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Space weathering of small Koronis family members

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ABSTRACT

The space weathering process and its implications for the relationships between S- and Q-type asteroids and ordinary chondrite meteorites is an often debated topic in asteroid science. Q-type asteroids have been shown to display the best spectral match to ordinary chondrites (McFadden, L.A., Gaffey, M.J., McCord, T.B. [1985]. Science 229, 160–163). While the Q-types and ordinary chondrites share some spectral features with S-type asteroids, the S-types have significantly redder spectral slopes than the Q-types in visible and near-infrared wavelengths. This reddening of spectral slope is attributed to the effects of space weathering on the observed surface composition. The analysis by Binzel et al. (Binzel, R.P., Rivkin, A.S., Stuart, J.S., Harris, A.W., Bus, S.J., Burbine, T.H. [2004]. Icarus 170, 259–294) provided a missing link between the Q- and S-type bodies in near-Earth space by showing a reddening of spectral slope in objects from 0.1 to 5 km that corresponded to a transition from Q-type to S-type asteroid spectra, implying that size, and therefore surface age, is related to the relationship between S- and Q-types. The existence of Q-type asteroids in the main-belt was not confirmed until Mothé-Diniz and Nesvorny (Mothé-Diniz, T., Nesvorny, D. [2008]. Astron. Astrophys. 486, L9–L12) found them in young S-type clusters. The young age of these families suggest that the unweathered surface could date to the formation of the family. This leads to the question of whether older S-type main-belt families can contain Q-type objects and display evidence of a transition from Q- to S-type. To answer this question we have carried out a photometric survey of the Koronis family using the Kitt Peak 2.1 m telescope. This provides a unique opportunity to compare the effects of the space weathering process on potentially ordinary chondrite-like bodies within a population of identical initial conditions. We find a trend in spectral slope for objects 1–5 km that shows the transition from Q- to S-type in the main-belt. This data set will prove crucial to our understanding of the space weathering process and its relevant timescales.

1. Introduction

Space weathering has been a long-standing puzzle in asteroid science that affects spectroscopic interpretations of near-Earth and main-belt asteroids. The biggest debate surrounding space weathering has been the potential relationship between S-type asteroids and ordinary chondrite (OC) meteorites. Visible and near-infrared spectral data have shown both similarities and discrepancies between the S-type asteroid and ordinary chondrite data sets. Although their spectra qualitatively show the same absorption features and quantitatively show evidence of the same minerals, the spectral slopes of S-type asteroid spectra are significantly reddened with respect to OC meteorites (e.g. Pieters et al., 2000; Clark et al., 2002a). For years this created great difficulties in understanding the relationship between S-type asteroids and the OC meteorites.

The line of questioning surrounding the potential influence of space weathering on asteroid surfaces mirrors discussion surrounding lunar regolith following the Apollo sample return missions. Ever since lunar soils were returned for study during the Apollo era, it has been known that mature lunar soils have the same spectral properties as telescopically obtained spectra of undisturbed surface areas (McCord et al., 1972). Yet, powdered lunar rocks and unexposed lunar regolith showed spectral differences from these surface measurements. Optical maturity causes a decrease in the band depth, increase in the spectral slope, and decrease in albedo (Adams and McCord, 1971). This spectral slope mismatch has been interpreted as the result of a variety of external

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factors that affect constituent minerals over time, including radiation damage, solar wind implantation, and micrometeorite implantation.

The discovery of (1862) Apollo and subsequent Q-types in the near-Earth population brought to light a new spectral class that displays the best spectral match to ordinary chondrites (McFadden et al., 1985). A comparison of S- and Q-type bodies matches the idea of maturation due to space weathering on the lunar surface. Laboratory studies of maturation on the Moon implicate vapor-deposited nanophase iron as causing the observed spectral changes (Pieters et al., 2000). Quantitative modeling of maturation of ordinary chondrite spectra by adding nanophase iron is consistent with what is seen in the Q- and S-class populations (Noble et al., 2007).

Spectral changes due to space weathering should increase with time up to the point when saturation is reached and no further change occurs (e.g. Pieters et al., 2000; Noble et al., 2001). Theories on collisional evolution of small bodies show that the expected lifetime of a body varies with the asteroid size (Dohnanyi, 1969; O'Brien and Greenberg, 2005). A large object will have a longer collisional lifespan because it is less likely to be catastrophically disrupted. Smaller bodies will have far shorter survival times and will consequently have a younger age than their larger counterparts on average. For objects covered in regolith, the surface age need not date to the time the object was formed. Smaller impacts can seismically move regolith downslope and resurface the body (Richardson et al., 2005). Finally, the smallest objects may be unable to retain regolith due to their low surface gravity, and thus show unweathered, young-looking surfaces for very long times. Therefore, small bodies may display surfaces that are young enough to be unaltered by the space weathering process or may display surfaces that have not yet reached spectral maturity.

