Rosetta target asteroid 2867 Steins: An unusual E-type asteroid

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Abstract–ESA's Rosetta spacecraft will fly by main-belt asteroid 2867 Steins on September 5, 2008. We obtained new visible wavelength spectra of 2867 Steins on December 19, 2006 (UT), using the Palomar 5 m telescope and the facility Double Spectrograph. Two sets of spectra, taken ~3 h apart, one half of the rotation period for 2867 Steins, show it to be an E-type asteroid. The asteroid displays a 0.50 μm feature that is considered diagnostic of the E(II) sub-class, but is deeper than any previously observed E-type. This feature is most likely due to the presence of oldhamite (CaS) on the asteroid's surface. Also, the observed Steins spectra are far redder than any other known E-types. There is potential evidence for heterogeneity on hemispheric scales, one side of the asteroid appearing to be significantly redder than the other. No known recovered meteorite sample matches the unusual spectra of 2867 Steins, but the closest analog would be similar to an enstatite achondrite (aubrite).

INTRODUCTION

ESA's Rosetta spacecraft was launched on March 2, 2004. The goal of the mission is to rendezvous with periodic comet 67P/Churyumov-Gerasimenko (67P/C-G) and spend approximately two years studying the comet’s nucleus and coma in detail. En route to 67P/C-G, Rosetta will fly by two main belt asteroids, 2867 Steins, on September 5, 2008, and 21 Lutetia on July 10, 2010. Although Lutetia has been intensively studied in the past, relatively little was known about 2867 Steins at the time of its selection by the Rosetta mission in 2004.

We, along with other Rosetta investigators, are conducting a ground-based observational program to fully characterize 2867 Steins prior to the spacecraft flyby. Knowledge of the asteroid’s size, shape, rotation period, pole orientation, phase function, and taxonomic type are valuable to the spacecraft science and engineering teams in planning the encounter geometry and observations. Additionally, comparison between the ground-based and Rosetta observations provides important “ground-truth” for calibrating remote sensing techniques. We are using both CCD photometry and CCD spectroscopy to accomplish these goals.

Asteroid 2867 Steins is located at 2.36 AU in the inner third of the main belt in a fairly typical, low eccentricity and low inclination orbit. Orbital elements are shown in Table 1. Our CCD photometry in 2004 (Weissman et al. 2005, 2007) showed that 2867 Steins rotates with a synodic period of 6.048 ± 0.007 h (assuming a double-peaked light curve), in good agreement with earlier determinations of 6.06 ± 0.05 h by Hicks et al. (2004) and 6.05 ± 0.01 h by Warner (2004). The Rosetta OSIRIS imaging team later found a synodic period of 6.052 ± 0.007 h (Küppers et al. 2007), again in good agreement with our value.

We also showed that the Steins light curve provides a lower limit to the axial ratio, a/b, of 1.30 ± 0.04. After correcting for phase effects, this ratio dropped to 1.19. We fitted the available R-filter data to find a phase function of H = 12.9 ± 0.22 and G = 0.46 ± 0.20. For a typical S-type albedo of 0.20, this corresponds to a mean radius of 3.08 ± 0.30 km, while for a typical E-type albedo of 0.40, the derived H value corresponds to a mean radius of 2.18 ± 0.20 km. Our VRI photometry showed that Steins was unusually red in color, again in good agreement with earlier determinations by Hicks et al. (2004). Hicks et al. suggested that Steins was an S-type asteroid, similar to ordinary chondrite meteorites, but could not rule out a D-type, comparable to more primitive meteorite types.
Table 1. Orbital elements for asteroid 2867 Steins.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis (AU)</td>
<td>2.36342</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.14586</td>
</tr>
<tr>
<td>Inclination (degrees)</td>
<td>9.9454</td>
</tr>
<tr>
<td>Argument of perihelion</td>
<td>250.5196 degrees</td>
</tr>
<tr>
<td>Longitude of the node</td>
<td>55.5335 degrees</td>
</tr>
<tr>
<td>Time of perihelion</td>
<td>2005 June 23.4379</td>
</tr>
</tbody>
</table>

*Epoch: 2007-Apr-10.0.
From JPL Solar System Dynamics Group.

