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Note

Ordinary chondrite-like colors in small Koronis family members

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ABSTRACT

A survey of small (<5–10 km diameter) members of the Koronis family shows some objects with visible-wavelength broadband colors consistent with membership in the Q-class (Tholen, D.J. [1984]. Asteroid taxonomy from cluster analysis of photometry. Ph.D. Dissertation, University of Arizona, Tucson, AZ; Bus, S.J., Binzel, R.P. [2002]. Icarus 158, 146–177). This agrees with an ordinary chondritic composition for this family and suggests the timescale for changing Q-class to S-class spectra in the main belt is roughly comparable to the regolith refresh time in the 2–5 km size range.

1. Background and motivation

The "S asteroid problem" has been one of the longest-standing issues in asteroid science. In brief, the most common asteroids in the NEO and inner belt populations (the S asteroids) have spectral properties that are mismatched from the most frequently falling meteorites (the ordinary chondrites, OC). Qualitatively their spectra show evidence of the same minerals, but the spectral slope for the asteroids is substantially reddened and band depths muted compared with the meteorites, among other effects. This spectral slope mismatch has been interpreted as arising from external factors such as radiation damage, solar wind implantation, micrometeorite bombardment, and regolith maturation. grouped under the term "space weathering" (Clark et al., 2002). Such processing occurs in lunar soils. However, asteroids have a very different composition than the Moon and the expected energies and outcomes are substantially diminished at the greater distance of the asteroid belt (Gaffey, 2010). Asteroids with OC-like spectra do exist (typically grouped into the Q spectral class: Tholen, 1984; Bus and Binzel, 2002) but while Q asteroids are found in the NEO population they have until recently not been found in the main-belt population (Mothé-Diniz and Nesvorný, 2008). Below, we provide further evidence for Q-class objects in the main asteroid belt, with membership in a large S-class family. For completeness, we note that Mothé-Diniz et al. (2010) concluded that OC material could also be present in classes other than Q, described in Section 3.

While age *per se* is not an observable quantity, there is a correlation between collisional age (the mean time until a disruptive event destroys a body, and thus a gauge of how long it has already existed) and diameter. While the age of an individual object is difficult to constrain in this way, a population of smaller objects is expected to be younger on average than a population of larger objects with the same orbital parameters.

Current models suggest there should be a transition size at which young fresh surfaces should be more common than not in asteroid populations: *i.e.* these surfaces are young enough that the space weathering processes have not yet altered them. Binzel et al. (2004) found this transition from Q-type to S-type spectra among near-Earth asteroids (NEAs) in the 1–5 km range. This same transition should potentially be present in the main belt at some size, neglecting the specifics of the space weathering process. One possible approach for finding this transition in the main belt is via the study of members of a dynamical family. This should remove (or at least mitigate) differences in the strength of space weathering due to average solar distance. It also provides the best insurance that the target asteroids all share the same original composition and that spectral differences are not due to compositional effects.

We chose the Koronis family as the subject of this project. This family has S-class members in a region of the belt dominated by C-class background objects (Zappalà et al., 1995; Mothé-Diniz et al., 2005), making the identification of interlopers straightforward. The Koronis family is thought to have originated in the breakup of a ∼120–170 km object roughly 2 byr ago (Marzari et al., 1995; Tanga et al., 1999; Durda et al., 2007). Groundbased observations and the Galileo spacecraft flyby of 243 Ida, a Koronis family member, found it to have properties consistent with a space-weathered ordinary chondrite, including different regions on its surface of apparently differing maturity (Chapman, 1996). Extrapolating from those data, we might expect to find OC-like spectra on any freshly exposed regions on Ida or, more pertinently, the least-weathered members of the Koronis family.

The term "space weathering" as commonly used includes a variety of complex processes which, as noted by Gaffey (2010) seem to manifest differently on Ida, Eros, and the Moon in terms of changes in albedo, band depth, and spectral slope. As Ida exhibits little change in albedo in its different terrains (Helfenstein et al., 1996) but appreciable change in band depth and spectral slope (Chapman, 1996; Gaffey, 2010), we might expect to detect space weathering in the Koronis family by studying band depths and spectral slopes, both potentially available via broadband colors.

2. Observations and reduction

The observations presented here were obtained as part of a larger survey of Koronis family objects. This survey used the 2.1-m telescope on Kitt Peak, observing

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Table 1
Observational overview for the objects discussed in this work. "G-E fields" means these objects were reduced using the standard fields of Galadì-Enrìquez et al. (2000) as listed. (37411) 2001 XF152 was reduced using Sloan Digital Sky Survey (SDSS) stars in the same frame. Diameter assumes albedo of 0.25.

