Meteoritics & Planetary Science 36, 1727–1729 (2001)
Available online at http://www.uark.edu/meteor

Observations of 433 Eros from 1.25 to 3.35 microns

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(Received 2001 July 26; accepted in revised form 2001 September 10)
(Part of a series on the NEAR–Shoemaker mission to 433 Eros)

Abstract–We have spectrophotometrically observed 433 Eros, the target of the *NEAR–Shoemaker* spacecraft, on 1995 December 4 from 1.25 to 3.35 μm. As expected, Eros shows no evidence of an absorption feature >5% in the 3 μm region, and is interpreted to have an anhydrous surface within observational uncertainties. Our observations in the JHK region agree with previous work by Chapman and Morrison (1976) and Murchie and Pieters (1996), but differ from the near-infrared spectrometer spectra reported by Clark *et al.* (2001). Our calculations indicate that thermal flux from Eros is not responsible for this mismatch.

BACKGROUND AND PREVIOUS WORK

The *near-Earth asteroid rendezvous* (*NEAR*)*–Shoemaker* spacecraft completed its mission in 2001 February, having spent a year orbiting the near-Earth asteroid 433 Eros. Initial results from the onboard x-ray/gamma-ray spectrometer (XGRS) suggest a chondritic, or chondrite-like composition, although certain elemental ratios are decidedly non-chondritic (Trombka *et al.*, 2001). As described elsewhere (Izenberg *et al.*, 2000; Warren *et al.*, 1997), the near-infrared spectrometer (NIS) on NEAR was designed to measure the infrared spectral properties of the surface from 0.8 to 2.5 μm, the region diagnostic for olivine and pyroxene.

Although rare, aqueous alteration products have been found in ordinary chondrites, notably phyllosilicates in the LL chondrite Semarkona (Hutchison *et al.*, 1987) and halites and fluid inclusions in the H-chondrite breccias Zag and Monahans (Zolensky *et al.*, 2000). In addition, recent observations of the S asteroid 6 Hebe by Rivkin *et al.* (2001) show a 3 μm feature, evidence of OH- and/or H_2O-bearing minerals. This asteroid has been proposed to be the H-chondrite parent body by Gaffey and Gilbert (1998), and the Rivkin *et al.* observations show that absorption features due to hydrated and/or hydroxylated minerals can be found on S asteroids. The density of meteorites has been shown to be critically influenced by the amount of hydrated minerals present (Consolmango, pers. comm.). Therefore, additional spectral coverage of Eros in the 3 μm region bears upon the correct interpretation of its composition and its density/porosity.

Although Eros has been observed in the 1.25–2.5 μm region before (*e.g.*, Chapman and Morrison, 1976; Murchie and Pieters, 1996), and in the 3–4 μm region by Eaton *et al.* (1983), this is the first dataset to link these two regions and allow a constraint on band depth to be determined. Through relations developed by Miyamoto and Zolensky (1994) and Sato *et al.* (1997), band depths in the 3 μm region can be used to determine the hydrogen to silicon ratio in meteorites. This ratio was not determined for Eros by instruments on NEAR, and constraints on the water content of Eros will augment the elemental ratios available from the XGRS and aid in the interpretation of Eros' mineralogy through the synthesis of all available data (*e.g.*, McCoy *et al.*, 2001).

OBSERVATIONS

We used the RC2 photometer on the Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii to obtain spectrophotometric data of Eros on 1995 December 4 in the J, H, and K filters (effective wavelengths 1.25, 1.65, and 2.20 μm, respectively), and at 2.95 and 3.35 μm. At this time the asteroid was 0.69 AU from the Earth and 1.33 AU from the Sun, at a phase angle of 45.9°. The solar-type stars 51 Pegasi and Hyades 64 were observed during the night at a variety of airmasses to obtain zero-point and extinction corrections in each filter. A total of 26 min was spent on the asteroid, with integration times of 40 s per integration per filter for the JHK points and 80 s per integration for the 2.95 and 3.35 μm filters. Three exposures per filter were taken for the JHK filters, and

Prelude preprint MS#4608

two for the longer wavelength filters, interspersed so that the 3 μm points were sandwiched between JHK points. Because Eros was very close to pole-on (sub-Earth latitude of −88.5°, sub-solar latitude of −86.5° according to the Horizons ephemeris), lightcurve effects should not be detectable. Details of the observing and reduction technique can be found in Rivkin *et al.* (1997, 2000).

THERMAL CORRECTIONS: INFRARED TELESCOPE FACILITY DATA AND NEAR DATA

Beyond 3 μm, thermal emission from near-Earth and main-belt asteroids increases rapidly. In order to determine the reflectance spectrum of an asteroid in that wavelength region, thermal flux must be removed. This effect is more important for low-albedo bodies rather than higher-albedo bodies like Eros. However, since Eros was closer to the Sun than most main-belt asteroids travel, thermal corrections were still deemed necessary. We used the standard thermal model (STM) as described by Lebofsky and Spencer (1989), with an albedo value of 0.22, and a radius value of 11.8 km (Clark *et al.*, 2001; Harris and Davies, 1999). Because of the NEAR encounter, the physical parameters necessary for the STM are well-known for Eros. The "beaming parameter" (β or η), representing the roughness of the surface was set to 1.07, as found by Harris and Davies (1999). We find that at 2.95 μm, thermal emission accounted for 7% of the total flux, and at 3.35 μm, 31%. We note that over the span of the NEAR encounter (2000 February–2001 February), Eros was never closer than 1.43 AU from the Sun, and thermal flux accounted for less than 0.1% of the total flux over the wavelengths covered by the NIS.

