Evidence for Asteroid Space Weathering
from the Sloan Digital Sky Survey

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ABSTRACT

By studying color variations between young and old asteroid families, we find evidence for processes that modify colors of asteroids over time. We show that colors of ageing surfaces of S-types asteroids become increasingly ‘redder’. For the first time, we measure the rate of these spectral changes. We estimate that the mean spectral slope between 0.35 and 0.9 μm increases with time $t$ (given in My) as $\sim 0.01 \log_{10} t$ for $t \gtrsim 5$ My. We also find that Gy-old terrains of S-type asteroids reflect about 15% more light at $\sim$1-μm wavelengths then a $\sim$5-My-old asteroid surface when flux is normalized by the reflected light at 0.55 μm. We attribute these effects to space weathering. This result has profound implications for asteroid geology and for the origin of meteorites that we collect at the Earth. Our results also suggest that surfaces of C-type asteroids exhibit color alterations opposite to those of the S-type asteroids. We make this case by using the wide-wavelength photometry of 125K asteroids obtained by the Sloan Digital Sky Survey.
1. Introduction

Studies of soils and rocks collected by the Apollo astronauts provide evidence for processes that alter optical properties of the lunar surface (Pieters et al. 2000, Hapke 2001). Similarly, optical properties of an asteroid surface probably change over time (Chapman 1996, Clark et al. 2002, and references therein). Because we do not yet have soils taken directly from the surface of an asteroid, surface-aging processes on asteroids are not well understood. Following standard terminology, we will refer to processes that alter optical properties of surfaces of airless bodies (such as impacts, solar wind ion implantation, micrometeorite bombardment, etc.) as ‘space weathering’.

Two lines of evidence suggest that space weathering occurs on asteroid surfaces: (i) Though probably similar in bulk composition, surfaces of S-type asteroids are significantly ‘redder’ than colors of ordinary chondrite meteorites, and do not show a comparatively deep absorption band at 1 μm (Chapman & Salisbury 1973). (ii) Color variations of surfaces of S-type asteroids (243) Ida, (951) Gaspra and (433) Eros mimic the sense of the color differences observed for lunar soils, with older surfaces being darker and redder in appearance (Chapman 1996, Veverka et al. 2000, Murchie et al. 2002). Conversely, it is believed that other common asteroid types (such as, e.g., the C-types) show very little evidence of optical alteration with time (Veverka et al. 1999, Clark et al. 1999).

Here we use the photometric data obtained by the Sloan Digital Sky Survey (SDSS) to collect evidence for space weathering on asteroids. We find that the reflectance spectra of S-type asteroids become redder and that the broad absorption band at 1-μm becomes shallower over time. We also find indications that surfaces of the C-type asteroids may become bluer over time. If true, then the low-reflectivity material of C-type asteroids exhibits color alterations opposite to those inferred for the higher-reflectivity material of S-type asteroids. We base our evidence on a comparative study of colors of young and old asteroid families\(^1\) that we find by standard techniques, but using ten times more asteroid proper elements\(^2\) than previous works (Zappalà et al. 1994, 1995).

In section 2, we describe the photometric system of the SDSS, and perform a number

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\(^1\)An asteroid family is a group of asteroids with similar orbits that have originated by the catastrophic disruption of a large parent body. Some two dozen robust asteroid families have been identified in the main belt (Zappalà et al. 1994).

\(^2\)The proper elements are analytically defined as constants of orbital motion of a suitably simplified dynamical system. Unlike the instantaneous orbital elements, the proper elements are generally nearly constant on 10^7–10^8 year time scale, and are widely used to decipher the collisional history of the asteroid belt (Milani & Knežević 1994, Knežević et al. 2002).
of tests to verify that the SDSS’s colors of asteroids are good enough for our purposes. In sections 3 and 4, we explain how we find asteroid families and how we determine whether an asteroid family is young or old. In Section 5, we show that there exists a correlation between colors and ages of the asteroid families. This result and its implications are discussed in section 6.

2. SDSS Photometry

The recently-released Sloan Digital Sky Survey Moving Object Catalog, hereafter SDSS MOC\(^3\) lists astrometric and photometric data for asteroids observed by the 2.5-meter Sloan telescope located at Apache Point Observatory, in Sunspot, New Mexico. To date, the survey has mapped in detail one-eighth of the entire sky, determining positions, brightnesses, and five-color CCD photometry of 125,283 moving objects (Stoughton et al. 2001, Ivezić et al. 2001).

35,401 unique moving objects detected by the survey (i.e., about 28\% of the total) have been matched (Jurić et al. 2002) to known asteroids listed in the ASTORB file (Bowell et al. 1994)\(^4\). The flux densities of detected objects were measured almost simultaneously in five bands with effective wavelengths 3557 Å (\(u'\) band), 4825 Å (\(g'\) band), 6261 Å (\(r'\) band), 7672 Å (\(i'\) band), and 9097 Å (\(z'\) band) (Fukugita et al. 1996).

This data provide important and unique information about asteroids, because the SDSS MOC includes one to two orders of magnitude more asteroids than other catalogs that were used in the past to study asteroids’ reflectance spectra. For example, the Small Main-Belt Asteroid Spectroscopic Survey I (SMASS I, Xu et al. 1995) and II (SMASS II, Bus & Binzel 2002a), which are the largest spectroscopic surveys to date, produced a set of visible wavelength spectra for 1447 asteroids. Figure 1 shows a comparison between the total numbers and magnitude distributions of main-belt asteroids observed by the SDSS and SMASS. These two surveys provide complementary information, because different magnitude ranges were observed by each of them; the SDSS targeted smaller asteroids than the SMASS. The SDSS MOC has been recently used to show many asteroid families segregate in the color space from their local backgrounds (Ivezić et al. 2002), and that this segregation is apparent at least down to absolute magnitude \(H \approx 16.0\).

