AVAST Survey 0.4–1.0 $\mu$m 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 $\mu$m 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 $i - z \leq -0.2$, 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 identified beyond the 3:1 mean motion resonance with Jupiter, and six more were found with low ($< 5$ deg) inclination, placing these asteroids outside of the normal dynamical range of classic Vestoids, and are suggestive of a non-Vesta origin for at least some of the population.

Keywords: ASTEROIDS; ASTEROIDS, COMPOSITION; SPECTROSCOPY
1 Introduction

Increasingly evidence shows that the early solar system was a dramatically complex system with tremendous mass loss from the main asteroid belt, including many protoplanetary cores in this region. 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 correlating with topographic features, particularly an enormous crater near its south pole (Gaffey, 1997; Cochran & Vilas, 1998; Binzel et al. 1997; Thomas et al., 1997). 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 & Xu, 1993). Since then more than one hundred, small, Vesta-like (taxonomic V-type, or colloquially “Vestoid”) asteroids have been spectroscopically confirmed in the inner main asteroid belt (e.g. Xu et al., 1995; Bus & 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, 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 et al., 2008; Duffard & Roig, 2009), 7472 (Duffard & Roig, 2009).
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). 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 & Pieters (1998) find that non-family members have steeper visible slopes than family members, which they attributed to an increased degree of space weathering and de Sanctis et al. (2011) find an excess of diogenitic material among non-family members. Moskovitz et al. (2010) however, 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. Non-Vestoid mineralogies have also been inferred for 7472 and 10537 (Burbine et al., 2011; Moskovitz et al., 2008). 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$\mu$m 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 0.9–2.5μm 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 (∼300 deg²) 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; 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 λ = 100° to λ = 225°. The repeat scans of the Southern Galactic hemisphere (Stripe 82; crossing λ = 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 file¹ (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 & 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 8931Å). 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} ∼ −0.1, and S-types at a_{pc} ∼ 0.15 (See Figure 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.

¹ see ftp://ftp.lowell.edu/pub/elgb/astorb.html
For AVAST, we have selected asteroids with $i - z \leq -0.2$ as shown in Figure 1. It is important to note that our intent never has been to produce an unbiased sampling across the main belt. We have preferentially selected non-Vesta family targets, focusing our efforts on those in interesting dynamical locations (e.g. in the middle and outer belt, or at inclinations significantly less than that of Vesta). As such this target selection is independent of similar SDSS selection criteria used by other studies (e.g. Roig & Gil-Hutton (2006), Binzel et al. (2007), and Moskovitz et al. (2008)) though naturally there exists overlap in target lists.

This criteria was applied to the Third Release of the SDSS MOC which contains data on 204,305 moving objects, including astrometric and photometric observations of 43,424 previously known asteroids (Ivezić et al., 2002b). While the Third Release SDSS MOC data set has been supplanted by the Fourth Release, it remains the “gold standard” for photometric quality, as the fourth release includes SDSS-II data (Abazajian et al., 2009) obtained in non-photometric conditions, requiring additional processing to assure robust, uniform data quality (see Parker et al. 2008 for details). In order to keep our selection criteria uniform through this work we choose to focus on our initial set of candidates chosen from the third release of the SDSS MOC, with additional candidates selected with quality control requirements from the fourth release. The color-color plot of asteroids observed by AVAST are seen against the membership of the SDSS MOC3, along with the AVAST color-cut in $i - z$ in Figure 1.

We have observed the spectra of 61 asteroids selected by our criteria. The majority ($\sim 77\%$ of our targets have proven to have classifiable spectra with V-type asteroids based on the feature-based taxonomy of Bus & Binzel (2002a). Table 1 presents a list of the observed asteroids. Furthermore all but one observed asteroid show the 0.9 $\mu$m absorption feature characteristic of a thermally metamorphosed surface mineralogy from highly processed V-types to less processed members of the S-type complex. The single case where our selection criteria failed to select an asteroid with a prominent 0.9 $\mu$m feature, asteroid 44496 (1998 XM5) can be traced to the asteroid’s photometric position being coincident with an artificial satellite trail in the SDSS $i$-band image. This false positive prompted the inclusion of SDSS photometric processing flags (Stoughton et al., 2002) into our revised selection criteria to exclude such cases. This C-type asteroid 44496 is not included in the discussion of the AVAST results.
2.2 Spectroscopy of Candidate V-type asteroids

The observations were performed from 2005-2007 at the Apache Point Observatory, using the Dual Imaging Spectrograph (DIS) on the Astrophysical Research Corporation 3.5m telescope.

