COLOR CONFIRMATION OF ASTEROID FAMILIES

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ABSTRACT

We discuss optical colors of 10,592 asteroids with known orbits selected from a sample of 58,000 moving objects observed by the Sloan Digital Sky Survey. This is more than 10 times larger than any sample that includes both orbital parameters and multiband photometric measurements previously available. We confirm that asteroid dynamical families, defined as clusters in orbital parameter space, also strongly segregate in color space. In particular, we demonstrate that the three major asteroid families (Eos, Koronis, and Themis) together with the Vesta family represent four main asteroid color types. Their distinctive optical colors indicate that the variations in chemical composition within a family are much smaller than the compositional differences between families, and they strongly support earlier suggestions that asteroids belonging to a particular family have a common origin. We estimate that over 90% of asteroids belong to families.

Key words: minor planets, asteroids — solar system: general

1. INTRODUCTION

Asteroid dynamical families are groups of asteroids in orbital element space (Gradie, Chapman, & Williams 1979; Gradie, Chapman, & Tedesco 1989; Valsecchi et al. 1989). This clustering was first discovered by K. Hirayama (1918; for a review, see Binzel 1994), who also proposed that families may be the remnants of parent bodies that broke into fragments. About half of all known asteroids are believed to belong to families; recent work (Zappalà et al. 1995, hereafter Z95), applying a hierarchical clustering method to a sample of 12,487 asteroids, has found over 30 families. The contrast between families and the background is especially strong in the space spanned by the so-called *proper* orbital elements. These elements are nearly invariants of motion and are thus well suited for discovering objects with a common dynamical history (Valsecchi et al. 1989; Milani & Knežević 1992, hereafter MK92). The current asteroid motion is described by *osculating* orbital elements, which vary with time as a result of perturbations caused by planets and are less suitable for studying dynamical families.

Asteroid clustering is much weaker in the space spanned by directly observed osculating elements than in the space spanned by derived proper elements. Figure 1 compares the distributions of osculating (*top*; Bowell 2001)[5] and proper (*bottom*; MK92) orbital inclination versus orbital eccentricity for 1720 asteroids from the outer region of the main asteroid belt (proper semimajor axis larger than 2.84 AU). This region contains all three major asteroid 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. Here a is proper semimajor axis, $\sin i$ is the sine of the orbital inclination angle, and e is eccentricity.

The proper elements are derived from the osculating elements by an approximate perturbation method (MK92), and it is possible that the overdensities evident in the bottom panel are at least partially created by that algorithm (Valsecchi et al. 1989; Bendjoya 1993). A firm proof that families are real therefore requires their confirmation by a method that is *not* based on dynamical considerations, for example, that dynamically selected groups have distinctive colors. While there is observational evidence that at least the most populous asteroid families have characteristic colors (Degewij, Gradie, & Zellner 1978; Chapman et al. 1989; Bus 1999), even the most recent studies of the colors of asteroid families include fewer than 50 objects per family (Florczak et al. 1998; Doressoundiram et al. 1998; Florczak et al. 1999). The large number (about 10,000) of color measurements for cataloged asteroids (Bowell 2001) recently made available by the Sloan Digital Sky Survey (SDSS; York et al. 2000) allow a detailed investigation of this question.

2. SDSS OBSERVATIONS OF ASTEROIDS

SDSS is a digital photometric and spectroscopic survey that will cover one-quarter of the celestial sphere in the north Galactic cap and produce a smaller but much deeper multiepoch survey in the southern Galactic hemisphere (Stoughton et al. 2002). The survey sky coverage will result in photometric measurements (Hogg et al. 2001; Smith et al. 2002) for about 50 million stars and a similar number of galaxies, and spectra for about 1 million galaxies and 100,000 quasars. Although primarily designed for observations of extragalactic objects, SDSS is significantly contributing to studies of solar system objects, because asteroids in the imaging survey must be explicitly recognized in order to avoid contamination of the quasar samples selected for spectroscopic observations (Lupton et al. 2001). SDSS will increase the number of asteroids with accurate five-color photometry (Fukugita et al. 1996; Gunn et al. 1998) by more than 2 orders of magnitude (to about 100,000), and to a limit more than 5 mag fainter than previous multicolor surveys (Ivezić et al. 2001, hereafter I01).