Barucci et al. (2005) classified Steins as an E-type asteroid based on visual and near-infrared spectra, in particular on the presence of a strong 0.50 µm absorption feature. E-type asteroids may be similar to enstatite achondrite meteorites and generally display only grey to moderately red colors. However, the visual spectrum obtained by Barucci et al. displayed the same strongly red color as seen in the broad-band photometry by Hicks et al. (2004) and Weissman et al. (2005, 2007).

Fornasier et al. (2006) used polarimetric measurements to estimate the albedo of 2867 Steins. They found a relatively high albedo of 0.45 ± 0.10. High albedo is consistent with an E-type taxonomic classification. Lamy et al. (2006) used the Spitzer Space Telescope to provide a preliminary albedo estimate of 0.35 ± 0.05, again relatively high, though also consistent with some high albedo S-type asteroids.

This paper reports results of CCD spectroscopy of 2867 Steins using the facility Double Spectrograph on the Palomar 5 m Hale telescope, in order to further clarify the taxonomic identity of 2867 Steins. Our results show that this is an unusual E(II)-type asteroid with the strongest 0.50 µm absorption band ever seen, and unusually red colors. Furthermore, by obtaining spectra spaced approximately three hours apart, half the rotation period of Steins, we show that there are potential differences in the strength of the red color on the two opposing hemispheres.

The organization of this paper is as follows. The next two sections describe the observations and instrumentation, and the data reduction, respectively. After that, four sections present our analysis of the Steins spectra: a principal component analysis, the spectral type identification, a mineralogic analysis, and a comparison with both asteroid and meteorite analogs, respectively. The last section provides a discussion and summary of our results.

**OBSERVATIONS**

Moderate resolution CCD spectrograms of 2867 Steins were obtained using the facility Double Spectrograph (Oke and Gunn 1982) mounted at the Cassegrain focus of the Hale 5 m telescope on Palomar Mountain, California, on the night of December 19, 2006 (UT). To explore possible hemispherical variability we collected two sets of spectra separated by ~3 h, or approximately half of the asteroid’s rotation period. The pertinent observational parameters are listed in Table 2.

The Double Spectrograph is a low-to-medium resolution (R ~ 1,000 to 10,000) grating instrument that uses a dichroic to split light into separate red and blue channels observed simultaneously. Slits are 12” in length and are available in a variety of widths. The red channel detector is a 1024 × 1024 CCD with 24 µm pixels, and the blue channel detector is a 2048 × 4096 CCD with 15 µm pixels. Both CCDs are thinned and anti-reflection coated.

Within the Double Spectrograph, the night sky and object are first imaged on the slit before being divided by the dichroic into red and blue beams, which are then dispersed and re-imaged with individual grating and camera set ups. For our observations we used the 5500 Å dichroic with the 300 lines mm⁻¹ (3990 Å blaze) grating for the blue channel, and the 158 lines mm⁻¹ (7500 Å blaze) grating for the red channel. This gave a spectral dispersion of 2.14 Å channel⁻¹ in the blue and 4.91 Å channel⁻¹ in the red. The telescope was tracked at the predicted rate of motion of the asteroid. We chose a relatively wide, 6 arcsecond spectroscopic slit. The tailpiece of the telescope was rotated such that the slit matched the parallactic angle, in order to negate any possibility of differential refraction effects, which have the potential to cause spurious slopes at the blue end of high air mass spectra.

In addition to 2867 Steins we also collected spectral exposures of the solar analog stars 97–29, Ru 149B, SAO 130415, PG 918 + 29 c, and 103–487 at a variety of air masses that bracketed and matched the air masses observed for Steins. Wavelength calibrations were accomplished with arc-lamp exposures and flat-fields were taken using the illuminated dome as well as the twilight sky. We took care to place Steins and the solar analog stars in the identical place within the slit, re-centering the objects between exposures. The asteroid was a few weeks short of opposition at a favorable northerly declination of +33 degrees. The estimated visual magnitude of the asteroid was 16.82 according to the JPL Horizons ephemeris service (Giorgini et al. 2007). Weather conditions were dry and cold, and the sky was not photometric, with thin clouds and seeing of ~3 arc-seconds.

**DATA REDUCTION**

The two channels of the spectrograph were analyzed separately and recombined into a composite spectrum spanning from approximately 3500 Å to 9500 Å. Our reductions proceeded in the standard manner and our methods are discussed in greater detail in Hicks and Buratti (2004).