The DIS uses two cameras to simultaneously record the blue and red spectral regions. The low resolution blue grating and medium resolution red grating provided dispersions of 2.42 and 2.31 Å pixel⁻¹, respectively. During the summer of 2006 the instrument’s gratings were replaced resulting in a blue dispersion of 1.83 Å pixel⁻¹. This configuration permits the coverage of the spectral range from approximately 0.36 – 1.0 μm. The dichroic mirror has a transition at approximately 0.55 μm, causing strong variations in throughput extending to about 0.25 μm on either side. These variations are imperfectly removed in reduced spectra, so the spectral region immediately around 0.55 μm is excluded from the plots of asteroid spectra.

The 1.5-arcsecond wide spectrograph slit was maintained at the parallactic angle to minimize the effects of differential refraction. Solar analog stars were observed periodically to remove telluric absorptions and for production of the reflectance spectrum. These solar analogs were chosen to match the airmass at which each asteroid was observed.

Data reduction was performed using the Image Reduction and Analysis Facility (IRAF) package, following standard procedures. After subtraction by an average bias frame and division by an average flat field, the spectra were extracted. Wavelength calibration was performed using observations of helium, neon, and argon arcs. The spectrum of each asteroid was divided by the spectrum of the solar analog star at similar airmass. Finally, the reflectance spectrum was normalized to unity at 0.55 μm by convention.

3 Results

3.1 Visible Spectra of Candidates

Because our spectral coverage terminates near 1 μm, our taxonomic classifications are based on the visible wavelength SMASS II / Bus taxonomy [Bus & Binzel, 2002a]. Our spectra continue to provide useful information in the near-infrared to around 1 μm, giving us more coverage of the 0.9 μm feature than was available to SMASS II. This permits the use of the band centers and band widths as aids in our classification. Using DIS, to date, we
have observed 46 objects which have spectra consistent with the taxonomic
class V and three asteroids with A-type spectra, potentially pointing to an
igneous nature. A-type asteroids, while fragments of differentiated asteroids,
lack the deep pyroxine absorption at 0.9 \( \mu m \), but have fairly blue \( i - z \) colors
due to a nearly uniformly declining slope in the \( z \)-band due to their olivine
chemistry. An additional four asteroids are best matched to S-complex types
in the Bus & Binzel (2002a), showing a less deep 0.9 \( \mu m \) absorption feature,
and another six asteroids, which show a deep 0.9 \( \mu m \) feature, but can not be
reliable classified with the Bus & Binzel (2002a) taxonomy. Table 1 presents
a list of the observing geometry, orbital elements and Bus & Binzel (2002a)
taxonomy of all of the 60 observed asteroids with a 0.9 \( \mu m \) absorption feature,
with each asteroid’s spectra being shown in Figure 4.

3.2 Igneous asteroids dynamically isolated from Vesta

AVAST has classified six V- and three A-type asteroids with orbital semi-
major axes greater than 2.5 AU, and eight V-types with inclinations outside
3\( \sigma \) of the Parker et al. (2008) defined Vesta family, six of which are at low
(\(< 5^\circ\)) inclinations. In particular these objects at large semi-major axis, or at
low inclination have a significant probability of being independent of Vesta
(Nesvorný et al., 2008; Roig et al., 2008) which affords us the chance to study
now-missing parent bodies of differentiated asteroids. It is especially inter-
esting to note one apparently igneous asteroid in the vicinity of Eos and its
associated family of asteroids, which may represent fragments of a partially
differentiated chondritic body (Mothé-Diniz et al., 2008). Figure 2 shows the
orbital distribution of the asteroids with deep V- or A-type 0.9 \( \mu m \) absorption
feature.

