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Letter to the Editor

E-type asteroid (2867) Steins: flyby target for Rosetta

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ABSTRACT

Aims. The mineralogy of the asteroid (2867) Steins was investigated in the framework of a ground-based science campaign dedicated to the future encounter with Rosetta spacecraft.
Methods. Near-infrared (NIR) spectra of the asteroid in the 0.8−2.5 μm spectral range have been obtained with SpeX/IRTF in remote-observing mode from Meudon, France, and Cambridge, MA, in December 2006 and in January and March 2007. A spectrum with a combined wavelength coverage from 0.4 to 2.5 μm was constructed using previously obtained visible data. To constrain the possible composition of the surface, we constructed a simple mixing model using a linear (areal) mix of three components obtained from the RELAB database. A space-weathering model was applied to the aubrite ALH-78113 spectrum.
Results. The four new NIR spectra reveal no major absorption features. The best-fit model for the constructed visible-plus-NIR spectrum is represented by a mixture of 57% enstatite, 42% oldhamite, and 1% orthopyroxene. These results place Steins in a subdivision of the E-type class with objects like Angelina, Eger, and Nereus. This group is not sampled by the current collection of aubrite meteorites. Interestingly, the reddened aubrite spectrum also provides a good match to the Steins VNIR spectrum.

Key words. minor planets, asteroids – techniques: spectroscopic – methods: observational

1. Introduction

The asteroid (2867) Steins is the first science target to be visited by ESA's flagship Rosetta spacecraft. Following the postponement of the mission due to problems with the launcher, Steins was later included among the mission's targets because of its relatively unusual spectral properties. After its successfull launch on 2 March 2004, the spacecraft will fly by (2867) Steins in September 2008 at a distance of 1745 km with a relative velocity of 8.5 km s^{-1}. Located in the inner part of the main belt, in an orbit with low eccentricity (a = 2.36, e = 0.14, i = 9°.9), (2867) Steins has an estimated diameter between 4.8 km and 6.0 km corresponding to a polarimetric albedo of 0.45 ± 0.1 (Fornasier et al. 2006) and a radiometric albedo of 0.35 ± 0.05 (Lamy et al. 2006), respectively. Both albedoes agree with the E-type taxonomic classification of (2867) Steins based on its visible and infrared spectra (Barucci et al. 2005).

E-type asteroids are considered to be thermally evolved, igneous bodies that have experienced at least partial melting and magmatic differentiation (Bell et al. 1989). They are common in the inner region of the main belt with a peak heliocentric distribution at 2 AU. Based on the spectral match with the laboratory spectra of aubrites and the high albedo, it was inferred that their surface mineralogy should mainly consist of iron-free or iron-poor silicates such as enstatite and forsterite. Keil (1989) considered that aubrites were not derived from the parent bodies of enstatite chondrites – EH or EL. The high temperature required to melt enstatite – 1580 °C will most probably lead to the melting taking place throughout the entire body. He postulated the existence of a third parent body for the aubrite meteorites with an enstatite chondrite-like composition but with a higher troilite/metallic Fe and Ni ratio. Since almost all aubrites have a heavily brecciated structure with some of them including xenoliths (Lorenz et al. 2005), their parent body was probably collisionally disrupted and gravitationally reassembled into a rubber-pile structure (Okada et al. 1988). The only non-brecciated aubrite known – Shallowater – might have then formed on the fourth enstatite meteorite parent body (Brett & Keil 1986). However the discovery of an absorbtion feature at 3 μm indicated the presence of hydrated minerals in the spectra of 6 E-type asteroids (Rivkin et al. 1995, 1997), thereby challenging the view of this taxonomic class as completely igneous and anhydrous.

As the first space mission ever to visit any E-type asteroid, Rosetta will play a crucial role in understanding the nature and the formation history of these peculiar objects. (2867) Steins has recently been the subject of more in-depth analysis. From ground-based photometric observations, Weissman et al. (2007) have found an R-filter absolute magnitude of 12.6 ± 0.02 and a double-peaked lightcurve with an amplitude of 0.29 ± 0.04 mag and a synodic period of 6.048 ± 0.007 h. Proving the capabilities

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Table 1. Observational circumstances of (2867) Steins at the UT date for the middle of the exposure interval, airmass, and total exposure time for asteroid and solar analog stars respectively (SA102-1081 in December 2006 and January 2007, HD 259516 in March 2007).