Each frame was first cleaned of cosmic ray strikes. A 21-pixel-wide object window was defined in the spatial dimension about the center-line with 5-pixel sky windows on either side immediately adjacent. The plate scale was 0.468 arcsec pixel⁻¹ for the red camera and 0.390 arcsec pixel⁻¹ for the blue camera. A linear fit to the sky windows was subtracted from each row in the object window, removing bias counts and night-sky emissions. Higher-order fits to the
sky continuum were tried, but gave essentially identical ratioed spectra. The digital counts within the object window were summed into a one-dimensional spectrum.

Solar analog stars were reduced in the same fashion and co-added to match the air mass of the 2867 Steins observations and ratioed by the Steins frames to produce relative reflectance spectra. By taking care to place the asteroid and the solar analog stars on the same part of the CCD detector the need for flat-fielding was eliminated. As a consistency check, individual raw spectra from each frame in the sequence were ratioed by their sum. Changes in slope or flux in the ratios would suggest problems in differential refraction or changing extinction but in no cases was it required to remove individual spectral frames from our sums. Similarly, we cross-checked our solar analog stars and found that 103–487 gave a spurious slope when ratioed to other solar analog stars and we removed it from our reductions.

**PRINCIPAL COMPONENT ANALYSIS**

The two spectra for 2867 Steins are shown in Fig. 1. In order to compare our Steins spectra with those of other asteroids, we performed a principal component analysis based on the method of Bus and Binzel (2002a, 2002b), which is a compilation and analysis of 1447 spectra of small main belt asteroids. Their system consists of three principal components: 1) the overall spectral slope between 0.44 and 0.92 µm, 2) PC2', which is a measure of the strength of the 0.95 µm olivine-pyroxene absorption band, and 3) PC3', a measure of the fall-off of the spectrum at the blue end. Our two relative reflectance spectra were each fitted to 48 values spaced every 0.01 µm from 0.44 to 0.92 µm, and then multiplied by the Bus and Binzel eigenvectors (R. Binzel, personal communication). Results are shown in Table 3.

In the Bus taxonomy, X-type asteroids (the degenerate E, M, and P types) with a 0.50 µm absorption band are referred to as Xe. The slope values of 0.9996 and 0.7313 that we find for our spectra of 2867 Steins are both redder than any other Xe spectra reported in Bus and Binzel (2002a). The reddest Xe object they find is 1014 Semphyra with a slope parameter of 0.6023. The mean slope for all of their Xe objects is 0.3394. Thus, Steins stands out as an unusual E-type object because of its strong red color.

This is illustrated in Fig. 2, which is a copy of Fig. 1 from Bus and Binzel (2002b). The locations of the major asteroid taxonomic groups as a function of the first two principal component parameters, slope and PC2', are shown in the figure. The X-type asteroids, which include the Xe subclass, cover a slope range of ~0.0–0.5, and a PC2' range of ~0.0–0.3 (there are a few outliers beyond these ranges). The locations of the two Steins spectra are indicated by large filled circles. Note that they lie completely outside the normal range for X-type asteroids and specifically for the Xe-types, shown by

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**Table 2. Observing geometry for observations of 2867 Steins on December 19, 2006 (UT).**

<table>
<thead>
<tr>
<th>Time (UT)</th>
<th>R (AU)</th>
<th>Δ (AU)</th>
<th>Phase (deg)</th>
<th>Airmass</th>
<th>Exposures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum #1</td>
<td>06:52–07:27</td>
<td>2.6664</td>
<td>1.7379</td>
<td>8.686</td>
<td>1.134</td>
</tr>
<tr>
<td>Spectrum #2</td>
<td>09:47–10:23</td>
<td>2.6665</td>
<td>1.7374</td>
<td>8.640</td>
<td>1.011</td>
</tr>
</tbody>
</table>

*All geometric properties are as calculated by the JPL Horizons ephemeris service.
open circles. It is this strong red color that led to the early identifications of Steins as an S-type (or D-type) asteroid (Hicks et al. 2004; Weissman et al. 2005). The PC2′ values of 0.0628 and 0.0634 are consistent with the absence of a noticeable 0.95 µm mafic silicate band. The PC3′ values of 0.0013 and –0.0692 are near the high and low ends, respectively, of the range for other observed Xe asteroids (see Bus and Binzel 2002b).