To start with, we first verified whether the SDSS photometry is consistent with published

\(^3\)http://www.astro.princeton.edu/~ivezic/sdssmoc/sdssmoc.html

\(^4\)ftp://ftp.lowell.edu/pub/elgb/astorb.html
spectra of asteroids. To this end, we have compared the SDSS colors with SMASS spectra\(^5\) for those asteroids that appear in both datasets; for 113 asteroids in total. In 64 cases (i.e., in 57%), the agreement was excellent. To illustrate this, Fig. 2 shows a comparison between the SDSS colors and the SMASS reflectance spectra for selected S-, C- and V-type asteroids. In 43% of cases, the agreement was less good. In these cases, the SDSS colors follow the global shape of the SMASS spectra, but either show a slightly steeper slope, or do not reproduce the full depth of the 9000 Å absorption band. Individual SDSS measurements of the flux may differ by as much as 10–20% from the values measured by the SMASS. The origin of these differences is unknown. Repeated observations of the same sources demonstrate that the spectrophotometric accuracies of the SDSS and SMASS are \(~0.02\) and \(~0.01\) mag, respectively (Ivezić et al. 2003, Bus & Binzel 2002a), which may contribute by only a small fraction to the observed discrepancy. The effect of phase reddening on the SDSS colors is also unlikely to cause a difference because the SDSS observed at low phase angles (\(\approx7^\circ\) rms, \(\approx35^\circ\) maximum). Similarly, errors in the SDSS colors generated by calibration, atmospheric extinction, etc., are also small.

To verify whether or not these differences may compromise our analysis, we have performed several tests. For example, the SMASS data provided a basis for developing a new asteroid taxonomic system (Bus & Binzel 2002a,b) that classifies reflectance spectra into a few categories that have clear interpretations in terms of the surface mineralogy of asteroids. For example, the S-type taxonomic category is characterized by a spectral redness that is usually attributed to the reflectance properties of metallic silicates such as olivine and pyroxene. We may thus ask whether the five-color SDSS photometry is good enough to classify asteroids into basic taxonomic types.

We have developed an algorithm that automatically analyzes photometric data in the SDSS MOC and classifies asteroids according to their taxonomic types. This algorithm uses Principal Component Analysis (hereafter PCA). PCA involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. In the result, the PCA creates linear combinations of the five SDSS colors, which maximize the separation between the taxonomic types in the SDSS data.

The first two principal components (i.e., the new uncorrelated variables) that this algo-

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\(^5\)The SMASS spectra have been downloaded from http://smass.mit.edu/
arithm yields are given by the following relationships:

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\begin{align*}
PC_1 & = 0.396(u' - g') + 0.553(g' - r') + 0.567(g' - i') + 0.465(g' - z') \\
PC_2 & = -0.819(u' - g') + 0.017(g' - r') + 0.09(g' - i') + 0.567(g' - z')
\end{align*}
\]

(1)

where \( u', g', r', i', z' \) are the measured fluxes in five bands. To illustrate the result of the PCA, Fig. 3 shows the principal components (Eq. 1) of \( \sim100 \) asteroids with known taxonomic types (Bus & Binzel 2002b) that were detected by the SDSS. This figure demonstrates that we can use the first two principal components to clearly distinguish taxonomic classes such as S, C, or X; indeed, these classes cluster at different locations in the \((PC_1, PC_2)\) plane. That alone is enough to classify SDSS’s asteroids into three taxonomic categories: \(^6\) S-type asteroids generally have \( PC_1 > 0.35 \), C-type asteroids have \( PC_1 < 0.35 \) and \( PC_2 \lesssim -0.1 \), X-type asteroids have \( PC_1 \lesssim 0.35 \) and \( PC_2 \gtrsim -0.1 \). Moreover, (4) Vesta and V-type asteroids in the Vesta family (see, e.g., Cellino et al. 2002) have \( PC_1 \gtrsim 0.35 \) and small \( PC_2 \) (only one example of a V-type asteroid is shown in Fig. 3: (2704) Julian Loewe has \( PC_1 \approx 0.5 \) and \( PC_2 \approx -0.4 \)). Based on these results, we conclude that the SDSS MOC is a useful, self-consistent dataset to study general, statistical variations of colors of small asteroids in the main asteroid belt, but that caution is required to interpret colors in individual cases.\(^7\)

3. Asteroid Families

The asteroid belt has collisionally evolved since its formation (see Davis et al. 2002, and other chapters in section 4.2 of the Asteroids III book). Possibly its most striking feature is the asteroid families, which represent remnants of large, collisionally disrupted asteroids (Hirayama 1918). In the present asteroid belt, most asteroid families can be clearly distinguished from the background, probably more primordial population of asteroids.

To make an intelligent use of the SDSS MOC, we want to sort the main-belt asteroids into family and background populations and analyze color variations within these sets sep-

\(^6\)Each of the three main categories has a number of taxonomic sub-divisions depending on the depths of the absorption bands, relative redness or blueness of the reflected light, and other features such as the presence/absence of specific absorption bands (e.g., Bus & Binzel 2002b). Classification into these categories is generally difficult to achieve with SDSS photometry, because there is usually not enough resolution with only five colors to detect these spectral signatures.

\(^7\)For example, Fig. 3 shows that about 5% of asteroids in the C-class region (\( PC_1 \leq 0.35 \) and \( PC_2 \lesssim -0.1 \)) are not C-type bodies and that about 2% of asteroids in the S-class region (\( PC_1 \geq 0.35 \)) are not S-type bodies. Also, about 3% of the SDSS MOC entries are instrumental artifacts (Ivezić et al. 2002).
arately. While the analysis of the asteroid families may tell us about things like asteroid interior, geological differentiation in the main belt, or about phenomena that alter asteroid colors with time, the analysis of background asteroids is more related to issues like the primordial temperature gradient in the proto-planetary nebula, subsequent dynamical excitation and mixing of bodies formed at different distances from the Sun. Here, we concentrate on the first subject, i.e., on systematic color variations between the asteroid families.

To identify asteroid families, researchers look for clusters of asteroid positions in the space of proper elements: the proper semimajor axis ($a_p$), proper eccentricity ($e_p$), and proper inclination ($i_p$) (Milani & Knežević 1994, Knežević et al. 2002). These orbital elements describe the size, shape and tilt of orbits. Proper orbital elements, being more constant over time than instantaneous orbital elements, provide a dynamical criterion of whether or not a group of bodies has a common ancestor.

To identify an asteroid family, we use a numerical code that automatically detects a cluster of asteroid positions in the 3-dimensional space of proper elements. We based our code on the so-called Hierarchical Clustering Method (hereafter HCM, Zappalà et al. 1990). The HCM requires that members of the identified cluster of asteroid positions in the proper elements space be separated by less then a selected distance (the so-called ‘cutoff’).