Object	Date of observation	H magnitude	Diameter	Standard stars
45610 2000 DJ48	3 January 2009	14.4	3.5 km	G-E fields 1,9
26970 Elias	3 January 2009	15.3	2.3 km	G-E fields 1,9
37411 2001 XF152	7 May 2008	15.7	1.9 km	On-chip SDSS

Table 2
BVRI colors for the objects discussed in this paper, compared to the typical values for the Q and S-classes as found by Dandy et al. (2003). These objects have colors much more akin to the Q than the S-class, as also shown in Fig. 1. Uncertainties were not presented for the class average colors in Dandy et al., we estimate them as 0.03–0.04 magnitudes.

Object	*B–V*	*V*	*V–R*	*V–I*
45610 2000 DJ48	0.82 ± 0.03	18.5	0.45 ± 0.02	0.74 ± 0.03
26970 Elias	0.79 ± 0.06	20.1	0.43 ± 0.04	0.69 ± 0.06
37411 2001 XF152	0.93 ± 0.17	20.1	0.43 ± 0.01	0.63 ± 0.10
"Typical Q-class"	0.82		0.42	0.73
"Typical S-class"	0.85		0.48	0.89

90 objects over a total of 19 nights in May and December 2008, and January, April, and September 2009, with targets chosen from the Mothé-Diniz et al. (2005) list,[2] the majority of targets with $H > 13.5$ and 17 with $H \geqslant 15$. Full details of the survey will appear in Thomas et al. (2010).

The T2KB CCD was used along with BVRI filters. Table 1 contains the observational circumstances for the target asteroids. Data reduction was via IRAF, using the photometry package *phot* (Tody, 1986). Synthetic apertures of 5 pixel radius (∼3.1″ radius) were used for the objects. Two types of photometric standards were used: one object in this work was in a field covered by the Sloan Digital Sky Survey (SDSS), and on-chip standards were used along with the SDSS photometry for those standards. Standard star observations were transformed from SDSS to BVRI magnitudes using equations on the "SDSS Photometric Equations" website.[3] Where SDSS standards were not available on-chip for an object, standard photometric fields in Galadì-Enrìquez et al. (2000) were observed over the course of the night and extinction coefficients and zero points were calculated and applied to the asteroids. The average Q and S-class colors included in Table 2 were calculated by Dandy et al. (2003) by transforming the average ECAS colors to the BVRI bandpasses.

As noted, the results of the entire 90-object survey will be presented in Thomas et al. (in preparation). Here we highlight three of the target objects with BVRI colors most consistent with the Q asteroid class and the OC meteorites (Fig. 1, Table 2), easily identified based on the *V–I* color difference between typical Q and S asteroids. These are among the first OC-like objects detected in the main asteroid belt (Mothé-Diniz and Nesvorný, 2008; Mothé-Diniz et al., 2010). Their association with the Koronis family suggests the Koronis parent body, and all of the family members, are likely ordinary chondritic in composition.

3. Implications

The existence of small Koronis family objects with Q/OC-like BVRI colors is not surprising, given the background in Section 1. We discuss here the overall context for our observations, and recent work by other authors relevant to our findings.

Recent work by Vernazza et al. (2009) suggests the rate of space weathering on asteroids is sufficiently rapid (∼10^6 year timescales) that we might not expect to find any Q asteroids at all, even in the NEA population where many are present. Binzel et al. (2010) addressed this paradox by looking at the orbits of Q-class NEAs, finding them to preferentially make close passes to the Earth–Moon system compared to S-class NEAs. Binzel et al. proposed these close passes served to refresh the regolith and return spectra to Q-type from S-type. This follows the prediction of Marchi et al. (2007) that tidal effects could disturb asteroid regoliths on timescales similar to the space weathering rate for NEOs.

The observations presented here are consistent with the work of Mothé-Diniz and Nesvorný (2008) who found OC-like spectra among small members of the very young Datura, Emilkowalski, 1992 YC2 and Lucascavin clusters. The ages of these clusters, however, are shorter than the space weathering timescale suggested by Vernazza et al. and we would not expect them to be fully weathered.

Mothé-Diniz et al. (2010) found "no shortage" of main-belt objects with OC-like spectra based on new and published visible-wavelength asteroid spectra (including two objects with spectra consistent with Q asteroids) and a reconsideration of the range of OC meteorite spectra, comparing them to a larger sample of asteroids and expanding their equivalent asteroid analog taxa to include the Sk and Sq classes as well as the Q-class. Their findings are consistent with what we conclude.