Current models suggest there should be a transition size below which young surfaces should be observable. Binzel et al. (2004) identified this transition for a sample of 145 ordinary chondrite-like bodies (S-, Sq- and Q-spectral type) in near-Earth space. That study showed a trend of increasing spectral slope with increasing size over the 0.1–5 km range. The work linked ordinary chondrites to near-Earth S-type objects, but the connection to a main-belt source was incomplete. The first Q-type object was confirmed in a study of young families by Mothé-Diniz and Nesvorny (2008). That work was not able to confirm the existence of multiple fresh objects or of a transition from Q- to S-types in the main-belt. Several main-belt sources have been proposed for ordinary chondrites (e.g. (6) Hebe for the H chondrites, Gaffey and Gilbert, 1998), but these observations lack the final observational link between fresh ordinary chondrite-like surfaces and the current weathered objects. Finding this transition among main-belt asteroids would demonstrate a number of new conclusions: (1) that ordinary chondrites have verifiable and directly observable main-belt source regions, (2) that populations of fresh, unweathered surfaces exist in the main-belt, and (3) that near-Earth and main-belt asteroids undergo the same external processing, even if the relative strength or speed of different components may vary between the populations.

To examine the potential slope effects of space weathering in the main asteroid belt, the present work examines the spectral colors of members of the Koronis dynamical family. By studying members of a single family we intend to mitigate any differences in space weathering due to average distance from the Sun. Larger members of the Koronis family have been shown to have similar S-type spectra (Barucci and Lazzarin, 1993; Binzel et al., 1993), and spacecraft data from the Galileo encounter with family member (243) Ida have shown that the object is likely chondritic in composition (Chapman, 1996). We assume that these traits should extend to the small, unclassified bodies. Observing members of an undifferentiated parent body ensures that the objects share the same composition and that any observed spectral differences are due to the effects of space weathering rather than due to compositional variation within the original parent body. This provides a unique opportunity to compare the effects of the space weathering process on potentially ordinary chondrite-like bodies within a population that has essentially identical initial conditions.

This work presents the results of a photometric survey of small Koronis family members using the Kitt Peak 2.1 m telescope. We performed broadband visible-wavelength spectrophotometry on 90 members of the Koronis family in order to examine their spectral shape and spectral slope. First results from this project are presented in Rivkin et al. (2011). In this paper we present the details of our entire observational program (Section 2) and our global results (Section 3). In Section 4 we discuss the implications of our findings. This work completes the connection between ordinary chondrites and a potential source population in the main asteroid belt.

2. Observations and reduction

To study the effects of space weathering within an ordinary chondritic population we need to investigate a change in slope that indicates a transition from S- to Q- taxonomic type. One approach would be to use spectroscopy, which would allow us to assign a taxonomic type to each asteroid and would provide a data set directly analogous to the Binzel et al. (2004) near-Earth asteroid investigation of the Q- to S-type transition. However, the combination of distance and small size puts our targets at magnitudes beyond the capabilities of readily available visible and near-IR spectrographs. Instead of using traditional spectroscopy, we use broadband color photometry. This paper uses the photometry results to identify changes in average slope over a range of asteroid sizes. Using broadband colors has several advantages over attempting this survey with spectroscopy. For instance, a spectroscopic survey would require a large investment of observing time to complete. By undertaking a photometric survey we were able to use smaller telescopes (such as the 2.1-m), access larger amounts of observing time, and obtain object observations quickly and efficiently.

This study utilized the Kitt Peak 2.1-m telescope during the 2008A–2009B observing semesters. During 2008 our observations used the Harris BVRI filter set. For 2009, we sought to expand our spectrophotometry further into the near-infrared and added z filters. During 2009A we used the SDSS z′ filter. Unfortunately this filter was not available for our 2009B observations and we instead used the Gunn z filter. This paper presents results from May 2008 (17 objects), December 2008–January 2009 (35 objects), April 2009 (31 objects), and September 2009 (7 objects). The objects observed, the time of observation, and the phase angle of the observation are given in Table 1. The Koronis family members observed were chosen using Stephen Slivan's online observing target calculator[3] and the Koronis family membership of Mothé-Diniz et al. (2005). Additional small targets were added using a membership list from Vokrouhlický, D. (personal communication, 2006). The objects were chosen to cover a wide range of H magnitudes, which implies a wide size range. The final sample includes objects with H magnitudes from 9.24 to 16.8. All observations were taken in a sequence (e.g. VBVRVIV) that allowed us to identify and correct for lightcurve variations. The correction procedure is described below.

All data reduction was done using the Image Reduction and Analysis Facility (IRAF). All images were calibrated using bias frames and sky flats of the appropriate filter. Most objects were observed in the north celestial hemisphere or the equatorial region of the celestial sphere. While observing in these regions we were able to use the Sloan Digital Sky Survey (SDSS) online database[4]

[3] www.koronisfamily.com.

[4] http://cas.sdss.org/dr7/en/tools/chart/navi.asp.