In the first step, we apply the HCM to a catalog of the proper asteroid elements (Milani & Knežević 1994, Knežević et al. 2002). The catalog we downloaded a few months ago (on 10/10/2002) and used for this work includes 106,284 proper elements. The procedure starts with an individual asteroid position in the proper elements space and identifies bodies in its neighborhood with mutual distances less than a threshold limit ($d_{\text{cutoff}}$). We define the distance in the ($a_p, e_p, i_p$) space by

$$d = n a_p \sqrt{C_a (\delta a_p / a_p)^2 + C_e (\delta e_p)^2 + C_i (\delta \sin i_p)^2},$$

(2)

where $n a_p$ is the heliocentric velocity of an asteroid on a circular orbit having the semimajor axis $a_p$, $\delta a_p = |a_p^{(1)} - a_p^{(2)}|$, $\delta e_p = |e_p^{(1)} - e_p^{(2)}|$, and $\delta \sin i_p = |\sin i_p^{(1)} - \sin i_p^{(2)}|$. The indices (1) and (2) denote the two bodies in consideration. $C_a$, $C_e$ and $C_i$ are weighting factors; we adopt $C_a = 5/4$, $C_e = 2$ and $C_i = 2$ (Zappalà et al. 1994). Other choices of $C_a$, $C_e$ and $C_i$ yield similar results.

The cutoff distance $d_{\text{cutoff}}$ is a free parameter. With small $d_{\text{cutoff}}$, the algorithm identifies tight clusters in the proper element space. With large $d_{\text{cutoff}}$, the algorithm detects larger and more loosely connected clusters. For the main belt, the appropriate values of $d_{\text{cutoff}}$

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8 Available at http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo
range between 1 and 150 m/s. To avoid an a priori choice of \( d_{\text{cutoff}} \), we developed software that runs HCM starting with each individual asteroid in our \( N = 106,284 \) sample and loops over 150 values of \( d_{\text{cutoff}} \) between 1 and 150 m/s, with a 1 m/s step. The code has been optimized so that this job takes only a few days on a fast workstation.

In Fig. 4, we visualize the final product of this algorithm using a ‘stalactite’ diagram (Zappalà et al. 1994). For each \( d_{\text{cutoff}} \) on Y-axis we plot all clusters found by the HCM. For example, with \( d_{\text{cutoff}} = 150 \) m/s, nearly the whole main belt is linked to a single asteroid, (1) Ceres. We plot a horizontal line segment at \( d_{\text{cutoff}} = 150 \) m/s with length equal to the total number of members in this cluster. At smaller \( d_{\text{cutoff}} \), the complex structure of the main asteroid belt emerges. The stalactite diagram is extremely useful when we want to systematically classify this information. In fact, more than fifty significant groups are shown in Fig. 4, about a double of the asteroid families known previously. We label each stalactite by the lowest numbered asteroid in the group (not all these labels appear in Fig. 4), and proceed to the second step of our algorithm.

In the second step, we select appropriate \( d_{\text{cutoff}} \) for each particular cluster. Unlike the first step of our algorithm that is fully automated, the second step requires some non-trivial insight into the dynamics of the main-belt asteroids, and cannot be fully automatized. We show this in the example of the Koronis family (Zappalà et al. 1994). Figure 5 shows how the number \( N(d_{\text{cutoff}}) \) of members of the cluster linked to (158) Koronis changes with \( d_{\text{cutoff}} \). The two bottom panels show derivatives of \( N(d_{\text{cutoff}}) \) that we use to find values of \( d_{\text{cutoff}} \), where \( dN(d_{\text{cutoff}})/dd_{\text{cutoff}} \) is large (these \( d_{\text{cutoff}} \) are labeled by vertical dashed lines). Each of these four \( d_{\text{cutoff}} \) values has a clear interpretation. To correlate these values of \( d_{\text{cutoff}} \) with structures and processes operating in the main belt, we generate movies that show projections of the dynamical structure of families into \((a_p, e_p)\) and \((a_p, i_p)\) planes.\(^9\) Moreover, we programmed an interactive visualization tool that allows us to work in three dimensions thus avoiding problems generated by the projection effects into either \((a_p, e_p)\) or \((a_p, i_p)\) planes.

With \( d_{\text{cutoff}} \lesssim 12 \) m/s, the algorithm accumulates members of a very tightly clustered group - the product of a collisional breakup of the Koronis family member about 5.8 My ago (Karin cluster, Nesvorný et al. 2002a). With \( d_{\text{cutoff}} \sim 23 \) m/s, the HCM starts to agglomerate the central part of the Koronis family. With \( d_{\text{cutoff}} \sim 40 \) m/s, the algorithm steps over the secular resonance that separates central and large semimajor axis parts of the Koronis family (this particular shape resulted from long-term dynamics driven by radiation forces, Bottke et al. 2001). Finally, with \( d_{\text{cutoff}} \gtrsim 95 \) m/s, the algorithm starts to select other structures in the outer main belt that have unrelated origins. This can be seen in Fig. 4,\(^9\)

\(^9\)http://www.boulder.swri.edu/~davidn/morby/NEWfam(100,000PE)/
where many small stalactites join the Koronis family at $d_{\text{cutoff}} \gtrsim 100$ m/s.

According to these considerations, $d_{\text{cutoff}} = 10-20$ m/s is the best choice of for the Karin cluster, and $d_{\text{cutoff}} = 50-90$ m/s is best for the Koronis family. For other families, we choose $d_{\text{cutoff}}$ using similar reasoning. This effort requires human intervention because it is difficult (if not impossible) to program a general algorithm that takes into account all relevant processes operating in the main belt (such as resonances, radiation forces, etc.). A systematic analysis of 50+ clusters required a few days of work.\textsuperscript{10} The final product of our algorithm are the asteroid families (Table 1), lists of their members selected at appropriate cutoffs, and the list of background asteroids showing no apparent groups. Figure 6 illustrates this result: from top to bottom, the panels show all main-belt asteroids, family members, and background asteroids, respectively. From the total of 106,284 main-belt asteroids, 38,625 are family members (36.3% of total) and 67,659 are background asteroids (63.7%).

4. Ages of Asteroid Families

Motivated by issues related to space weathering, we want to correlate the SDSS colors of asteroids with their surface ages. Unfortunately, the surface ages of asteroids are unknown. On the other hand, asteroid families may be useful in this context, because asteroid members of each family share the same origin (i.e., the same age). If we knew ages of asteroid families, we could presumably better understand space weathering issues by studying the color variations among them. For example, recent work has suggested that S-type asteroids with ‘fresh’ surfaces may have spectra that resemble (or trend toward) the ordinary chondrite spectra (see, for example, Binzel et al. 1996). If so, members of young S-type asteroid families (such as the Karin cluster, Nesvorný et al. 2002a) may show redder colors than those S-type asteroid families that are older (such as, e.g., the Koronis family; Marzari et al. 1995, Bottke et al. 2001).

