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AVAST survey 0.4–1.0 μm spectroscopy of igneous asteroids in the inner and middle main belt

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ABSTRACT

We present the spectra of 60 asteroids, including 47 V-types observed during the first phase of the Adler V-Type Asteroid (AVAST) Survey. SDSS photometry was used to select candidate V-type asteroids for follow up by nature of their very blue *i–z* color. 47 of the 61 observed candidates were positively classified as V-type asteroids, while an additional six show indications of a 0.9 μm feature consistent with V-type spectra, but not sufficient for formal classification. Four asteroids were found to be S-type, all of which had *i–z* values very near the adopted AVAST selection criteria of $i–z \leqslant -0.2$, including one candidate observed well outside the cut (at a mean *i–z* of -0.11). Three A-type asteroids were also identified. Six V-type asteroids were observed beyond the 3:1 mean motion resonance with Jupiter, including the identification of two new V-type asteroids (63085 and 105041) at this distance. Six V-type asteroids were observed with low (<5°) orbital inclination, outside of the normal dynamical range of classic Vestoids, and are suggestive of a non-Vesta origin for at least some of the population.

1. Introduction

Increasingly evidence shows that the early Solar System was a dramatically complex system. The mechanisms at work in the early Solar System would leave their imprints in the asteroid belt, preserving within the dynamics of this population clues to the late stages of Solar System and giant planet formation (Bottke et al., 2006). Tremendous mass loss may have taken place in the vicinity of the asteroid belt, including the loss of protoplanetary cores. Such large objects would be expected to be differentiated and hence show unique and characteristic surface chemistry, especially when compared to smaller bodies which did not undergo such large scale melting and differentiation.

Spectral studies of Vesta in 1970 indicated a strong signature of the silicate mineral pyroxene on Vesta's surface, bearing striking similarities to spectra of the basaltic achondrite meteorites (McCord et al., 1970), adding to the evidence of Vesta being perhaps the only remaining remnant of these differentiated planetary cores. Further work has refined that basic picture, uncovering evidence for surface compositional heterogeneity on a global scale, particularly a distinct mineralogy for surface regions suggestive of non-impact driven evolution, and an enormous crater near its south pole (e.g. Gaffey, 1997; Thomas et al., 1997; Li et al., 2010; Reddy et al., 2010). Vesta is the first *in situ* target of the Dawn spacecraft mission, which will presumably shed great light on this object's composition and complex geological history (Russell et al., 2004).

The discovery of small (~5–15 km) apparently basaltic asteroids bridging the gap between Vesta and the 3:1 mean motion resonance with Jupiter has been regarded by many as the demonstrable link between Vesta and the HED meteorites (Binzel and Xu, 1993). Since then more than fifty, small, Vesta-like (taxonomic V-type) asteroids have been spectroscopically confirmed in the inner main asteroid belt (e.g. Xu et al., 1995; Bus and Binzel, 2002b; Lazzaro et al., 2004). Additionally, a dynamic family centered around Vesta includes 4000 known members exhibiting photometric colors that suggest similar surface compositions (Parker et al., 2008). The majority of these asteroids are likely to be fragments of Vesta, colloquially "Vestoids," potentially liberated by large crater-forming impacts more than one billion years ago (Nesvorný et al., 2008).

The discovery of a basaltic asteroid in the outer main belt, 1459 Magnya, that appears to be dynamically unrelated to Vesta (Lazzaro et al., 2000) has opened the door to studies of the remnants of other differentiated asteroids. In a detailed spectroscopic mineralogical analysis, Hardersen et al. (2004) find that Magnya is distinct from Vesta in orthopyroxene chemistry, concluding that the compositional difference precludes an origin on Vesta.

Other studies have found several additional middle and outer main-belt basaltic asteroids, including 21238 (Hammergren et al., 2007; Binzel et al., 2007; Carruba et al., 2007), 10537 (Moskovitz

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et al., 2008a; Duffard and Roig, 2009), 7472 (Duffard and Roig, 2009), and 40521 (Carruba et al., 2007; Roig et al., 2008). Because these objects have orbital semi-major axes greater than 2.5 AU, and thus reside on the other side of the powerful barrier to cross-diffusion that is the 3:1 mean motion resonance with Jupiter, many if not most of them are unlikely to be runaways from the Vesta family (Nesvorný et al., 2008; Roig et al., 2008). These V-type asteroids that appear to be unrelated to Vesta (either dynamically or compositionally) are commonly referred to as non-Vestoids.

While most of the V-type asteroids in the inner belt are likely to be members of the Vesta dynamical family, it is almost certain that other large protoplanetary cores existed in the region at early times, as evidenced by the diversity of iron meteorites in the meteoritic record (Scott, 2002). Even the among the HED meteorites themselves is isotopic inhomogeneity which point to additional parent bodies (Scott et al., 2009). Dynamically this idea is supported in the asteroid belt by the identification of a substantial population of V-type asteroids with low orbital inclinations that are difficult to explain as dynamically evolved collisional members of the Vesta family. Indeed Nesvorný et al. (2008) suggest that a substantial fraction of these low inclination objects may have an origin independent of Vesta, or may have formed from a different and possibly earlier collisional event than the one that formed the main Vesta family.