Date (UT)	V (mag)	Phase angle (°)	r (UA)	Δ (UA)	Airmass	$T_{\rm exp}$(s)	Airmass★	$T_{\rm exp}$(s) ★
2006/12/22.5694	16.74	7.49	2.66	1.72	1.13	2400	1.10	16
2007/01/21.4014	16.83	8.45	2.68	1.75	1.04	2400	1.07	16
2007/03/12.3141	17.78	20.71	2.70	2.26	1.15	2400	1.18	30
2007/03/13.2270	17.79	20.80	2.70	2.27	1.03	2400	1.02	30

of the OSIRIS imaging system onboard Rosetta, Küppers et al. (2007) observed Steins continuously for 24 h and find an absolute magnitude of 13.05 ± 0.03 and a period of 6.052 ± 0.007 h.

Here we present four NIR spectra of (2867) Steins in the 0.8−2.5 μm wavelength domain obtained in January and March 2007. Together with already available data published by Barucci et al. (2005), this helps to better characterize the nature of Steins before the flyby and, accordingly, to maximize the science output of the Rosetta mission.

2. Observations and data reduction

We obtained four spectra of (2867) Steins in the 0.8−2.5 μm wavelength domain using the spectrograph SpeX on the 3-m NASA Infrared Telescope Facility (IRTF) in Mauna Kea, Hawaii (Table 1). The instrument was operated in remote mode from the Centre d'Observation à Distance en Astronomie de Meudon (CODAM) (Birlan et al. 2004) and from the MIT campus in Cambridge, MA, using the low-resolution Prism mode ($R = 100$) of SpeX (Rayner et al. 2003). The slit was 0.8 × 15″ in size and oriented North-South. In order to minimize the atmospheric and telescope influences we used the nodding technique; i.e. the spectra for the asteroid and the solar analog stars were obtained alternatively on two separated locations on the slit denoted A and B.

The data reduction process followed a standard procedure (Rivkin et al. 2004). Images in each of the A and B apertures were first corrected for nonlinearities using an iterative procedure (Vacca et al. 2004), and then the flat field correction was applied using a master flat-field frame. The A−B images were then corrected for dark-current, telescope and sky effects and flat-fielded. From the subtracted images, each containing a negative and a positive spectrum, the one-dimensional spectra were extracted and wavelength-calibrated using an argon lamp spectrum. The final normalized reflectance spectrum was corrected for the telluric absorption lines using the ATRAN atmospheric model (Lord 1992).

The asteroid and the reference star were observed at similar, low airmasses and close to meridian in order to minimize the light loss due to the atmospheric differential refraction. These spectra are presented in Fig. 1.

We notice some slight differences in the slopes shortward of 1.2 μm. Given that (2867) Steins was a relatively faint target during the March 2007 run and that our observations do not sample the entire rotational period we cannot claim that these variations are real. Incomplete removal of telluric absorption bands in the data reduction process and instrumental artifacts could also be responsible for these differences.

For the spectrum with the lowest SNR – acquired on 13 March 2007 – we computed a slope of 0.39 ± 0.04 μm^{-1} for the 0.8−1.2 μm region while we obtained a value of 0.31 ± 0.02 μm^{-1} for 12 March 2007. It is known that individual spectra obtained with SpeX in a time interval of several minutes show slope variations of about 2% at best (Rayner et al. 2004).