\textsuperscript{10}To demonstrate the statistical significance of each determined family, we generated synthetic distributions of the proper elements and applied the HCM to them. For example, to demonstrate larger than 99% statistical significance of the Karin cluster, we generated 100 synthetic orbital distributions corresponding to the Koronis family determined at $d_{\text{cutoff}} = 70$ m/s (i.e. 2388 asteroid positions at $2.83 < a_p < 2.95$ AU, $0.04 < e_p < 0.06$, and $0.033 < i_p < 0.04$), and applied our HCM algorithm to these data. With $d_{\text{cutoff}} = 10$ m/s, we were unable to find a cluster containing more than five members, yet the Karin family contains 84 members with this $d_{\text{cutoff}}$ (Fig. 5). We also used the HCM algorithm on 100 computer-generated asteroid belts (i.e. 106,284 random orbital positions at $2.1 < a_p < 3.25$ AU, $e_p < 0.3$, and $i_p < 0.3$). Once again, $d_{\text{cutoff}} = 10$ m/s yielded no meaningful structures. We are thus confident that the Karin cluster and other families to which we applied the same technique are statistically robust.
To date, we know of four methods that allow us to estimate the age of an asteroid family:

(i) Marzari et al. (1995) has modeled the collisional evolution of three prominent asteroid families. Their collisional code evolves the initial size-frequency distribution (SFD) with time to match the modeled SFD with the observed SFD of a family. Using this method, Marzari et al. (1995) estimated that the Themis and Koronis families are of order of 2 Gy old. These ages are uncertain because the initial SFD, scaling laws for impacts, and other parameters of the method are not known a priori. Moreover, in the case of the Eos family, Marzari et al.’s collision code generated no reasonable match to the observed SFD. Despite these limitations, Marzari et al.’s work was important because it showed that most prominent asteroid families are probably billions of years old.

(ii) Durda & Dermott (1997) modeled the global collision evolution of the main asteroid belt. Once the code is calibrated against the present SFD of the main belt, it can be used to calculate the typical time interval that elapses between breakups of diameter $D$ asteroids. For example, Durda (personal communication) estimated that a $D \sim 100$-km asteroid disrupts somewhere in the main belt every $10^9$ years, a $D \sim 50$-km asteroid disrupts every $2 \times 10^7$ years, and a $D \sim 30$-km asteroid disrupts every $5 \times 10^6$ years. Although, again, these estimates are largely uncertain, they again show us that the large families that correspond to breakups of $D \sim 100$ km and larger parent bodies should be billions of years old. On the other hand, families originated from smaller parent bodies should be more numerous. For example, at least several hundreds of asteroid families with $D \sim 30$ km parent bodies should have been generated in the asteroid belt since its formation. Such a large number of small asteroid families is not observed today. One obvious solution to this problem is to invoke some erasure mechanism that eliminates small asteroid families over time. Indeed, a number of erasure mechanisms are operating in the asteroid belt today (Marzari et al. 1999, Bottke et al. 2001, Nesvorný et al. 2002b). It is thus plausible that the observed asteroid families derived from smaller parent bodies are younger than those created by breakups of $D \sim 100$-km parent bodies (such as Themis, Koronis and Eos families).

(iii) A recent analysis has shown that asteroid families are subject to slow spreading and dispersal via numerous tiny resonances in the main belt (Nesvorný et al. 2002b). Moreover, $D < 20$ km asteroids are moved inward toward the Sun and outward away from the Sun over comparatively long timescales by the Yarkovsky thermal effect; this mechanism provides another means for dispersing families (Bottke et al. 2001, Vokrouhlický et al. 2003, Carruba et al. 2003). Therefore, older family’s orbital parameters in $(a_P, e_P, i_P)$ space do not reflect the immediate outcomes of cratering events or catastrophic disruptions. Instead, they reveal how the family has been “etched” in $(a_P, e_P, i_P)$ space over long timescales by dynamical
diffusion and chaotic resonances. On the other hand, tight clusters in \((a_P, e_P, i_P)\) space should represent young families that have not yet had an opportunity to disperse via dynamical mechanisms. Using theoretical models of the Yarkovsky effect, Vokrouhlický et al. (2003) estimated that the Eos family is 2.1 ± 0.5 Gy old, and Nesvorný et al. (2003) found that the Themis and Massalia families are 2.5 ± 1.0 Gy and 300 ± 100 My old, respectively. See Fig. 7 for a brief description of this method. Using the same method, Bottke (personal communication\(^{11}\)) determined the approximate ages of many other asteroid families. We used the same means and determined ages for most asteroid families that we have identified.

When available, we list these ages in Table 1. These values are probably subject to a number of systematic and random errors. For example, physical parameters of asteroids such as the thermal conductivity, albedo, rotation speed, surface and bulk densities, etc., are generally unknown. Yet, the strength of the Yarkovsky effect depends on them in complicated ways (see, e.g., Vokrouhlický 1999). If varied in reasonable ranges, these parameters generate up to about 50% uncertainties in the age estimates.

More fundamental limitation of an age estimate derived from the spread of an asteroid family in \(a_P\) is that some part of this spread may come from the collisional ejection of fragments, rather than from the subsequent gradual spreading of the family members by thermal effects. This is probably not an important issue for most prominent families that are spread enough to allow us to gauge their age properly, but poses difficulties for smaller and possibly younger families. For example, we know that the Karin cluster has been generated by a breakup of a \(\approx\)25-km-diameter parent S-type body \(\approx\)5.8 My ago (Nesvorný et al. 2002a); this family is spread about 0.1 AU in \(a_P\). Because the 2 to 4-km-diameter members of the Karin cluster drift at speeds of only about \(7 \times 10^{-5}\) AU per My, the observed spread of the Karin cluster in \(a_P\) must have been generated by the breakup of the parent body rather than by the latter slow evolution; we estimate that it would take \(\sim\) 70 My for the Yarkovsky effect to generate the observed spread, which is much longer than the actual family’s age.

To roughly compensate for the ejection field component, we assumed ejection velocities in infinity \(V_\infty \sim 15\) m/s and \(V_\infty \sim 30\) m/s for the S- and C-type families, respectively. The values of this order are suggested by dynamical structures of young asteroid families (Nesvorný et al. 2002a, 2003) and by the SPH simulations of asteroid breakups (Michel et al. 2002, 2003). For example, to explain structures of two known pristine asteroid families, the S-type Karin cluster and the C-type Veritas family, we find \(V_\infty \sim 15\) m/s and \(V_\infty \sim 30\) m/s, respectively. These corrections produce ages that are about 70 My and 140 My shorter than those determined if \(V_\infty = 0\) is assumed.