Of particular note are those objects with a > 2.5 AU, i.e., on the other side
of the 3:1 mean motion resonance from the Vesta family. We independently
selected and confirmed a basaltic nature for the middle and outer main belt
asteroids 1459, 7472, 10537, and 21238. In addition to these objects, we find
that asteroids 63085 and 10504 also display strong 0.9 \( \mu m \) absorption fea-
tures indicative of basalt and with visible spectra consistent with a V-type
classification.

3.3 A-type asteroids

Differentiation is generally believed to result in an object with a basaltic crust,
olivine-dominated mantle, and nickel-iron core. Although more than one hun-
dred basaltic asteroids and dozens of apparently metallic asteroids have been
identified in the main belt, only a relative handful of asteroids have been
found to bear the distinctive signature of a dominant olivine composition (corresponding to taxonomic type A). This lack of mantle material among the asteroids is mirrored by the lack of olivine-dominated asteroidal meteorites. This unusual paucity has long been considered a serious problem in our understanding of the asteroid belt (see Burbine et al. [1996] for a review of the subject). A leading hypothesis is that the disruption of differentiated planetesimals occurred so early in the history of the solar system, and that the subsequent collisional evolution of the asteroids was so violent, that fragments of the mantle and crust material of those objects have been ground down to sizes below observable limits, or “battered to bits” (Burbine et al., 1996). If this is the case, then there may be a population of small, olivine-rich asteroids that simply have not yet been identified and characterized. We have classified three A-type asteroids in AVAST, all of which have orbits beyond 2.5 AU. Figure 2 shows the orbital distribution of these A-type asteroids. These discoveries, enabled by the vast increase in the numbers of known asteroids since 1996, combined with our ability to selectively target the relatively rare A- and V-type asteroids through their SDSS colors, suggest that our survey may be reaching down to the size of the larger fragments of the population implied by the “battered to bits” model.

4 Discussion

The results of the AVAST survey add additional weight to the use of SDSS photometric colors in selecting populations of asteroids for follow up work, in particular the use of $i - z$ color to select candidate V-type asteroids. 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 of insufficient quality for formal classification. Four asteroids were formally classified as part of the S-type complex, all of which had $i - z$ values very near the adopted AVAST selection criteria of $i - z \leq -0.2$, including one candidate observed well outside the cut. This asteroid, 46262, was observed three times by the epoch of MOC3, and showed a wide range of measured SDSS $i - z$ colors, from -0.48 to 0.13. The relatively low photometric errors ($\sigma_{i - z} < 0.1$) combined with its semi major axis of 2.76 AU, and potential for longitudinal color variation warranted its inclusion in the survey. AVAST spectroscopy of this object was consistent with an S-type. Adopting a more conservative color cut of $i - z \leq -0.25$ removes all of the confirmed S-types from the survey, leaving a sample of only V-types among the spectroscopically classified asteroids by AVAST. While doing so would eliminate false positives from the V-type sample, it would also eliminate the serendipitously selected A-type asteroids, which are also thought to come from differentiated asteroids. Indeed in the SDSS z-band the almost linearly declining olivine absorption
feature of A-type asteroids and the less pronounced 0.9
µm feature of the S-types produce a similar i − z colors, and any conservative color cut made
to remove outlier S-types would strip the sample of A-type asteroids as well.
Regardless of which cut is used, this high rate of successful identification of V-
type asteroids from SDSS colors (77% with our original cut, 100% with a more
conservative one) bodes well for the future study of asteroids selected from
current and future large scale surveys based on well calibrated photometric
colors.

The meteoritic record, particularly the diversity of iron meteorites, provides
evidence for the former presence of large, differentiated, parent bodies. AVAST
has revealed a significant amount of dynamically separated igneous material
through the identification of V- and A-types asteroids in non-Vestoid orbits.
One such population found are low inclination V-types which are difficult to
link dynamically to the current family of Vestoids, potentially pointing to
a non-Vesta origin, or a past orbit of Vesta significantly different than today [Nesvorný et al., 2008]. Even more suggestive of being fragments of non-
Vesta parent bodies are the V-types beyond the 3:1 mean motion resonance
with Jupiter at 2.5 AU. Studies of the dynamical evolution of the Vestoids
compared to individual V-types beyond 2.5 AU show a high improbability
that these distant asteroids could be “run-away” members of the Vesta family
[Nesvorný et al., 2008, Roig et al., 2008]. The largest of these distant V-types,
1459 Magnya, has been shown to have surface chemistry distinct from that
of the Vestoids [Hardersen et al., 2004]. The additional V-types identified by
this, and other spectroscopic surveys, are smaller and fainter, and will require
further high quality near-infrared spectra to determine whether their pyrox-
ine chemistries are distinct from Vesta, and would serve to strengthen the
dynamical case for their independent origin.