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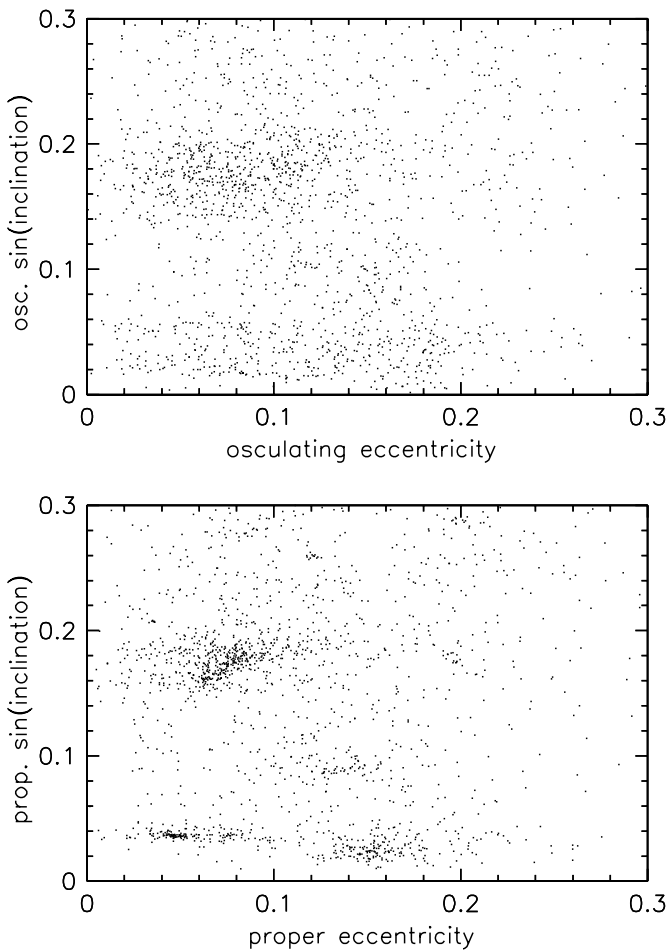
[5] See ftp://ftp.lowell.edu/pub/elgb/astorb.html.

FIG. 1.—Distribution of 1720 asteroids from the outer region of the main asteroid belt (proper semimajor axis larger than 2.84 AU). The top panel is constructed with osculating elements, and the bottom panel with proper elements. The clustering is much stronger in proper-element space.

2.1. *SDSS Moving-Object Catalog*

Most of the asteroids observed by SDSS are new detections, because SDSS finds moving objects to a fainter limit ($V \sim 21.5$) than the completeness limit of currently available asteroid catalogs ($V \sim 18$). However, SDSS observations, which are obtained with a baseline of only 5 minutes (Lupton et al. 2001; I01), are insufficient to determine accurate orbits, and we consider only objects that have previously determined orbital parameters. The details of the matching procedure and a preliminary sample are described in Jurić et al. (2002, hereafter J02). Here we extend that analysis to a significantly larger sample and introduce a new method for visualizing the distribution of asteroids in a multidimensional space spanned by orbital parameters and colors.

The currently available SDSS moving-object list (MOC)[6] includes over 58,000 observations; 10,592 are detections of unique objects listed in the catalog of known asteroids (Bowell 2001), and 2010 detections are multiple observations of the same objects. For a subset of 6612 objects from this list, the proper orbital elements are also available (MK92) and are analyzed here. These samples are about an order of magnitude larger than used in previous studies of

the colors of asteroids, and they also benefit from the wide wavelength range spanned by SDSS filters (Gunn et al. 1998).[7]

2.2. *Asteroid Colors as Observed by SDSS*

SDSS colors can distinguish asteroids of at least three different color types (I01; J02). Using four of the five SDSS bands, we construct the color-color diagram shown in Figure 2. The horizontal axis[8] is

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

and the vertical axis is $i-z$, where $g-r$, $r-i$, and $i-z$ are the asteroid colors measured by SDSS (accurate to about 0.03 mag). Each dot represents one asteroid and is color-coded according to its position in this diagram (note that these colors do not correspond directly to asteroid colors as would be seen by the human eye). As discussed in I01, the asteroid distribution in this diagram[9] 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^* colors similar to S-type asteroids and distinctively blue $i-z$ colors. They are dominated by Vesta-type asteroids (Binzel & Xu 1993; J02).