The results here and in Mothé-Diniz et al. center on main-belt asteroids that are not members of young families and do not make close passes to the Earth. The presence of Q-class asteroids in these populations seems at odds with the Binzel et al. findings. However, there are several possibilities for reconciling all these results.

First, we note that Vernazza et al. found evidence of two different weathering rates: the rapid one discussed above, which they associated with solar wind implantation, and a more subtle longer-term one (order 10^8–10^9 years) they associated with micrometeorite impacts. Willman et al. (2008) studied the Ionnani family, another main-belt S asteroid family, and calculated a weathering rate of 570 ± 220 Myr, updating an earlier value by Jedicke et al. (2004). The Willman et al. spectra, like ours, extended further into the UV than the Vernazza et al. observations, which cut off shortward of 0.52 μm. It is possible that while the short-term weathering is dominant at longer wavelengths where S/Q asteroids have absorption bands, it is more subtle at shorter wavelengths. Clementine studies of the lunar surface indicate that soil continues to mature and have observable spectral changes in the visible even as it approaches 1 Gyr in age (Grier et al., 2001), providing further support for an expectation of long-term effects on the asteroids. This is also consistent with the suggestion of Mothé-Diniz and Nesvorný, based on studies of the Karin family, that space weathering may first reduce spectral contrast before reddening takes place. It is also consistent with the schematic picture of space weathering presented by Gaffey (2010), who noted the different apparent effects of the process on Ida, Eros, and the Moon. Cellino et al. (2010) analyzed polarimetric observations of Koronis family objects, finding no difference between the sample as a whole and the subset of the smallest members or the subset of Karin cluster objects. This too is consistent with our finding, which suggests only a relatively small fraction of the smallest objects may be unweathered.

Recent modeling by Nesvorný et al. (2010) identifies a slightly different weathering timescale of ∼1 Myr over which space weathering *does not yet* affect NEA spectra, rather than the Vernazza et al. interpretation of that timescale as a space weathering completion timescale. Nesvorný et al. also find a relation between perihelion distance (q) and weathering timescale (t), $t \sim q^2$, assuming that the weathering is dominated by sputtering. At the perihelion distances of the Koronis family (2.57 and larger), this implies that their space weathering timescale may be more on the order of 7 Myr or longer, still much shorter than collisional lifetimes but of potential importance in the context of seismic shaking and resetting (see below). Conversely, Nesvorný et al. note that micrometeorite impacts will be more frequent in the main asteroid belt, which could serve to reduce the weathering timescale.

Richardson et al. (2005) modeled crater creation and erasure on 433 Eros, obtaining a good fit when including seismic shaking, and finding 2 m to be a sufficient impactor size to create downslope movement everywhere on an Eros-sized object with non-cohesive regolith and nominal seismic conditions, and 40 m for cohesive regolith and "more severe" seismic propagation. Their model suggests that impacts of 20 cm objects cause "vertical launching" of regolith on the surface of a 5 km object, assuming the cohesive regolith/severe propagation case and a small mean free path for seismic scattering (in other words, the most difficult case considered). We might expect larger (but sub-catastrophic) impacts in this range lead to globally "resetting" the surface and exposing fresh regolith. To get a rough sense of regolith refresh times, we assume a 10 m (50 times larger than the minimum size above and thus over 10^5 times more massive and energetic) impactor is sufficient to actually reset the surface of such a 5 km object. Using the impact recurrence times presented in O'Brien and Greenberg (2005) for such impactors on an Eros-sized body in the main belt, and scaling to the smaller surface area of a 5 km object, we might expect regolith to reset on timescales of ∼10^6 years on average, erasing evidence of space weathering. Obviously, this is only a rough order-of-magnitude calculation, but it suggests that even the rapid weathering rates suggested by Vernazza et al. are not at odds with the presence of unweathered 5-km scale objects in the main belt. Even if our estimates of refresh times are shown to be insufficiently conservative by a factor of 10 or more, we might statistically expect several percent of the ∼5 km diameter objects in the main belt to be unweathered. Interestingly, the crater population on the Rosetta flyby target 2867 Steins, the only asteroid in a similar size range to our Koronis family targets to be visited by a spacecraft, suggests its surface was reset by an impact ∼2–10 Myr ago (Marchi et al., 2010), again quantitatively consistent with our results.

A possible cautionary note exists in the story of Boznemcova, reported to have an OC-like spectrum based on visible data (Binzel et al., 1993), but with an IR

[2] We used the Koronis Family Asteroids Rotation Lightcurve Observing Program (http://koronisfamily.com/) to generate target lists.

[3] http://www.sdss.org/dr6/algorithms/sdssUBVRITransform.html, 3 September 2010.