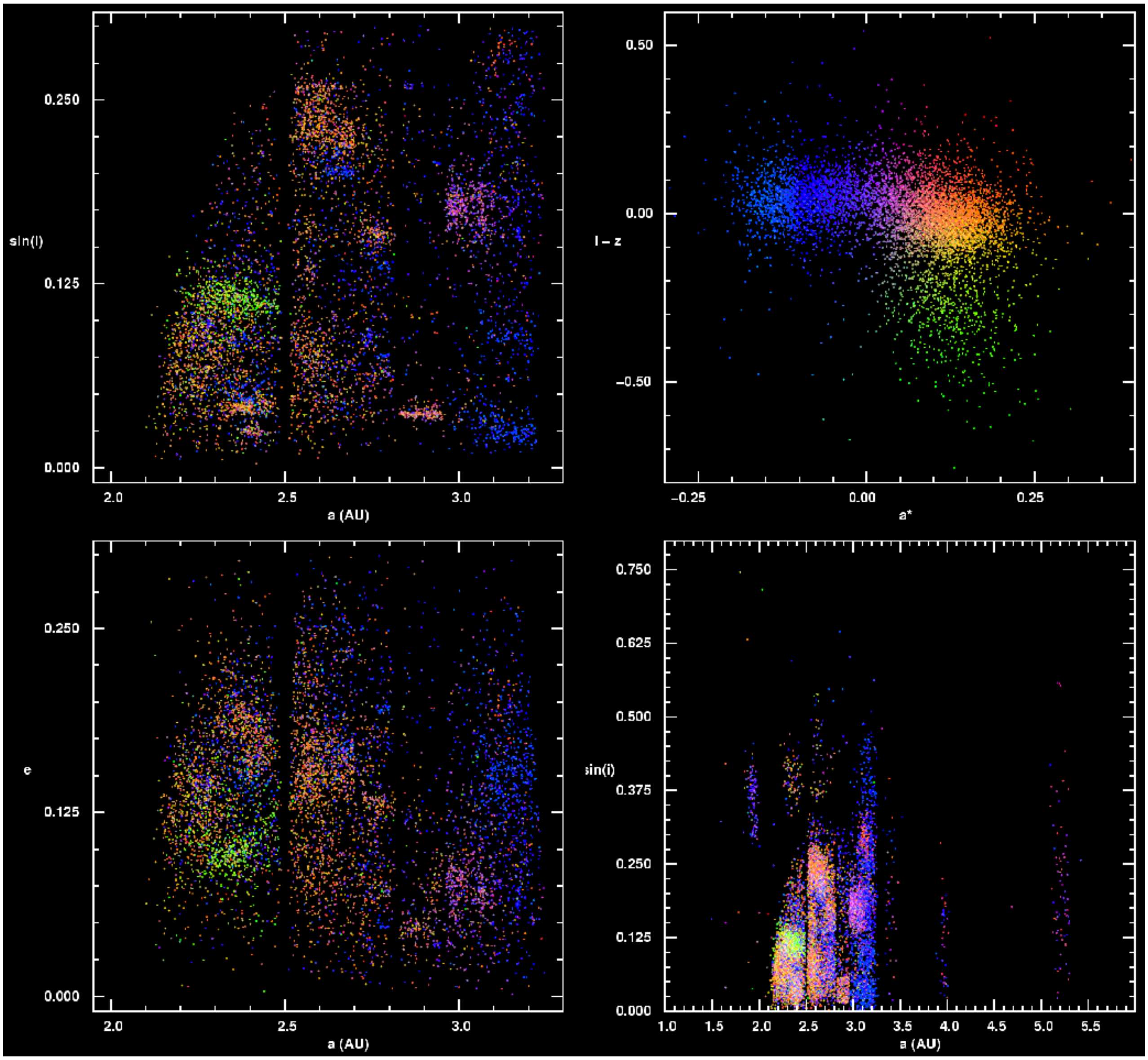

Figure 1. The top right panel shows color-color diagram constructed using the principal axes for the asteroid distribution in the SDSS photometric system. Each dot represents one asteroid. The top and bottom left panels show two two-dimensional projections of the asteroid distribution in the space spanned by proper orbital elements, with the points color-coded as in the top right panel. The bottom right shows the distribution of all the 10,592 known asteroids observed by the SDSS in the space spanned by osculating semi-major axis and the sine of the orbital inclination angle.