\(^{11}\)http://www.boulder.swri.edu/~bottke/Yarkovsky/
We used the above corrections in an attempt to resolve an apparent problem with ages determined from $V_\infty = 0$: three families for which the rigorous method (iv) worked (see below) are all younger than 10 My (the Karin, Veritas and Iannini families). On the other hand, none of the ages determined from families’ dispersions in $a_P$ using $V_\infty = 0$ was larger than 10 My but shorter than 100 My, and yet, we find no particular reason to believe that such ages should not occur. Although our solution of this problem may be simplistic, we adopted it to improve the consistency between methods (iii) and (iv).

(iv) To determine the exact age of a family, the orbits of the family members must be numerically integrated into the past. The goal is to show that in some previous epoch, the orbits of all cluster members were nearly the same (Nesvorný et al. 2002a). There are two angles that determine the orientation of an orbit in space: the longitude of the ascending node ($\Omega$), and the argument of perihelion ($\omega$). Due to planetary perturbations, these angles evolve with different but nearly constant speeds for individual asteroid orbits. Today, the orbits of the family members are oriented differently in space because their slightly dissimilar periods of $\Omega$ and $\omega$ produce slow differential rotation of their orbits with respect to each other. Eventually, this effect allows $\Omega$ and $\omega$ to obtain nearly uniform distributions in $[0^\circ, 360^\circ]$. For a short time after the parent body breakup, however, the orientations of the fragments’ orbits must have been nearly the same. Nesvorný et al. (2002a, 2003) used this method to determine the ages of the Karin ($5.8 \pm 0.2$ My) and Veritas ($8.3 \pm 0.5$ My) families, and also found that the tight family associated with (4652) Iannini is probably $\lesssim 5$ My old. Unfortunately, Nesvorný et al.’s method can not be used to determine ages of asteroid families that are much older than $\approx 10$ My, because the orbital evolution of asteroids is usually chaotic and non-reversible on $\gtrsim 10$-My time scales.

In Table 1, we list ages for those asteroid families for which the age estimates are available. Ages of the Themis and Koronis families determined from (i) ($\approx 2$ Gy) are consistent with determinations obtained from (iii) ($\approx 2.5$ Gy). We list the latter values in Table 1, because we believe that (iii) generally provides a more reliable estimate of age. Similarly, (iv) is obviously more reliable and precise than (iii) for the young asteroid families.

5. Colors of Asteroid Families

We used the SDSS MOC to study questions such as: What are the colors of family members and background asteroids? Are there any correlations of color with size, distance from the Sun, or age of an asteroid family? To this end, we used the subset of entries in the SDSS MOC which were matched to asteroids with known orbit elements (Jurić et al. 2002) and that have $\delta PC_1 < 0.1$ and $\delta PC_2 < 0.1$, where $\delta PC_1$ and $\delta PC_2$ are the
measurement errors in the principal components.\textsuperscript{12} In total, we studied colors of 7,593 main-belt asteroids, of which 3,026 are the family members, and 4,567 are background main belt objects (Fig. 8). In the following analysis, we will concentrate on color variation between asteroid families, and its possible correlations with age of an asteroid family. Other issues, such as the color variations within families, colors of the background population, etc., will be discussed elsewhere (Jedicke et al. 2003).

Table 1 shows taxonomic types of families for which the classification was obvious according to the criteria defined in section 2. In a case, where the taxonomic type of a family was known previously from observations of its large members (see Cellino et al. 2002 and references therein), we find that this taxonomic type is also predominant for small asteroid family members observed by the SDSS (see also Iv\v{e}zi\v{c} et al. 2002). Our simple criteria, however, do not distinguish between sub-categories of four broad taxonomic classes S, C, X, and V. For this reason, we list some families as being S-type although more refined classification is possible from the SDSS colors in some cases (e.g., the Eos family has K-, T-, and D-type asteroids, Vokrouhlický et al. 2003).

We select those families that are clearly either S- or C-type. Unusual cases, such as the Flora and Erigone families that have large numbers of both S- and C-type members, are excluded from the following analysis. Next, we remove all interlopers from the S- or C-type families (e.g., those members that have unusual colors relative to most other members), and calculate \( \langle PC_1 \rangle \) and \( \langle PC_2 \rangle \), where \( \langle PC_j \rangle \) is the arithmetic mean of the \( j \)th principal component over the remaining members of each studied asteroid family.

Figure 9 shows that the S- and C-type families (red and blue, respectively) are located within two well-defined regions in the principal component plane. The S-type families have significantly larger PC\textsubscript{1} than the C-type families. The V-type Vesta family (denoted in green) differs from the S-type families by small PC\textsubscript{2}. The Karin cluster and the Veritas family, the two youngest known asteroid families for which we have good color data, are located on a periphery of regions in the (PC\textsubscript{1}, PC\textsubscript{2}) plane that are populated by the S- and C-type families.

There happens to be a significant spread of PC\textsubscript{1} and PC\textsubscript{2} for families of the same taxonomic category. For example, two C-type families can differ by as much as \( \sim 0.2 \) in both the PC\textsubscript{1} and PC\textsubscript{2}. Because measurement errors and color variability within families are smaller than this amount, we believe that Fig. 9 documents true color differences between families. This is the first time that such color differences between families have been pointed

\textsuperscript{12}For those asteroids that were observed more than once by the SDSS, we use the color measurement that has the smallest error.
out.

A simple explanation for this behavior is to interpret colors in terms of compositional differences between parent bodies of asteroid families. To this end, we must know how PC$_1$ and PC$_2$ correlate with spectral features that are diagnostic for presence of specific minerals. Figure 10 shows that PC$_1$ is an effective measure of the average spectral slope between 0.35 and 0.9 $\mu$m. On the other hand, PC$_2$ correlates with the spectral curvature generated by broad absorption features (such as the 1-$\mu$m absorption band). Unfortunately, these spectral features are also affected by asteroid surface properties such as the presence of particulate regolith, temperature, etc. (e.g., Johnson & Fanale 1973, Roush & Singer 1984). Moreover, the spectral slope and the depth of the 1-$\mu$m absorption band may be affected by space weathering processes (Chapman 1996).

To address these issues, we have searched for correlations of PC$_1$ and PC$_2$ with asteroid size, distance from the Sun, age of an asteroid family, etc. We have found no other statistically significant correlation than the one between PC$_1$ and the age of an asteroid family (Fig. 11).

Fig. 11 shows a plot of PC$_1$ vs. age for the S- and C-type asteroid families. The trends are opposite. Young S-type families generally have smaller PC$_1$ than old S-type families, while young C-type tend to have larger PC$_1$ than old C-type families. This produces a sort of convergence, where in the limit of zero age the S- and C-type families have similar values of PC$_1$ (~0.3).