Figures 3 and 4 show two two-dimensional projections of the asteroid distribution in the space spanned by proper semimajor axis, eccentricity, and the sine of the orbital inclination angle, with the points color-coded as in Figure 2. 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). Figure 5 is analogous to the bottom panel of Figure 1.

3. DISCUSSION

A striking feature of Figures 3, 4, and 5 is the color homogeneity and distinctiveness displayed by asteroid families. Each of the three major Hirayama families—Eos, Koronis, and Themis—and also the Vesta family, at (a, sin i, e) of (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 (Chapman, Morrison, & Zellner 1975; Gradie & Tedesco 1982; Zellner, Tholen, & Tedesco 1985; Gradie et al. 1989). Our analysis indicates that this mean correlation (see, e.g., Fig. 23 in I01) is mostly a reflection of the distinctive colors of asteroid families and their heliocentric distribution.

When only orbital elements are considered, families often partially overlap each other (Z95), and additional independent information is needed to improve their definitions. With such a massive, accurate and public database as that discussed here (the SDSS MOC), it will be possible to improve the classification of asteroid families by simultaneously

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[6] Available from http://www.sdss.org/science/index.html.

[7] The z band extends to the near-infrared range and allows efficient recognition of Vesta-type asteroids (Binzel & Xu 1993).

[8] See I01 for a discussion of a^* color.

[9] For the position of asteroid taxonomic classes in this diagram, see Fig. 10 in I01.
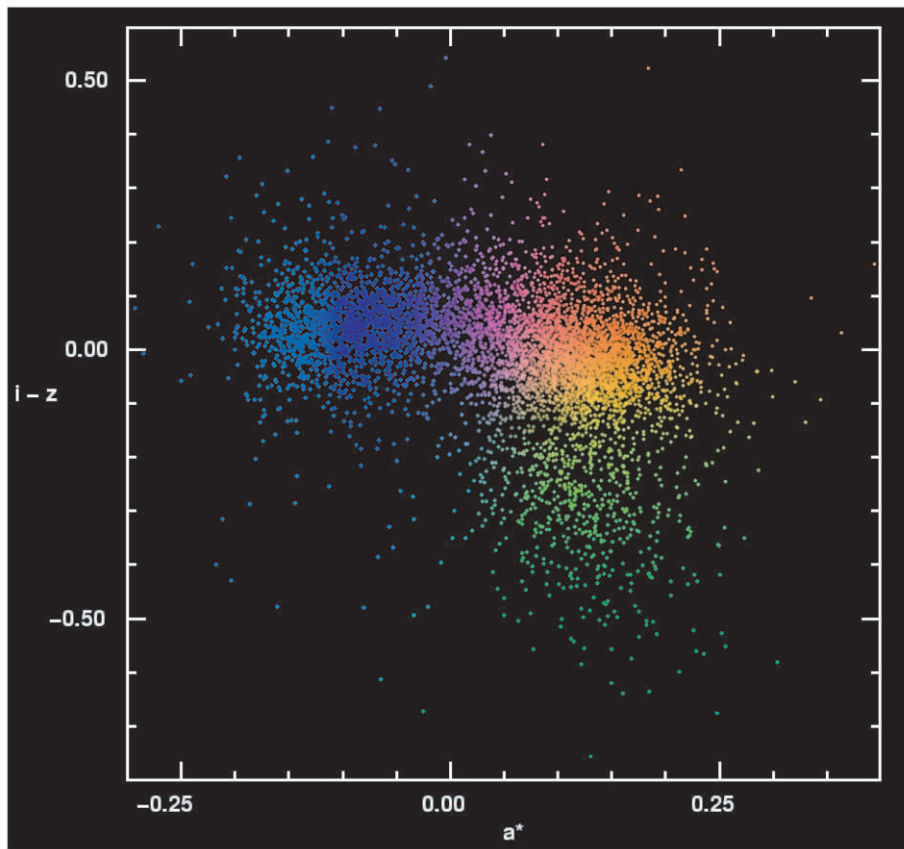
FIG. 2.—Distribution of 6612 asteroids with available proper orbital elements in the space spanned by SDSS colors
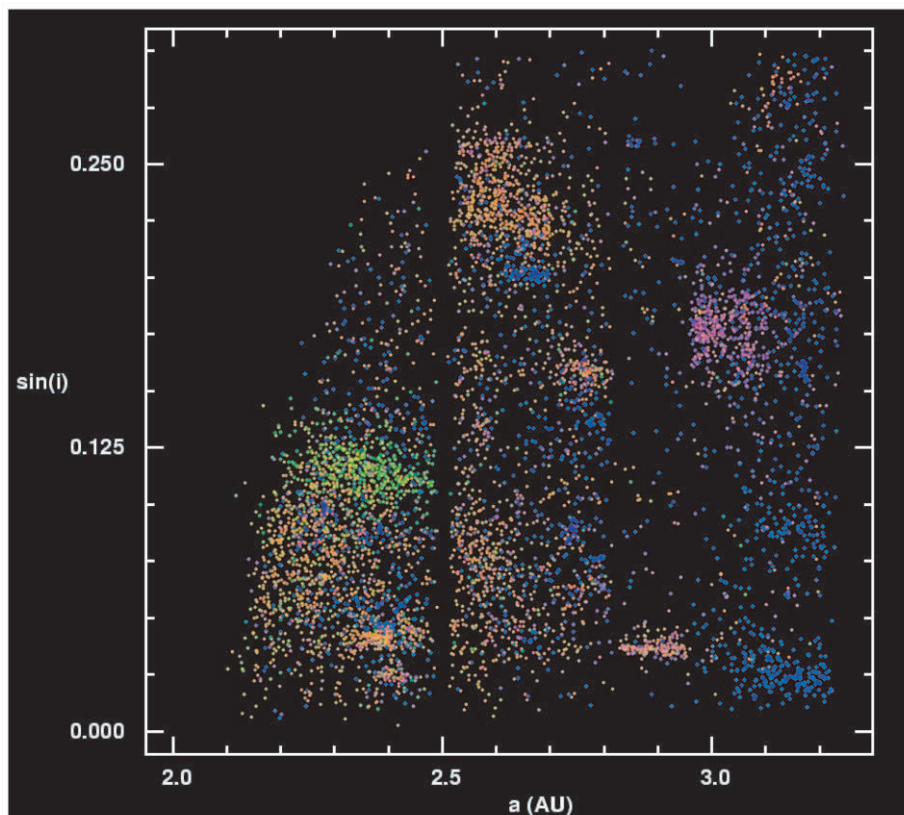