Each dot represents one asteroid, and is color-coded according to its position in this diagram. The asteroid distribution in this diagram is highly bimodal, with over 90% of objects found in one of the two clumps that are dominated by rocky S type asteroids ($a^* \sim 0.15$), and carbonaceous C type asteroids ($a^* \sim -0.1$). Most of the remaining objects have a^* color similar to S type asteroids, and distinctively blue $i^* - z^*$ colors. They are dominated by Vesta type asteroids.[8,14]

The top and bottom left panels in Figure 1 show two two-dimensional projections of the asteroid distribution in the space spanned by proper† semi-major axis, eccentricity, and the sine of the orbital inclination angle, with the points color-coded as in the top right panel. The vertical bands where practically no asteroids are found (at a of 2.065, 2.501, 2.825 and 3.278 AU) are the 4:1, 3:1, 5:2, and 2:1 mean motion resonances with Jupiter (the latter three are the Kirkwood gaps). A striking feature of these two diagrams is the color homogeneity and distinctiveness displayed by asteroid families. Each of the three major Hirayama families, Eos, Koronis and Themis, with approximate $(a, \sin(i), e)$ of (3.0, 0.18, 0.08), (2.9, 0.03, 0.05) and (3.15,0.02, 0.15), respectively, and also the Vesta family at (2.35, 0.12, 0.09), has a characteristic color. This strong color segregation provides firm support for the reality of asteroid dynamical families. The correlation between the asteroid colors and their heliocentric distance has been recognized since the earliest development of asteroid taxonomies.[6,7,16,17] Our analysis indicates that this mean correlation is mostly a reflection of the distinctive colors of asteroid families and their heliocentric distribution.

Proper orbital elements[11] are not available for asteroids with large semi-major axis and orbital inclination. In order to examine the color distribution for objects with large semi-major axis, such as the Trojan asteroids ($a \sim 5.2$) and for objects with large inclination, such as asteroids from the Hungaria family ($a \sim 1.9, \sin(i) \sim 0.38$), we use osculating orbital elements. The bottom right panel in Figure 1 shows the distribution of all the 10,592 known asteroids observed by the SDSS in the space spanned by osculating semi-major axis and the sine of the orbital inclination angle, with the points color-coded as in the top right panel. It is remarkable that various families can still be easily recognized due to SDSS color information. This figure vividly demonstrates that the asteroid population is dominated by objects that belong to numerous asteroid families.

When only orbital elements are considered, families often partially overlap each other,[18] and additional independent information is needed to improve their definitions. With such a massive, accurate and public database as that discussed here, it will be possible to improve the classification of asteroid families by simultaneously using both the orbital elements and colors. For example, the SDSS colors show that the asteroids with $(a, \sin(i))$ about (2.65, 0.20) are distinctively blue (the top left panel in Figure 1), proving that they do not belong to the family with $(a, \sin(i))$ about (2.60, 0.23), but instead are a family in their own right. While this and several similar examples were already recognized as clusters in the orbital parameter space,[18] this work provides a dramatic independent confirmation. Figure 1 suggests that the asteroid population is dominated by families: even objects that do not belong to the most populous families, and thus are interpreted as background in dynamical studies, seem to show color clustering. Using the definitions of families based on dynamical analysis,[18] and aided by SDSS colors, we estimate that at least 90% of asteroids are associated with families.

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†The proper orbital elements are nearly invariants of motion and are well suited for discovering objects with common dynamical history.[11,15]

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