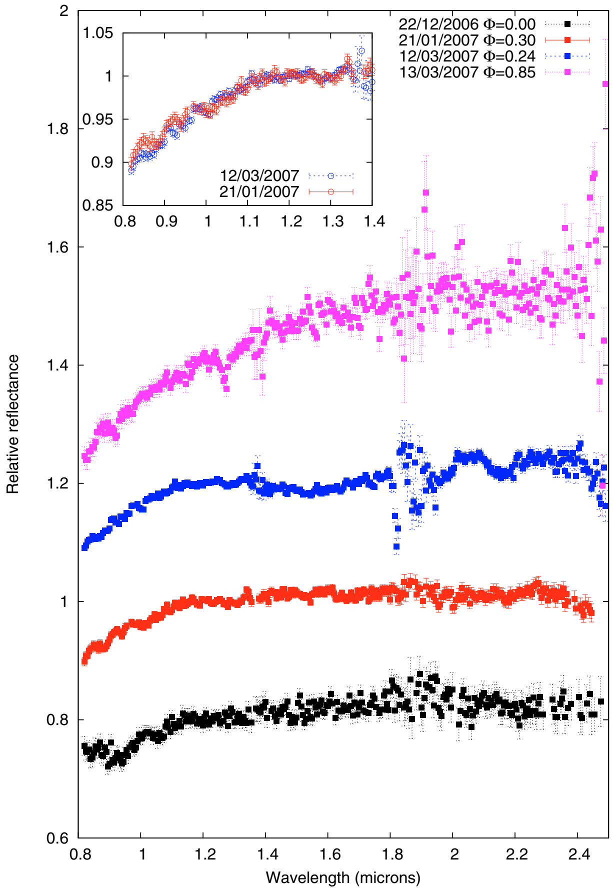

Fig. 1. NIR spectra of (2867) Steins obtained in December 2006, January and March 2007. All spectra were normalized at 1.20 μm and vertically-shifted for visibility with 0.2 reflectance units. The inset image shows the agreement between the 21/01/2007 and 12/03/2007 spectra obtained at 0.30 and 0.24 rotational phase, respectively.

The current estimation of the Steins rotational period (Küppers et al. 2007) does not allow us to reliably link our spectra with the rotational phase since they were obtained one year later than the estimated zero phase. However, since the spectra were acquired in a time span of less than 3 months we could still find their relative separation in terms of rotational phase. We conventionally defined the moment of our earliest spectrum – 22 December 2007 – as the new zero phase. Figure 1 presents all our spectra with the corresponding phase indicated. Two of the spectra were obtained at almost the same phase: on 21 January 2007 at 0.30 and 12 March at 0.24. Those two spectra are also the most similar.

In general, all our NIR spectra of Steins are featureless with a slightly red or neutral trend. The only apparent absorption features around 1.9 μm are almost certainly the effects from the

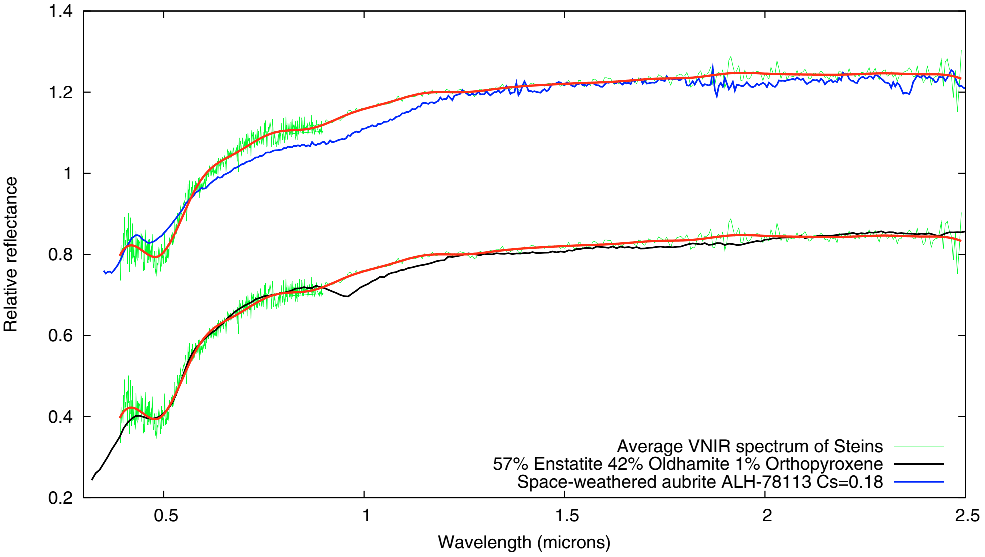

Fig. 2. The visible, plus averaged NIR, spectrum of (2867) Steins (green line) smoothed with a bicubic spline function (red line). The spectrum was fitted with a linear (areal) mix of three components taken from the RELAB database as presented in the text (black). The second fit represents a modeled space-weathered spectrum of the aubrite ALH-78113 (blue).

incomplete removal of telluric absorption lines since this region is dominated by strong absorption due to atmospheric water vapors.