SPECTRAL TYPE

A brief examination of the visible spectra obtained from each hemisphere of the asteroid (Fig. 1) demonstrates that this asteroid has a significant absorption feature located near 0.50 µm, and a strongly red spectral slope at longer wavelengths up through 0.92 µm. The decrease in signal-to-noise towards either end of each spectrum is due to a lack of sensitivity of the Double Spectrograph at these wavelengths. No other significant absorption features, apart from those possibly due to minor stellar and telluric (atmospheric water) features located at approximately 0.38 µm and 0.89 µm, respectively, can be positively identified in these spectra.

The measured spectral characteristics of 2867 Steins can be used to determine its taxonomic classification, and to identify potential affinities to other asteroids within the same taxonomic class. Asteroid taxonomic classifications are determined based on observational parameters such as broadband colors, albedo, and/or spectral reflectance. In order to identify a plausible taxonomic match to an asteroid, all asteroids of a specific taxonomic class must have the same (or similar) spectral response. The first attempt to determine the taxonomy of Steins (Hicks et al. 2004) was based solely on broadband colors, which showed no evidence for the presence of spectral absorption features. Based on this limited data set, Hicks et al. suggested that 2867 Steins was an S-type asteroid, though they could not rule out a D-type (see also Weissman et al. (2007), Fig. 1).

In the absence of albedo data and spectral features, some asteroids can be more difficult to categorize in these broad classification schemes, given that their spectral parameters are degenerate, e.g., E-, M-, and P-types, which are collectively known as the X-types (Tholen 1989; Tedesco et al. 1989). Fortunately, the data obtained for 2867 Steins reveal the presence of a prominent absorption feature located near 0.50 µm. In addition, investigators have determined that the albedo of the asteroid is ~0.30–0.55 (Fornasier et al. 2006, Lamy et al. 2006). Among all the known taxonomic classes, only members of the E-type asteroids appear to have an absorption feature located in this portion of their visible spectra and have high albedo values similar to that of 2867 Steins. E-type asteroids 64 Angelina and 3103 Eger have been observed to have features located near 0.50 µm (Fornasier and Lazzarin...
MINERALOGICAL ANALYSIS

Taxonomic classifications can be useful for placing asteroids with similar spectral parameters into groups, but are not diagnostic for determining specific mineralogies or compositions. It is well noted that asteroids belonging to one taxonomy may be different compositionally or physically from asteroids belonging to another taxonomic class, e.g., S-type asteroids appear to be compositionally/physically distinct from C-type asteroids, etc. However, it has been shown that even within several individual taxonomic groups there appears to be a range of diverse spectral characteristics, which in turn suggest that a wide variety of compositions and mineralogies exists among these populations (Gaffey et al. 1993a; Vilas et al. 1994; Emery and Brown 2003; Gaffey and Kelley 2004; Hardersen et al. 2005). For example, asteroids belonging to the S(I) subclass appear to have been thermally processed and may possess olivine mantles, whereas asteroids of the S(IV) subclass do not show any evidence for thermal processing and may be similar to ordinary chondrite meteorites (Gaffey et al. 1993a).

The E-type taxonomic classification was originally used to describe objects that had a flat or somewhat reddish spectrum and relatively high albedos (Tholen 1989; Tedesco et al. 1989). More recent investigations of the spectra of E-type asteroids indicate that there is some degree of spectral diversity among this taxonomic population due to the presence of minor, but spectrally significant, mineral phases on the surfaces of these objects. These mineral phases could be due to trace amounts of sulfides or the presence of small amounts of Fe$^{2+}$ within a predominantly iron-free silicate (enstatite) assemblage (−Fs$_{1-3}$) (Burbine et al. 2002; Gaffey and Kelley 2004).

The spectroscopic data suggest that there are at least three different subclasses, E(I), E(II), and E(III), that exist among this high-albedo population of asteroids, with each one representing a different mineralogy and thermal history (Gaffey and Kelley 2004). Objects belonging to the E(I) subtype are characterized by a slightly reddish or curved spectra with no discernible mineral absorption features. These objects probably consist of an aubrite pyroxene assemblage. In contrast, the E(II) asteroids have reddish spectra with a strong feature near 0.50 µm and a weaker feature at 0.96 µm. The E(III) sub-type is characterized by a flat or somewhat reddish spectral response and exhibits a weak absorption feature near 0.9 µm. This type spectra is characteristic of enstatite pyroxene that contains a trace amount of Fe$^{2+}$ at the few tenths of a mole per cent level. Another proposed system breaks the E-type asteroids into three subtypes labeled Hungaria-like, Angelina-like, and Nysa-like (Clark et al. 2004).