FIG. 3.—Distribution of the 6612 asteroids in the space spanned by proper inclination and semimajor axis. The dots are colored according to their position in the SDSS color-color diagram shown in Fig. 2.
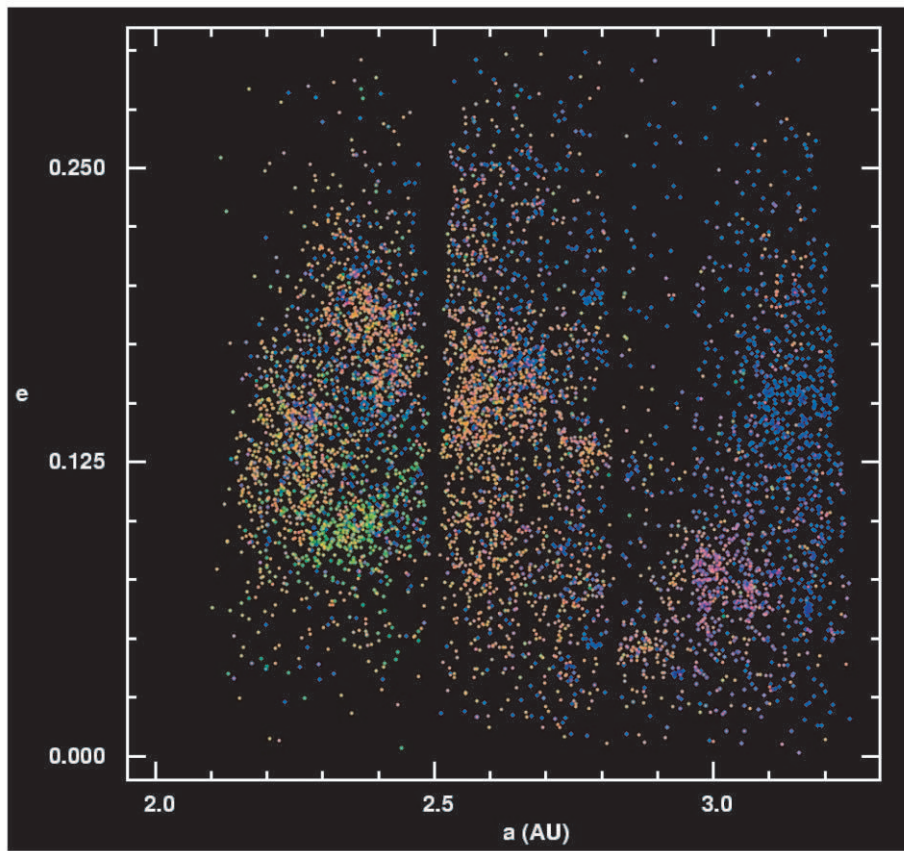
Fig. 4.—Same as Fig. 3, except that here the distribution in proper eccentricity vs. semimajor axis is shown
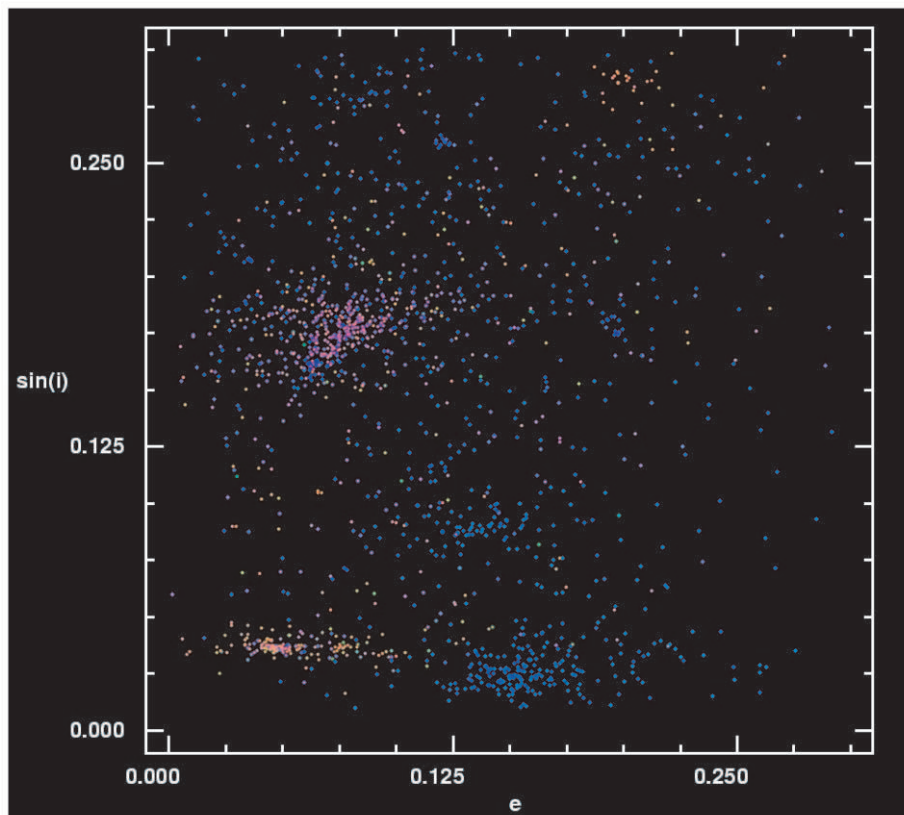