Several studies have pointed to spectral differences between Vesta family and non-family members, although there is some disagreement. Hiroi and Pieters (1998) find that non-family members have steeper visible slopes than family members, which they attributed to an increased degree of space weathering, which may also play a role in why the spectra of observed Vestoids tend to be much redder than that of Vesta itself and the HEDs (Mayne et al., 2011). While de Sanctis et al. (2011) find an excess of diogenitic material among non-family members Moskovitz et al. (2010) find no slope effect in the near-infrared, nor new evidence for mineralogical differences between family and non-family members beyond that previously noted for 1459 and 21238, a disagreement raising the need for additional observations and analysis to be performed on this class of object. Non-Vestoid mineralogies have also been inferred for 7472 and 10537 (Burbine et al., 2011; Moskovitz et al., 2008b). The discovery and characterization of additional non-Vestoids is needed to address these disagreements, as well as potentially provide clues to the existence and composition of differentiated parent bodies independent of Vesta. The identification of such objects is the major aim of our ongoing observational program, the AVAST (Adler V-type ASTeroid) Survey.

2. Observation and reduction

Since 2005 the AVAST survey has conducted a program of visible-to-near-infrared spectroscopic confirmation of asteroids with unusually blue i–z band colors, as measured by the Sloan Digital Sky Survey (SDSS). In this paper we present the results of the 0.4–1.0 μm reflectance spectroscopy of these candidate asteroids using the Dual Imaging Spectrograph (DIS) on the ARC 3.5-m telescope at the Apache Point Observatory. A future paper will present the results of complementary, ongoing, near infrared reflectance spectroscopy in the 0.9–2.5 μm regime.

2.1. SDSS target selection

The SDSS was a digital photometric and spectroscopic survey that covered about one quarter of the Celestial Sphere in the North Galactic cap and a smaller ($\sim$300 deg^2) but much deeper survey in the Southern Galactic hemisphere and began standard operations in April 2000 (see York et al. (2000), Stoughton et al. (2002), and

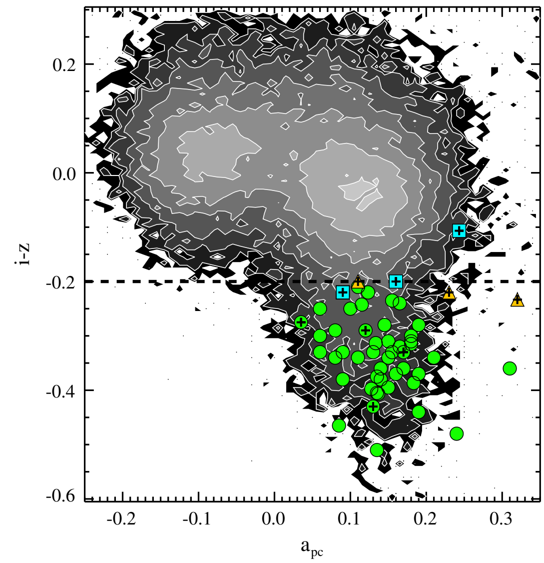

Fig. 1. The a_{pc} vs. i–z colors of the asteroids classified in the course of the AVAST survey displaying a significant 0.9 μm absorption as seen against the colors of asteroids from SDSS MOC3 (background contours of 2^n). AVAST V-type asteroids are seen as green circles, A-type asteroids as orange triangles, and S-type as pale blue squares. Observed asteroids with a semi-major axis greater than 2.5 AU are indicated by crosses. The dashed line represents the main AVAST selection criteria of i–$z < -0.2$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Abazajian et al. (2009, and references within)). The Seventh SDSS Public Data Release (Abazajian et al., 2009) ran through July 2008 and contains over 357 million unique photometric objects. Of particular interest to Solar System studies, the survey covers the sky at and near the ecliptic from approximately ecliptic latitude $\lambda = 100°$ to $\lambda = 225°$. The repeat scans of the Southern Galactic hemisphere (Stripe 82; crossing $\lambda = 0°$) also pass through the Ecliptic.

Although designed mainly for observations of extragalactic sources, the SDSS has significantly contributed to studies of the Solar System, notably in the success it has had with asteroid detections, cataloged in the SDSS Moving Object Catalog (hereafter SDSS MOC, Ivezić et al., 2002a). This public, value-added, catalog of SDSS asteroid observations contains, as of its fourth release, measurements of 471,000 moving objects, 220,000 of which have been matched to 104,000 known asteroids from the ASTORB file[1] (Jurić et al., 2002). The SDSS MOC data has been widely used in recent studies of asteroids (e.g. Ivezić et al., 2001; Jurić et al., 2002; Binzel et al., 2007; Parker et al., 2008; Assandri and Gil-Hutton, 2008; Carvano et al., 2010).

While the SDSS filters were not specifically chosen for asteroid reflectance studies, they have proven to be able to distinguish the major taxonomic types (Ivezić et al., 2001; Parker et al., 2008). The strong 0.9 μm absorption features of the V taxonomic types lies within the z-band (centered at 8931 Å). This absorption feature produces very blue i–z band colors relative to asteroids without such an absorption feature (e.g. C-types) or a weak one (e.g. S-types). A color–color plot of the MOC3 asteroids in i–z and the principle component color a_{pc}, with a_{pc} defined by Ivezić et al. (2001) as $a_{pc} = 0.89(g–r) + 0.45(r–i) - 0.57$, clearly shows a highly bimodal distribution of C-types at $a_{pc} \sim -0.1$, and S-types at $a_{pc} \sim 0.15$ (See Fig. 1). Those asteroids consistent with a V-type taxonomy form a population below the S-types at bluer i–z colors and allow for selection via a simple color cut.

For AVAST, we have selected asteroids with $i–z \leqslant -0.2$ as shown in Fig. 1. It is important to note that our intent never has been to

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