Of the three spectral subclasses of the E-type population, 2867 Steins seems to most closely resemble the Angelina-like, E(II) subclass (see Fig. 3). The E(II) asteroids are distinguished from the other subtypes by spectral absorption features located near 0.50 µm and 0.96 µm, as mentioned above. The preferred mineralogical interpretation is that these features are produced as a result of the presence of the calcium sulfide mineral oldhamite (CaS) on the surface of the asteroid (Burbine et al. 2002; Gaffey and Kelley 2004). Oldhamite is characterized by two absorption features located near 0.50 µm and 0.96 µm that are probably produced by trace amounts of a bivalent ion, such as Fe$^{2+}$, that has been substituted into the sulfide instead of Ca$^{2+}$ (Fig. 3).

Oldhamite is present only in highly reduced mineral assemblages such as aubrite (enstatite achondrite) meteorites (Keil 1989; Fogel et al. 1997; McCoy et al. 1999), which have been postulated by several investigators as the most probable analogues to the E-type asteroid assemblages (e.g., Zellner et al. 1977; Gaffey et al. 1992). Enstatite aubrites (aubrites) are brecciated pyroxenites that formed under highly reducing conditions and are almost entirely composed of FeO-free enstatite as the primary phase (Watters and Prinz 1979). These rocks also contain minor and trace accessory phases of plagioclase, diopsid, forsterite, Fe-Ni metal, and sulfides (e.g., oldhamite and troilite) (Keil 1989; Mittlefehldt et al. 1998). The oldhamite spectrum shown for comparison in Fig. 3 was obtained by extracting oldhamite from the Norton County meteorite, which is a well known aubrite assemblage (Burbine et al. 2002).

Both of the spectra of 2867 Steins obtained in this study have a well-defined feature located near 0.50 µm. After fitting a straight line continuum to the spectra, and dividing out the continuum, the band centers of both spectra are determined to be at 0.50 ± 0.01 µm, which is consistent with the similar feature observed in the spectrum of oldhamite (Burbine et al. 2002). However, identification of a 0.96 µm feature within our spectra of asteroid 2867 Steins is difficult due to the increasing noise near that wavelength. Although our data show no definitive evidence of a 0.96 µm feature, other investigators have seen this feature in the near-IR spectra of Steins (e.g., Barrucci et al. 2005).

The presence of the 0.50 µm and 0.96 µm absorption
features due to oldhamite is consistent with spectra of other asteroids within the E(II) taxonomic subclass, such as 64 Angelina, 3103 Eger, and 4660 Nereus (Fornasier and Lazzarin 2001; Binzel et al. 2004; Lazzarin et al. 2004). However, it is not clear how much oldhamite is required to produce such distinctive features in these asteroids. A mixing experiment of 5% oldhamite and 95% enstatite only produced a 0.50 µm feature approximately 1% deep, which failed to match the depth of the feature of 64 Angelina (Burbine et al. 2002). Given that the amount of oldhamite found within the aubrites is much less than 1%, it appears that higher abundances of this mineral may be required to produce these features on the E(II)-type asteroids (Burbine et al. 2002).

It is understood that the terrestrial meteorite collections almost certainly represent a biased sample of materials from the known asteroid population, and therefore it is entirely possible that exact mineral assemblages to these asteroids may not exist on Earth. However, aubrite meteorites such as Allan Hills (ALH) 78113 do have distinctive spectra that clearly exhibit well-defined 0.50 µm absorption features with smaller features located near 0.96 µm (Fig. 4). The strength of these features in ALH 78113 are less intense than those observed for asteroid 2867 Steins, and the spectral response is less steeply sloped towards longer wavelengths, but the band locations demonstrate that a genetic link between the aubrite meteorites and E(II) asteroids is plausible.