We believe that these correlations are signatures of space weathering. In our scenario, surfaces of the member asteroids of a family are initially covered by ‘fresh’ material that is excavated by the disruption event from the parent body interior. This surface material and is then subject to space weathering effects. Color modifications due to these effects should be similar for all member asteroids of a single asteroid family, because their surfaces have the same age. Because PC$_1$ is a proxy for the spectral slope (Fig. 10), Fig. 11 suggests that colors of the S- and C-type asteroid become increasingly ‘red’ and ‘blue’ over time, respectively.

Correlations between PC$_1$ and $\log_{10} t$ can be fitted by straight lines. We used the fitexy routine from Numerical Recipes (Press et al. 1992) which let us fit PC$_1$ vs. $\log_{10} t$ accounting for errors associated with them (for PC$_1$ errors, we use the RMS range of PC$_1$ values within the family). The dashed lines in Fig. 11 show the best-fit result. For the S-type families, we find that $PC_1 = A\log_{10} t + B$ ($t$ in My), where $A = 0.07 \pm 0.02$ and $B = 0.3 \pm 0.05$. The slope of the distribution is significant at greater than the 3-$\sigma$ level. There is a 76% correlation between PC$_1$ and $\log_{10}(t)$. Using Fig. 10, we find that the mean spectral slope
increases with time as \( \sim 0.01 \log_{10} t \) (\( t \) in My).

The correlation shown in Fig. 11 for the S-type families would be much weaker than calculated above, if the data points corresponding to the youngest families (such as the Iannini, Karin, Brangane and Agnia families) were excluded from the analysis. For this reason, the youngest families provide a crucial constraint on our scenario. Fortunately, youngest of all, the Karin and Iannini clusters are robust dynamical families with solid age determinations (Nesvorný et al. 2002a, 2003). Also, the S-type members of the Iannini cluster have distinct colors from their local background that shows predominantly C-type asteroids. It is thus difficult to explain the colors of Karin and Iannini cluster members by using other assumptions.

The young Veritas family (denoted by 490 Fig. 11) in and the old Themis and Hygiea families (denoted by 24 and 10, respectively) are similarly important to constraint the color-age correlation for the C-type families in Fig. 11. The Veritas family is a robust dynamical family with solid age determination (Milani & Farinella 1994, Nesvorný et al. 2003). The ages of the Themis and Hygiea families are certain only to about a factor of two. On the other hand, Fig. 11 shows asteroid family ages over a three orders of magnitude range: the Iannini, Karin, and Veritas families being the youngest (< 10 My) and the Maria family being probably the oldest (~3 Gy). For this reason, a factor-of-two errors in some family age estimates are insignificant in the current context.

It may be also argued that Fig. 11 shows a correlation of color with size of an asteroid, rather than with its surface age. Indeed, younger families have usually smaller parent bodies, because small main-belt asteroids are disrupted at higher rates than the large ones. Also, fragments of small parent bodies are smaller than those produced by breakups of large parent bodies. We have tested this possibility and found no significant correlation of color with size. We also argument that the parent body of the young Veritas family (~140 km in size; Tanga et al. 1999) was larger than parent bodies of many prominent old families. Thus, the unusual colors of the Veritas family must be a signature of its recent origin rather than the size of its parent body.

The color-age correlation for the C-type families is weakened by two outlaying families with large \( PC_1 \). Indeed, the Padua and Chloris families (denoted by 363 and 410 in Fig. 11, respectively) have large spectral slopes, but are not particularly young. We are not sure how to interpret their colors. One possibility is that the parent bodies of these two families had significantly distinct composition. In fact, some part of the \( PC_1 \) variability between families must come from the compositional variability between their parent bodies. For this reason, the large fluctuations of data points around the dashed lines in Fig. 11 are not surprising. On the other hand, we find it hard to believe that the compositional variability has a dominant
effect in Fig. 11, because we do not see a reason why colors of young families would differ from colors of old ones in such a case.

To probe the effect of composition on PC$_1$, we compare the spectral slopes of members of the Karin cluster with those of the Koronis family members. Because the Karin cluster was produced by a breakup of a former Koronis family member, the bulk composition of these bodies should be similar. Yet, the colors are significantly different (Fig. 12). The spectral slope at 0.5-0.9 $\mu$m found among the Karin cluster members is shallower than the spectral slope that is typical for the Koronis family. Moreover, the Karin cluster members show an absorption feature at $\sim$0.9 $\mu$m that is deeper than the similar feature found for Koronis family members. Quantitatively, we find about 15% difference in flux at $\sim$0.9 $\mu$m.

What we see here is very probably the effect of space weathering. For comparison, Chapman (1996) found that fresh craters and Azzura ejecta on (243) Ida$^{13}$ show the 1-$\mu$m absorption band at that is deeper than the same spectral feature observed on weathered Ida’s terrains. In that case, 10-15% difference in flux around 1$\mu$m was reported. Comparing these values with the ones found in our study, we conclude that the youngest studied surface features on (243) Ida have ages that are comparable to or slightly larger than that of the Karin cluster. This result may have important implications for the geology of (243) Ida. We discuss this result in the next section.

Unfortunately, a similar comparison can not yet be done for the C-type families, because we have not yet identified a recent breakup of member of an old C-type family. We may, however, compare the colors of the Veritas family (youngest known C-type family) with some compositional analog. Possible analogs we found are the Themis and Hygiea families. These families are located in the same region of the main belt as the Veritas family ($a \sim 3.2$ AU) suggesting that their parent bodies accreted from roughly the same part of the protoplanetary disk. The Themis and Hygiea families are also the oldest C-type families known ($2.5 \pm 1$ and $2 \pm 1$ Gy, respectively). By comparing their colors with the 8.3 $\pm$ 0.5 My old Veritas family, the effects of space weathering can be best identified. Because the Themis and Hygiea families have nearly identical colors, we concentrate on comparison between the Veritas and Themis families (Fig. 13).

Figure 13 illustrates a significant difference between colors of the two families. The spectral slope of the Veritas family is on average steeper than that of the Themis family. No counterpart exists among the Themis family members for the steep spectral slope at short wavelengths that is typical for Veritas family members. Other young C-type families (such as, e.g., the Brasilia and Naema families) have spectral slopes that are similar to

$^{13}$ (243) Ida is a member of the Koronis family.
that of the Veritas family. We believe that these facts may indicate that space weathering processes modify colors of C-type asteroids over time. It is also possible, however, that the compositional differences cause these spectral variations between the C-type families. If Veritas, Themis and Hygiea families were removed from Fig. 11, evidence for the age-color correlation for C-type families would become much weaker.