The growing number of confirmed V-types beyond 2.5 AU lends weight to
an argument for a non-Vesta origin for many of them. They are still lacking,
however, in the number of bodies needed to potentially identify family member-
ship, of either known or, as of yet unknown, dynamical families. Although
three of the objects studied in our survey (7472, 27202, and 105041) appear
to be clumped near the Eos family around 3.0 AU, only one of them (27202)
was found to be a member of the Eos family by Nesvorny (2010). An exam-
ination of the proper elements of asteroids in that region (Figure 2) shows
that asteroids 27202 and 105041 are on the outskirts of the Eos family, both
having proper eccentricities higher than the bulk of the Eos family. However,
this region is threaded with numerous mean motion, secular, and three-body
resonances (Vokrouhlický et al., 2006), which may have helped to potentially
drive these asteroids away from the family.

A more rigorous classification of asteroid spectra is available to those with
both visual and near-infrared spectroscopy. Particularly for V-type asteroids
the addition of the near-infrared spectra adds the $\sim 2.0 \mu m$ absorption, and combined with the 0.9 $\mu m$ feature allows for a much more robust classification (DeMeo et al. 2009), and variant mineralogies may be determined by the analysis of both these spectral regions. In some cases the reliance on only the visible spectra from 0.4 - 1.0 $\mu m$ may also lead to mis-identification. The reflectance spectrum of 7472 Kumakiri shows a classic V-type 0.9 $\mu m$ absorption feature, leading this work to classify it based on the visible spectrum as a V-type. Burbine et al. (2011) has shown that 7472 does not match a V-type spectra template in the near infrared, lacking the corresponding V-type absorption feature at $\sim 2.0 \mu m$, but rather resembles the O-type asteroid 3628 Boznemcova. With this in mind, the next phase of the AVAST survey, currently underway, is a complimentary NIR survey of these asteroids with the goal of finding evidence of independent mineralogy in addition to dynamical independence for the asteroids outside of the Vesta family.

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| Asteroid | Date    | V   | φ   | H   | a   | e   | i   | Taxonomy |
|----------|---------|-----|-----|-----|-----|-----|-----|----------|
| 854      | 20060101| 16.3| 9.6 | 11.9| 2.37| 0.17| 6.09| *        |
| 1459     | 20060101| 15.1| 10.9| 10.3| 3.14| 0.23| 16.95| V        |
| 2168     | 20060204| 17.7| 23.6| 12.5| 2.45| 0.15| 4.74| V        |
|          | 20061216| 17.6| 17.5| 12.5| 2.45| 0.15| 4.74| V        |
| 2614     | 20070108| 16.9| 12.1| 13.3| 2.34| 0.17| 6.92| V        |
| 2704     | 20061216| 16.2| 14.5| 13.2| 2.39| 0.10| 4.52| V        |
| 5037     | 20060101| 15.9| 12.1| 13.1| 2.27| 0.11| 7.03| *        |
|          | 20060126| 16.6| 22.2| 13.1| 2.27| 0.11| 7.03| *        |
| 5525     | 20060101| 16.8| 12.6| 13   | 2.22| 0.15| 7.62| V        |
| 5560     | 20070108| 17.5| 26.1| 13.6| 2.29| 0.11| 5.62| V        |
| 6504     | 20070108| 17.6| 17.5| 13.8| 2.42| 0.16| 6.09| V        |
| 6944     | 20060204| 17.8| 5.5  | 14.1| 2.32| 0.14| 7.66| V        |
| 7472     | 20061025| 17.0| 17.6| 12   | 3.02| 0.10| 9.92| V        |
|          | 20061216| 15.8| 2.0  | 12   | 3.02| 0.10| 9.92| V        |
| 7794     | 20060101| 17.2| 8.4  | 13.6| 2.30| 0.15| 5.67| V        |
| 8108     | 20060204| 17.4| 1.2  | 14   | 2.37| 0.12| 6.74| *        |
| 8149     | 20060425| 16.5| 15.9| 13.2| 2.32| 0.14| 6.58| V        |
| 9147     | 20051224| 16.5| 13.7| 13.7| 2.19| 0.11| 5.82| V        |
| 9254     | 20070108| 17.5| 17.3| 13.8| 2.36| 0.19| 6.06| V        |
| 9531     | 20060101| 17.2| 9.4  | 13.7| 2.23| 0.19| 5.82| V        |
| 9553     | 20060101| 17.2| 11.6| 14.6| 2.20| 0.12| 1.92| V        |
| 10537    | 20051104| 18.3| 19.7| 12.4| 2.85| 0.07| 7.26| V        |
|          | 20061025| 17.4| 6.3  | 12.4| 2.85| 0.07| 7.26| V        |
| 11504    | 20061025| 16.0| 11.4| 13.9| 2.29| 0.16| 7.24| V        |
| 12407    | 20060603| 18.3| 20.3| 14.3| 2.40| 0.13| 6.73| V        |
| 14322    | 20060101| 16.8| 12.0| 13.8| 2.23| 0.14| 7.83| V        |
| 14326    | 20061216| 16.2| 3.3  | 14.2| 2.47| 0.17| 6.85| V        |