One of the more intriguing characteristics of 2867 Steins is the depth of its 0.50 µm band. Previous investigators have
determined similar absorption bands for two other E(II) asteroids, 64 Angelina and 3103 Eger, to be 8% and 9% deep as measured with respect to straight line continua (Fornasier and Lazzarin 2001). In contrast, the 0.50 \( \mu \)m feature in each of our spectra of 2867 Steins is \(~13\%\) deep with respect to an estimated straight line continuum. If the absorption features of all three of these E(II) asteroids are assumed to be due to the presence of the same material, olivine, then the deeper band depth of 2867 Steins’ feature suggests that the absorbing species present on the surface is either more abundant, contains a higher concentration of Fe2+, lacks an obscuring phase, is composed of larger crystals, or has some combination of any or all of these properties (Gaffey et al. 1993b). Therefore it is highly probable that asteroid 2867 Steins represents an assemblage with different physical properties than those contained on asteroids 64 Angelina and 3103 Eger and may therefore have had a different petrogenesis. Hence, even though 2867 Steins may have affinities to these other E(II) asteroids in terms of its mineralogy, it may have originated from a completely different parent body under different geologic conditions.

It is interesting to note that spectral slopes of the two Steins spectra appear to differ somewhat from one hemisphere to the other (see Fig. 1 and the PCA analysis above), which suggests possible differences in physical properties of the asteroid at hemispheric scales. Differences in spectral slopes can be dependent upon many factors such as changes in particle size, compositional variation, and surface alteration processes. However, given that both spectra of 2867 Steins appear to be identical in terms of band position and depth, it would be difficult to reconcile the slope differences in terms of compositional differences or particle size variations on hemispherical scales.

An alternative, although less likely possibility, is that such differences between spectral slopes may be the result of minor instrumental errors or changing atmospheric conditions (e.g., seeing) during the collection of the data. We note that both spectra were taken at low air mass, \(<1.14\), so it is unlikely that errors in the atmospheric correction can explain the difference. Hence it would be desirable to observe Steins again over several rotation periods to determine if the hemispheric differences observed in this investigation can be confirmed. If such differences were found, then this would suggest that Steins has some degree of hemispheric variation across its surface that the Rosetta spacecraft instruments should be able to detect during the upcoming encounter in September 2008.

**METEORITE ANALOGUES AND THERMAL HISTORY**

Asteroids 44 Nysa, 64 Angelina, and 434 Hungaria were some of the first asteroids to be recognized as members of the E-type taxonomic class. Based on their high albedo and relatively featureless spectra, a proposed link between these types of asteroids and the enstatite achondrites (aubrites) was first suggested by Zellner et al. (1977). More recently, data with higher spectral resolution and better signal-to-noise have been collected on these and other E-type objects (e.g., 2867 Steins, 3103 Eger, 4660 Nereus). The preferred interpretation
for the composition of these E-type asteroids based upon plausible geologic and meteoritic materials is that they are composed almost entirely of iron-free enstatite with some trace phases, such as sulfides and low-iron pyroxene (−Fe₃₋₅), responsible for producing the absorption features seen in the spectra of these asteroids (Fig. 3) (Fornasier and Lazzarin 2001; Burbine et al. 2002; Kelley and Gaffey 2002; Gaffey and Kelley 2004).

In the case of the E(II) subclass of asteroids, and asteroid 2867 Steins, the probable starting composition of their parent bodies was likely an enstatite-chondrite-like precursor that eventually attained a high enough temperature, ~1300–1500 °C (McCoy et al. 1999), through radiogenic or magnetic induction heating to produce extensive partial melts, or even the complete melting of the precursor object. Such parent bodies that underwent significant partial melting and differentiation would produce mantles resembling the aubrites (Keil 1989; McCoy et al. 1999). Any basaltic-type materials produced as a result of this melting would be enriched in incompatible trace elements and mineral phases. Given that the exact behavior of oldhamite in these types of reduced igneous conditions is not completely understood (Fogel 1997; McCoy et al. 1999), it is plausible that any basaltic component produced would be enriched in oldhamite as melt production proceeded. Therefore the E(II) asteroids could be composed of the early partial melt material from enstatite chondritic parent bodies (Gaffey and Kelley 2004).

A direct spectral comparison of typical enstatite chondrites and aubrites (enstatite achondrites) demonstrates that these two meteorite groups have very different spectral responses (Fig. 4). Enstatite chondrites have not experienced the high degree of melting that the aubrites have (Keil 1989; McCoy et al. 1999) and contain a significant amount of metal, which is responsible for their higher reflectivity towards near-infrared wavelengths (red slopes) and lower visual albedos compared to the aubrites (Gaffey 1976). The enstatite chondrites generally have visual albedo values ranging from 0.07 to 0.16, whereas the aubrites have values ranging from 0.23 to 0.50, with the majority of these meteorites having albedos in excess of 0.40 (Gaffey 1976: Gaffey, personal communication).