Fig. 5.—An analogous diagram to that shown in the bottom panel of Fig. 1, except that here the SDSS color information is also displayed, using the color-coding shown in Fig. 2 (only objects with proper semimajor axis larger than 2.84 AU are displayed).

using both the orbital elements and colors. For example, the SDSS colors show that the asteroids with $(a, \sin i) \sim (2.65, 0.20)$ are distinctively blue (Fig. 3), proving that they do not belong to the family with $(a, \sin i) \sim (2.60, 0.23)$ 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 (Z95), this work provides a dramatic independent confirmation. Figures 3, 4, and 5 suggest 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 objects in dynamical studies, seem to show color clustering. Using the definitions of families based on dynamical analysis (Z95), and aided by SDSS colors, we estimate that at least 90% of asteroids are associated with families.[10]

Proper orbital elements (MK92) are not available for asteroids with large semimajor axis and orbital inclination. In order to examine the color distribution for objects with large semimajor axis, such as 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. Figure 6 shows the distribution of all the 10,592 known asteroids observed by SDSS in the space spanned by osculating semimajor axis and the sine of the orbital inclination angle, with the points color-coded as in Figure 2. It is remarkable that various families can still be easily recognized thanks to SDSS color information. This figure vividly demonstrates that the asteroid population is dominated by objects that belong to numerous asteroid families.

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[10] The preliminary analysis indicates that about 1%–5% of objects do not belong to families. A more detailed discussion of the robustness of this result will be presented in a forthcoming publication. Similarly, it is not certain yet whether objects not associated with the families show any heliocentric color gradient.
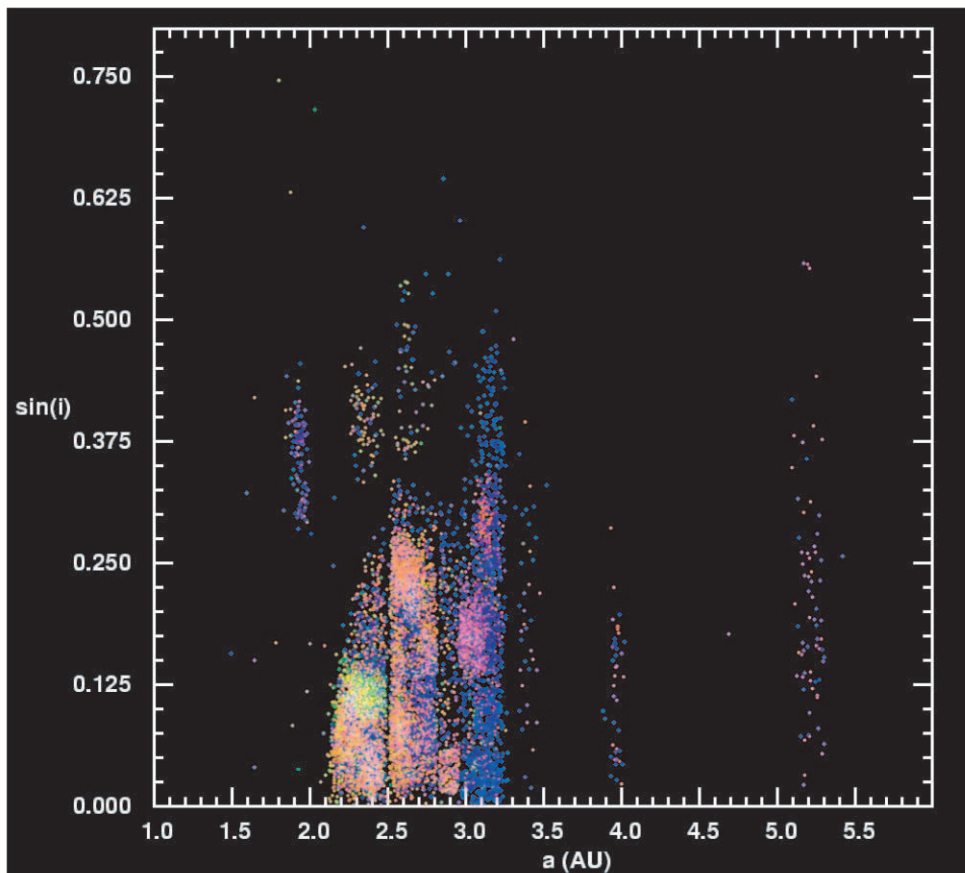

FIG. 6.—Distribution of 10,592 known asteroids observed by SDSS in the space spanned by the osculating inclination and semimajor axis. The dots are colored according to their position in SDSS color-color diagram shown in Fig. 2. Note that the asteroid population is dominated by families.

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