6. Discussion

Our work provides new evidence for space weathering effects. Using a novel method, we found that reflectance spectra of the S-type asteroids become redder and that the broad absorption band at 1-\mu m becomes shallower over time. We measured, for the first time, the rate of space weathering affects on S-type asteroids. We estimate that the spectral slope changes as \( \sim -0.01 \log_{10} t \) (\( t \) given in My) due to these effects. We also found that reflectance spectra of 5.8 \pm 0.2-My old Karin cluster members show much deeper 1-\mu m absorption band than the ones of 2.5 \pm 0.2-My old Koronis family members. The difference in flux at \( \sim 0.9 \) \mu m is about 15%.

The S-type families with \(<10\) My ages (Karin and Iannini clusters) were important to establish the age-color correlation for the S-type families. Unfortunately, only one such a recent C-type family is known (Veritas family). This makes it more difficult to obtain conclusive evidence on space weathering on C-type asteroids. Nevertheless, we find a statistically sound correlation between ages and colors of C-type families. If real, our work suggests that the C-type asteroids show spectral alterations by space weathering that increases its mean spectral slope over time. This result needs verification. For example, if a new young C-type family is identified in the main belt, we predict that its members will show mean spectral slope that is similar to the one of Veritas family members.

By comparing colors of the Koronis and Karin families, we found that compositional differences can not account for the observed color differences. These two families have originated from the same primordial object. Yet, their colors are different. It is also difficult to explain how compositional differences could produce correlations shown in Fig. 11.

Our work has important implications for the origin of ordinary-chondrite (OC) meteorites, which are the most abundant class of the meteorites found on the Earth. The reflectance spectra of OC meteorites that are obtained in laboratories show a very deep 1-\mu m absorption band, which is an extremely uncommon spectral feature among the main-belt asteroids; i.e., only (3628) Bozemcová (Binzel 1993) shows similarly deep absorption band from \( \sim 1500 \) asteroids for which we currently have spectroscopic data. Yet, meteorites are
thought to be fragments of the main-belt asteroids. The spectral characteristics of the OC meteorites and many main-belt asteroids should thus be similar.

To resolve this apparent paradox, Chapman & Salisbury (1973) proposed a number of processes that may account for the observed difference. More recently, color variations on surfaces of S-type asteroids observed by Galileo and NEAR spacecrafts ((243) Ida, (951) Gaspra, (433) Eros) provided strong evidence for the space weathering hypothesis, because older surfaces were found to be darker and redder in appearance (Chapman 1996, Veverka et al. 2000, Murchie et al. 2002). This shows that the space weathering processes may convert the spectra of OC meteorites to having the spectra traits of S-type asteroids. Micrometeorite impacts and/or solar wind irradiation that produces nanophase iron particles on asteroid regolith grains may be responsible for these spectral alterations (Sasaki et al. 2001).

Because we were able to measure the rate of these spectral alterations, we can now draw several important conclusions for the origin of OC meteorites and for surface geology of asteroids:

(1) The reflectance spectrum of an S-type asteroid with a few-million-year surface age (such as the Karin or Iannini family member) and that of a sub-class of OC meteorites such as the L5 chondrites appear to be compatible. It is thus plausible that L5 chondrites are fragments of common S-type main-belt asteroids. The origin of other classes of OC meteorites that show still deeper 1-μm absorption band needs yet to be explained. Unfortunately, our data lack resolution to determine space weathering effects on <1 My time scales.

(2) The youngest studied impact features on (243) Ida, (951) Gaspra, and (433) Eros have ages that are probably comparable to or somewhat longer than those of the Karin (5.8 ± 0.2 My) and Iannini (≤ 5 My) clusters. We draw this conclusion from comparison of depths of the 1-μm absorption band. In principle, these impact features may be given absolute dates by carefully sorting their spectra and by using the space weathering rate that we have determined.

The 5-color photometry obtained by the Sloan Digital Sky Survey is the only current source that provides enough spectral information on small asteroid families. For example, none of the Karin and Iannini cluster members have been observed by SMAS (Bus & Binzel 2002a) or any other spectroscopic survey. Yet, these families are very important to measure the rate of space weathering on My time scales. To verify our results, it is thus crucial to obtain low-resolution spectra for a representative number of members of the Karin and Iannini clusters.

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Vokrouhlický, D. et al. 2003, in preparation
Table Captions

TABLE 1. List of selected asteroid families. Only families that are statistically robust are listed here. The columns are: lowest numbered asteroid family member; cutoff limit used ($d_{\text{cutoff}}$); number of family members determined at this cutoff; number of family members in the SDSS MOC (for small families we list $N_1/N_2$; where $N_1$ is the number of family members with 0.1 or smaller errors in PC$_1$ and PC$_2$, and $N_1$ is the number of family members with 0.3 or smaller errors PC$_1$ and PC$_2$); common taxonomic types among the family members as suggested by PC$_1$ and PC$_2$; and the published age of the family, when available. Sources for family ages are: (a) Marzari et al. (1995, 1999), (b) Durda & Dermott (1997), (c) Bottke et al. (2001), (d) Nesvorný et al. (2002a,b, 2003), (e) Carruba et al. (2003), (f) Vokrouhlický et al. (2003), and (g) http://www.boulder.swri.edu/~bottke/Yarkovsky.
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<th># in SDSS</th>
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<th>Age (Gy)</th>
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<td>3830</td>
<td>387</td>
<td>S</td>
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† The Karin cluster is excluded.

‡ (1639) Bower is probably an interloper (Nesvorný et al. 2003).

* (293) Brasilia is probably an interloper (Nesvorný et al. 2003).