We compare the enstatite meteorite spectra and our 2867 Steins spectra in Fig. 4; all spectra have been normalized to unity at 0.55 μm and then scaled for spectral albedo. The visual albedos of the enstatite meteorites have been estimated based on the typical values for these two groups of meteorites, with Atlanta, an enstatite chondrite, having an albedo of 0.16, at the higher end of the enstatite chondrite range, and ALH 78113, an aubrite, having an albedo of 0.42. As noted in the Introduction section, asteroid 2867 Steins’ albedo has been determined by ground- and space-based observations to be ~0.30–0.55; herein we use a value of 0.45. Upon examination of all three spectral curves, it is readily apparent that the enstatite chondrite Atlanta is not a good spectral match for asteroid 2867 Steins. The albedo value is well below that of the asteroid and there is no discernible 0.50 μm feature. In contrast, the aubrite ALH 78311 is a more suitable match to the spectral reflectance of the asteroid. The albedo value of this aubrite is consistent with that determined for the asteroid, and it also has the distinctive 0.50 μm feature seen in this asteroid and others of the E(II) class. However, it is not an exact match because the spectral slope is considerably flatter than that of 2867 Steins, and the aubrite’s 0.50 μm absorption feature is not as deep. It should be noted that such differences in spectral slope may not be significant when comparing laboratory and telescopic observations. Even taking this into consideration, no known meteoritic assemblage is recognized or exists within the terrestrial collections that is identical to 2867 Steins. Still, the similarities between the asteroid and aubrite spectra are very suggestive of a plausible compositional link. Hence the most likely meteoritic analog to this asteroid is an aubrite meteorite with a spectrally significant amount of sulfide, such as oldhamite (CaS) present in its assemblage.

**DISCUSSION AND SUMMARY**

We have shown that asteroid 2867 Steins is an E(II)-type asteroid, though with an unusually strong 0.50 μm feature and a significantly redder spectral slope than previously studied E-types, or their terrestrial meteorite analogs, the enstatite achondrites (aubrites). This is shown by the principal component analysis of our spectra as well as direct comparisons of our spectra with those measured for similar asteroids and meteorites. We have also shown evidence for possible compositional heterogeneity on hemispheric scales.

The Rosetta spacecraft will perform a flyby of asteroid 2867 Steins on September 5, 2008. It will be the first spacecraft to examine an E-type asteroid in detail, and perhaps confirm the possible genetic connection of these E-type asteroids to the aubrites (enstatite achondrites). Given the range of albedos estimated for this object (~0.30–0.55) and its likely enstatite composition, some bright/white areas should be present on the surface of Steins. If this is correct, then the Rosetta spacecraft will be able to detect such albedo features during its encounter with the asteroid.

In addition, Rosetta should be able to more completely characterize the 0.50 μm band and provide independent confirmation that this asteroid has perhaps the deepest band, possibly due to oldhamite, ever seen on an E-type asteroid. Given that other E(II) asteroids appear to have weaker 0.50 μm bands in their spectra, e.g., 64 Angelina and 3103 Eger (Fornasier and Lazzarin 2001), it is possible that Rosetta may be visiting a minor planet that is unique among other E(II) asteroids that have previously been recognized from ground-based spectroscopic investigations. Rosetta may also be able to confirm the presence of any hemispheric differences across the 4.4 km diameter asteroid (Weissman et al. 2007) due to changes in particle size, alteration products, or compositional
variations. These heterogeneities may also be present at smaller spatial scales and should be detectable by the remote sensing instruments on Rosetta.

More specifically, the Rosetta spacecraft instruments, in particular the visual and infrared spectrometer (VIRTIS), should be able to characterize spectral features that previous ground-based investigations have only detected at relatively low signal-to-noise, e.g., the 0.96 µm feature. Identification of such features should allow for a more complete interpretation of the asteroid’s surface assemblage, strengthening the constraints of any trace phases present, which may aid in the understanding of potential thermal histories and compositions of its original parent body. This in turn will aid in deciphering the range of thermal and oxidation states that once existed during the latter stages of the solar nebula and the early formation of the inner solar system.

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