Continued on next page
| Asteroid | Date     | V  | $\phi$ | H  | a   | e  | i   | Taxonomy |
|----------|----------|----|--------|----|-----|----|-----|----------|
| 14343    | 20060101 | 16.7| 3.7    | 13.7| 2.24| 0.14| 6.79 | V        |
| 17035    | 20060127 | 17.2| 5.5    | 13.6| 2.44| 0.15| 6.24 | V        |
| 17469    | 20060425 | 16.1| 8.5    | 13.2| 2.37| 0.08| 6.17 | V        |
| 18386    | 20060425 | 17.4| 3.9    | 15.1| 2.27| 0.16| 5.48 | V        |
| 19258    | 20060603 | 17.0| 9.3    | 14.6| 2.29| 0.14| 7.46 | V        |
| 19979    | 20051224 | 16.4| 20.6   | 12.6| 2.46| 0.10| 5.17 | V        |
| 20455    | 20060425 | 17.5| 15.4   | 14.6| 2.32| 0.13| 6.78 | V        |
| 21238    | 20050415 | 16.4| 5.4    | 13.1| 2.54| 0.11| 11.44| V        |
| 21412    | 20070108 | 17.1| 6.2    | 14.7| 2.15| 0.04| 3.38 | V        |
| 22759    | 20060204 | 17.5| 27.2   | 13.4| 2.39| 0.18| 8.21 | V        |
| 25327    | 20060522 | 17.3| 11.2   | 14.2| 2.43| 0.15| 13.41| V        |
| 27202    | 20051224 | 17.5| 16.6   | 12.9| 3.06| 0.07| 9.62 | A        |
| 27437    | 20051224 | 16.9| 3.9    | 13.9| 2.31| 0.14| 7.26 | V        |
| 28256    | 20051224 | 16.6| 5.0    | 13.8| 2.34| 0.06| 7.24 | V        |
| 28291    | 20051224 | 16.6| 17.9   | 13.1| 2.43| 0.10| 7.22 | V        |
| 29550    | 20060127 | 17.7| 25.5   | 13.3| 2.69| 0.20| 13.87| *        |
| 30282    | 20060127 | 17.8| 17.1   | 14.5| 2.32| 0.12| 6.31 | V        |
| 30802    | 20060127 | 17.3| 0.7    | 14.1| 2.45| 0.23| 1.91 | S        |
| 31584    | 20060127 | 17.2| 9.6    | 14.7| 2.38| 0.06| 7.50 | V        |
| 31692    | 20060127 | 17.3| 10.5   | 14   | 2.42| 0.04| 6.63 | V        |
| 32272    | 20060122 | 17.0| 1.3    | 14.6| 2.40| 0.06| 5.59 | *        |
| 33490    | 20060204 | 17.9| 3.5    | 14.2| 2.43| 0.15| 6.42 | V        |
| 35062    | 20060122 | 16.7| 7.0    | 14.2| 2.37| 0.24| 10.53| V        |
| 36767    | 20060603 | 18.5| 25.3   | 15.4| 2.18| 0.11| 5.82 | *        |
| 37705    | 20060603 | 18.2| 21.6   | 15.3| 2.18| 0.10| 4.69 | V        |
| 43964    | 20061216 | 16.5| 5.7    | 14.3| 2.24| 0.09| 6.79 | V        |
| 45708    | 20060718 | 18.1| 4.5    | 14.2| 2.76| 0.15| 7.64 | S        |