RESULTS

The 1.25–3.35 μm spectrophotometry and results from NEAR and Chapman and Morrison (1976) with 1σ uncertainties are presented in Fig. 1, scaled to equal 1.37 at 1.25 μm. As can be seen, our observations are in agreement with Chapman and Morrison in the area of overlap. The agreement with the spectrum of Murchie and Pieters (1996) is also quite good. Eaton *et al.* (1983) observed Eros in the 3–4 μm region, and our data again match well in the region of overlap. The spectrophotometric data agree with the NIS spectra up to roughly 2 μm, where the NIS data show a rapid increase in reflectance not seen in other data (Clark *et al.*, 2001). The reason for the discrepancy is unknown, but cannot be due to uncorrected thermal flux in the NEAR data.

Eros shows no evidence of an absorption feature at 3 μm within ~5%. This is generally what is expected for an S-class asteroid (Jones *et al.*, 1990). For comparison, carbonaceous chondrites have 3 μm absorption features of 30–40% or more (Jones, 1988; Hiroi *et al.*, 1996), and 1 Ceres and 2 Pallas have band depths near 20–30% (Lebofsky *et al.*, 1981; Jones *et al.*, 1990). The absorption band depth on the S asteroid 6 Hebe is ~5%, close to the observational uncertainties in these Eros data (though the Hebe observations have much smaller error

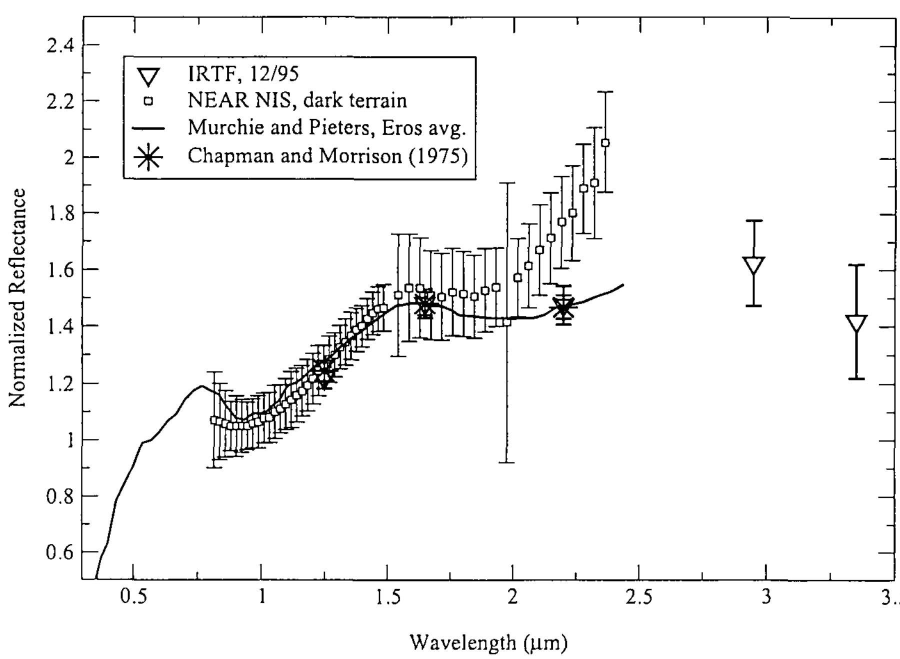

FIG. 1. Spectra of Eros: The thermally corrected IRTF spectrum of 433 Eros is shown with the average Eros spectrum of Murchie and Pieters (1996) and the spectrophotometric results of Chapman and Morrison (1976). Excellent agreement is seen in the area of overlap (1.25 μm < λ < 2.5 μm). All the ground-based data disagree with the NEAR spectrum from Clark *et al.* (2001) beyond 2 μm. This disagreement is not due to uncorrected thermal flux. Eros shows a flat continuum beyond 2.5 μm, with no absorption feature seen. The Murchie and Pieters spectrum is normalized to 1 at 0.55 μm. The other data are normalized to match the Murchie and Pieters data at 1.65 μm.

bars). While the exact relation between band depth and concentration of water or hydroxyl is a complicated function based on albedo, particle size, and other factors (to say nothing of possible maturation effects), an approximate upper limit can be placed on the water content of Eros' regolith. If we assume an upper limit of 5% on the possible band depth on Eros, that corresponds to an upper limit on the integrated intensity for the 3 μm features of 50 cm^{-1} using the work of Sato *et al.* (1997). This is similar to values for Karoonda in Sato *et al.* and for Vigarano in Miyamoto and Zolensky (1994). Miyamoto and Zolensky show that there is a close correlation between the hydrogen to silicon ratio and the integrated intensity of the 3 μm feature. The upper limit integrated intensity for Eros suggests an H:Si ratio of 0.5 or less. This range is occupied by meteorites not generally considered to contain hydrated minerals. If we assume an L or LL-like weight percentage of SiO_2 (~40%), this results in an upper limit of ~3% water on the surface of Eros. For comparison, CI chondrites have ~17% water (Rubin, 1996), CM chondrites have ~10% water, and OC meteorites have <1% water on average (Jarosewich, 1990). The continuum behavior beyond 2.2 μm is generally flat, similar to ordinary chondrites, but not diagnostic for that mineralogy. The lack of a 3 μm feature is consistent with both an anhydrous chondritic assemblage and an achondritic assemblage for Eros.

Acknowledgments–This work was partially done in the course of dissertation work by A. S. R., who would like to acknowledge his dissertation director Larry Lebofsky, and the telescope operators at the IRTF. A. S. R. acknowledges support from grant NAG5-8916. Reviews by Tom Burbine and John Davies greatly improved this manuscript.

Editorial handling: A. Cochran

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