3. Discussion and conclusion

E-type asteroids represent a very rare taxonomic class that was originally defined by its high albedo and slightly red or neutral spectra. Fewer than 30 members are known (Clark et al. 2004a). They were originally proposed as parent bodies for the enstatite achondrite (aubrite) meteorite (Zellner et al. 1977; Gaffey et al. 1989). Dynamical considerations make the largest of them, (44) Nysa, able to deliver meteorites to Earth. However the detection of an absorption band near 0.90 μm, characteristic of FeO-bearing pyroxene, may rule out this hypothesis. The amount of Fe^{2+} required to produce this absorption feature, although small, is still much higher than what is found in the aubrite meteorites (Gaffey & Kelley 2004). Based on spectral features and orbital elements, the near-Earth asteroid, (3103) Eger (an E-type), was proposed as the parent body of aubrites (Gaffey et al. 1992). Another E-type in the near-Earth asteroid population is (4660) Nereus. Binzel et al. (2004) reports a strong absorption feature near 0.49 μm and Delbó et al. (2003) finds a relatively high thermal albedo. Interestingly, because of its much lower inclination, Nereus does not seem to originate from Hungaria region as does Eger.

The NIR spectra of 8 E-type and 8 Xe-type asteroids were obtained by Clark et al. (2004b) in a survey of X-complex asteroids. The Xe designation was proposed by Bus & Binzel (2002) as a subdivision of the X class, and it includes asteroids that present an absorption feature centered near 0.49 μm. This absorption band was detected in spectra of asteroids (64) Angelina, (434) Hungaria, and (3103) Eger. This feature was originally attributed to troilite (Burbine et al. 1998) and was later confirmed by Fornasier & Lazzarin (2001). They also found this feature in the spectrum of (2035) Stearns, while it is missing in the spectra of (317) Roxane and (1251) Hedera.

With all the data pointing to spectrally distinct subtypes among E-type asteroids, Clark et al. (2004a) attempted a compositional modeling of nine E-type asteroids. They combined the available data from the visible and NIR and used a Hapke-theory mixing-model simulation of E-type asteroid spectra. The inferred mineralogies suggest three possible compositional groups within the E-type class: 1) "Nysa-like" including objects with both 0.9 and 1.8 μm bands best fit by aubrite plus olivine and orthopyroxene 2) "Angelina-like" objects presenting 0.5 and 0.9 μm bands consistent with a aubrite plus oldhamite composition and 3) "Hungaria-like" – objects with only 0.9 μm band.

Using all known aubrite spectra alone in the model resulted in a poor fit for most of the E-type asteroids. The only exceptions were "Hungaria-like" objects (434) Hungaria and (2048) Dwornik. That makes this subclass probably the only source of aubrite meteorites with the other two unlikely contributors to the present collection. Accordingly, some of the E-type asteroids may have mineralogies for which there are no meteoritic analogs.

To place (2867) Steins into one of these recent E-type subclasses, we followed a similar approach. First we constructed a single spectrum of Steins by combining all four NIR spectra into a weighted mean spectrum with weights constructed from the reflectance errors. The visible counterpart of the spectrum was used from Barucci et al. (2005). This visible spectrum is in good agreement with newly acquired spectra (Fornasier, private communication). Both visible and NIR spectra were separately fit with a cubic spline function. The points affected by atmospheric water or the detector's drop in sensitivity were discarded. Finally the reflectance values of the smoothed spectra in the common wavelength range of 0.82–0.90 μm were used to normalize and connect the visible and the near-infrared parts of the spectrum. Figure 2 shows the resulting VNIR spectrum of Steins and the bicubic spline fit for the 0.40–2.50 μm wavelength range at a 0.005 μm interval. It presents a clear absorption band near 0.5 μm and a much weaker one at 0.9 μm. Their exact positions and depths were determined as in Burbine & Binzel (2002) by dividing the smoothed spectrum by the estimated linear continuum. We found a band at 0.49 μm with a depth of 9% with respect to the continuum and a weaker feature at 0.87 μm with a depth of 1%.