** Taxonomic type was determined for members with $\delta PC_1 < 0.3$ and $\delta PC_2 < 0.3$. 
Fig. 1.— Absolute magnitude ($H$) histograms of main-belt asteroids observed by the SDSS and SMASS. Number of observed asteroids per 0.5 magnitude bin is shown. The SDSS magnitude distribution is peaked at 14.0–15.0, where very few SMASS spectra are available. On the other hand, SMASS observed many asteroids with $H < 10.0$. For this reason, the overlap between both datasets is small. To date, only $\sim$100 asteroids were observed by both surveys.
Fig. 2.— Comparison between the SDSS colors and the SMASS reflectance spectra for selected S-, C- and V-type asteroids. We subtracted the solar analog from the photometric-calibrated SDSS magnitudes and converted the magnitudes into fluxes. The fluxes were then normalized to 1 at 5500 Å, and offset by 0 or ±0.5. Vertical segments at 3557, 4825, 6261, 7672, and 9097 Å show 1-σ error bars for the SDSS reflectances. (1854) Skvortsov (S-type), (474) Prudentia (C-type), and (3869) Norton (V-type) are shown as examples, where the agreement between the SDSS colors and SMASS spectra was good.
Fig. 3.— SDSS asteroids with known taxonomic types shown in the Principal Component Plane. This plot shows PC₁ and PC₂ (Eq. 1) of ~100 asteroids detected by the SDSS that have 0.1 or smaller errors in PC₁ and PC₂, and that have been taxonomically classified by Bus & Binzel (2002b). We see that members of taxonomic classes S, C, and X are located in three different regions (dashed lines schematically delimit these regions). S, R, K, T, D, L, Ld, A, Sa, Sl, Sq, Sr types are sub-categories of the S class. Similarly, C, B, Ch, Cb and X, Xc, Xk, Xe are sub-categories of the C and X classes, respectively (Bus & Binzel 2002b).
Fig. 4.— The dynamical structure of the main asteroid belt represented in the ‘stalactite diagram’. Each stalactite represents an asteroid family and is labeled by the member asteroid that has the lowest designation number. Large families, such as those associated with (158) Koronis, (24) Themis, (15) Eunomia, (221) Eos, (4) Vesta, and (44) Nysa, appear as thick stalactites that persist over a large range of $d_{\text{cutoff}}$. Smaller families are represented by thin stalactites that are often (but not always, see, e.g., (490) Veritas) vertically short meaning that their determination requires a specific narrow range of $d_{\text{cutoff}}$. About fifty asteroid families are shown in this figure.
Fig. 5.— From top to bottom, the panels show the logarithm of the total number of the Koronis family members $\log_{10}(N)$, the first derivative $dN/dd_{\text{cutoff}}$, and $(dN/dd_{\text{cutoff}})/N$ to enhance features for small $N$. The vertical dashed lines indicate $d_{\text{cutoff}}$ that correspond to important changes in slope of $N(d_{\text{cutoff}})$. 
Fig. 6.— Decomposition of the asteroid belt into the family members and the background asteroids. From top to bottom, the panels show all main-belt asteroids, the family members, and the background asteroids, respectively.
Fig. 7.— Absolute magnitudes (H) and proper semimajor axes (a_p) of the Themis (a) and Massalia (b) family members (dots). The V-shaped lines indicate positions of Yarkovsky-drifting bodies evolved from the center of the families over the indicated time intervals, assuming maximum drift rates inward and outward. The drift rates were computed analytically using linearized approximations of the Yarkovsky effect (Vokrouhlický 1999). Assuming a tight initial orbital distribution of a newly born family, the family members are expected to be localized within one of the V-shaped contours. In (a), the distribution in a_p of the Themis family members with H \gtrsim 12.5 is cut by the chaotic 11:5 and 2:1 mean motion resonances with Jupiter. Using members with H \lesssim 12.5, we estimate that the Themis family is 2.5 ± 1.0 Gy old. From (b), the Massalia family is 300 ± 100 My old. These estimates are robust over a wide range of the physical parameters compatible with the family’s taxonomic type (Themis is C, Massalia is S) and with asteroidal surfaces covered by regolith. The outliers shown in the figure are probably interlopers. From Nesvorný et al. (2003).
Fig. 8.— Principal color components $PC_1$ and $PC_2$ of the main-belt asteroids observed by the SDSS. We show only those data points that have $\delta PC_1 < 0.1$ and $\delta PC_2 < 0.1$. From the total of 7,593 main-belt asteroids, 3,026 are family members (right panel), and 4,567 are background main-belt objects (left panel). Vertical dashed line shows an approximate boundary between areas populated by the S- and C-type asteroids. We study the color variations within these categories separately for family members.
Fig. 9.— Asteroid families in the plane of the principal components PC$_1$ and PC$_2$. The bars show 1-$\sigma$ variations of PC$_1$ and PC$_2$ within each family. These bars, being generally larger than the measurement errors, indicate the true variability of colors within families. The C- (blue) and S-type (red) families clearly segregate in PC$_1$. The Veritas family and the Karin cluster are labeled and denoted in black. Their colors lay on a periphery of well defined regions in the (PC$_1$, PC$_2$) that are populated by the “blue” and “red” families. The Vesta family (green) has smaller PC$_2$ than all other families.
Fig. 10.— Correlation between PC₁ and the average spectral slope measured between 0.35 and 0.9 μm. The average slopes have been calculated from five colors listed in the SDSS MOC for those measurements that have δPC₁ < 0.1 and δPC₂ < 0.1. PC₁ is a strong function of the spectral slope. The dashed line is the best linear fit (Average Slope ∝ 0.165 × PC₁).
Fig. 11.— Principal color component $PC_1$ as a function of age for the S- (left panel) and C-type asteroid families (right panel). Each family is denoted by its lowest numbered member asteroid. For example, 832 and 158 in the left panel denote the Karin and Koronis families, respectively; 490 and 24 in the right panel denote the Veritas and Themis families, respectively. The horizontal bars show errors of family age estimates. The thin vertical bars show 1-$\sigma$ variations of $PC_1$ within each family and represent true color variations among family members. The mean errors of mean $PC_1$ are denoted by bold vertical bars for each family. Both S- and C-type families show correlations between $PC_1$ and age. These correlations (denoted by dashed lines) are significant on high-$\sigma$ levels. The trends are opposite. Young S-type families generally have smaller $PC_1$ than old S-type families, while young C-type tend to have larger $PC_1$ than old C-type families.
Fig. 12.— Colors of the S-type Koronis and Karin families. Using the same method as in Fig. 2, we plot the mean color of Koronis family members that have $\delta P C_1 < 0.1$ and $\delta P C_2 < 0.1$ (dashed line), and their 1-$\sigma$ color variation (shaded area around the dashed line). The mean color of the Karin cluster (solid line with 1-$\sigma$ error bars) was calculated with the same criteria. The Karin cluster shows shallower slope and deeper 1-$\mu$m absorption band than the Koronis family.
Fig. 13.— Colors of the C-type Themis and Veritas families. We plot mean color of Themis family members that have $\delta P C_1 < 0.1$ and $\delta P C_2 < 0.1$ (dashed line), and their 1-\(\sigma\) color variation (shaded area around the dashed line). The mean color of the Veritas family (solid line with 1-\(\sigma\) error bars) was calculated with the same criteria. The mean spectral slope of the Veritas family is steeper than the mean spectral slope of the Themis family.