Continued on next page
| Asteroid | Date       | V   | φ  | H  | a   | e  | i    | Taxonomy |
|---------|------------|-----|----|----|-----|----|------|----------|
| 46262   | 20050415   | 18.4| 21.0| 14 | 2.67| 0.14| 11.49| S        |
| 46690   | 20070108   | 17.3| 4.3 | 15.1| 2.24| 0.08| 3.99 | V        |
| 48629   | 20061216   | 17.3| 17.4| 14.6| 2.32| 0.19| 9.25 | V        |
| 52726   | 20051106   | 17.5| 2.8 | 13.4| 2.85| 0.04| 17.65| A        |
| 63085   | 20051106   | 18.2| 3.7 | 14.2| 3.14| 0.09| 12.09| V        |
| 67652   | 20060425   | 18.1| 11.7| 15.7| 2.26| 0.10| 8.07 | V        |
| 81542   | 20051106   | 16.6| 5.2 | 14.5| 2.59| 0.31| 4.42 | S        |
| 93250   | 20060204   | 17.9| 3.4 | 14.8| 2.48| 0.15| 5.30 | V        |
| 105041  | 20060718   | 18.4| 15.6| 14.2| 3.04| 0.18| 10.09| V        |
| 129474  | 20060524   | 19.1| 9.3 | 15.4| 2.75| 0.21| 9.78 | A        |

Table 1: Table of AVAST asteroid observations, with the asteroid number, date of the observation (yyyymmd), the estimated V magnitude and phase angle (φ) at the time of observation, the absolute magnitude (H), the orbital semi-major axis (a), eccentricity (e), inclination (i), and the assigned Bus & Binzel (2002a) taxonomy. (*) symbols indicate that the spectra display a strong 0.9µm silicate feature, but fails a rigorous classification. S-type here refers to spectra consistent with the S-complex of taxonomic types rather than the specific S-type.
Fig. 1. The $a_{pc}$ vs $i-z$ colors of the asteroids classified in the course of the AVAST survey displaying a significant (large dots) as seen against the colors of asteroids from SDSS MOC3 (background contours). AVAST V-type asteroids are in green, A-type asteroids are in orange, and S-type are in red. Those with a semi-major axis greater than 2.5AU are indicated by crosses.
Fig. 2. The semi major axis vs. inclination (top) and eccentricity (bottom) of the asteroids classified in the course of the AVAST survey displaying a significant 0.9 $\mu$m absorption feature (large dots) as seen against elements of known asteroids from SDSS MOC3 (background contours). AVAST V-type asteroids are in green, A-type are in orange, and S-type are in red. The location of Vesta and Eos are indicated by blue stars.
Fig. 3. The orbital location of the asteroids observed in the course of the AVAST survey displaying a significant 0.9 μm absorption feature (large dots) as seen against elements of V-type candidates chosen by the AVAST selection criteria from SDSS MOC3 (background points). Confirmed AVAST V-type asteroids are in green, A-type are in orange, S-type are in red, and those with a substantial 0.9μm feature but fail a rigorous classification identified with an x.
Fig. 4. Reflectance spectra of the asteroids observed by AVAST with significant 0.9 μm absorption feature consistent with V, A, or S-type taxonomy. The data (black lines) has been median filtered, and normalized to 0.55 μm by convention, with the Bus & Binzel (2002a) V-type taxonomy template overplotted in green. The small break in the spectra around 0.55 μm is the result of the dichroic in DIS.
Figure 4 (continued)