This may suggest that (2867) Steins belongs to the "Angelina-like" subgroup of E-type asteroids and that its main mineralogical constituents are enstatite, oldhamite, and small amounts of low-iron silicate mineral. To constrain the possible composition of the surface, we constructed a simple mixing model using a linear (areal) mix of three components obtained from the RELAB database. The endmembers we used were: Mayo Belwa enstatite achondrite (c1tb46), oldhamite (c1tb38), and for the minor component, orthopyroxene (c1pe30) or a flat neutral phase – the standard Spectralon (c1hl04). Based on the current determinations of the Steins albedo, we considered in the fitting process only the mixtures having an albedo (estimated as the reflectance value at 0.55 μm) in the 0.30−0.45 range. However, this may be a weak constraint since the available enstatite samples from RELAB have albedoes from 0.1 (Abee) to 0.75 (Bishopville). In general all compositional models are strongly limited by the choice of the endmembers.

In the first mixture type the best fit was obtained for a composition of 57% enstatite, 42% oldhamite, and 1% orthopyroxene (Fig. 2). In the case of a featureless, neutral component being used to simulate the meteorite matrix structure and reduce the spectral contrast, a composition of 58% enstatite, 40% oldhamite, and 2% Spectralon yielded the best fit. The χ^2 values were virtually the same: 0.0059. The inferred oldhamite abundance is much higher than that found in aubrites where oldhamite constitutes less than 1% (Burbine et al. 2002, 2001).

The inferred compositional model is a good indication for (2867) Steins belonging to the "Angelina-like" subgroup of the E-type asteroids. Their surface mineralogy may be similar with the known enstatite achondrite (aubrites), but with a higher oldhamite abundance. Indeed, the aubrite ALH-78113 has both absorbtion bands presented by Steins but also an overall neutral trend. Could space-weathering effects be responsible for the difference we see between Steins and this sample spectra?

Brunetto et al. (2006) developed a space-weathering model based on ion irradiation experiments of silicate-rich samples. The model was able to reproduce the slope evolution (i.e. spectral reddening) induced by increasing fluence and was found to be very stable for various silicates (olivine, jackson silicates, orthopyroxene, the H5 chondrite Epinal). The reddening and darkening of reflectance spectra in the 0.25−2.7 μm spectral range is strongly related to the number of displacements caused by colliding ions because of elastic collisions with the target nuclei. This process is efficent even at low fluences (10^{15}−10^{16} ions/cm^2), while the sputtering of iron from iron-bearing silicates due to ion irradiation and deposition of nanophase neutral Fe occurs at ion fluences higher than 10^{18} ions/cm^2. New experiments on the Eucrite meteorite Bereba (Vernazza et al. 2006) confirm the stability/validity of this space-weathering model. In the present case, a simple visual inspection shows that the aubrite ALH-78113 shows strong spectral similarities to the Steins spectrum, but its spectrum is not as red as its asteroidal counterpart. Since aubrites are silicate rich (≥80%), we consider that we can apply the Brunetto et al. (2006) model as a first-order estimate. We highlight that irradiation experiments on an aubrite would 1) test this hypothesis and 2) contribute to the preparation of the future fly-by. With this model, we obtained the best fit for a Cs parameter equal to 0.18 (Fig. 2). This value is similar to the one obtained by modeling (832) Karin's spectrum in Brunetto et al. (2006). This suggests that 1) Steins surface is as young as Karin's (i.e. few millions years) or that 2) aubrite-like material is less sensitive to solar wind irradiation than ordinary chondrite material. Finally, this approach is also limited by the low number of aubrites in meteorite collections. The linear mixture of materials found in aubrites (Fig. 2) shows that a different composition is able to match both the asteroid slope and overall spectrum without the need to add a space-weathering effect.

Our results place Steins in a subdivision of the E-type class with objects like Angelina, Eger, and Nereus, a group that is not sampled by the current collection of aubrite meteorites.

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