Spectral properties and rotational spectral heterogeneity of 433 Eros

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Abstract. Composite spectra of different rotational aspects of the S asteroid 433 Eros were assembled from previous studies, covering the wavelength range 0.33-2.5 μm. These data allow us to measure significant attributes of Eros's spectrum, its mafic mineral absorptions, and the degree and nature of compositional heterogeneity of its surface. We also evaluated previous S-asteroid taxonomies using independent methods and from this test determined that the taxonomy of Gaffey et al. [1993] provides a sound basis for relating Eros to other S asteroids. On average, Eros resembles the S(IV) asteroids, which bear the closest resemblance to ordinary chondrites in mafic mineralogy. However, Eros also exhibits distinct rotational spectral variations comparable to the greatest yet recognized on an S asteroid. One side of the asteroid has a shorter-wavelength 1-μm absorption and a stronger 2-μm absorption than the global average, and is interpreted to be richer in pyroxene; the opposite face has a longer-wavelength 1-μm absorption and a weaker 2-μm absorption, and is interpreted to be richer in olivine. The pyroxene-rich side coincides with a facet-like face identified in radar studies, and the olivine-rich side coincides with a convex-shaped face. Each side of the asteroid exhibits spectral affinities with a different spectral class of S asteroids, demonstrating that such subdivisions of S asteroids represent different parts of a compositional continuum. High spatial resolution measurement of the mineralogic and elemental compositions and especially the geologic settings of these different materials by the Near-Earth Asteroid Rendezvous mission will provide a great advance in the understanding of the origin and evolution of a candidate ordinary chondrite parent body.

Introduction

The rendezvous of the Near Earth Asteroid Rendezvous (NEAR) spacecraft with asteroid 433 Eros will represent the first detailed investigation of an asteroid from a spacecraft [Cheng, 1995]. Previous flyby encounters of Galileo with main-belt asteroids 951 Gaspra [Belton et al., 1992] and 243 Ida [Belton et al., 1994] provided moderate resolution CCD imagery of surface morphology, some color imagery that revealed variations in the asteroids' surface properties, and limited compositional information from a near-infrared imaging spectrometer [Granahan et al., 1994, 1995]. NEAR's investigation of Eros will be a totally different class of encounter, providing the first spacecraft investigation of a near-earth asteroid, and the first global coverage of an asteroid akin to Viking coverage of Mars and Magellan coverage of Venus. The instrument complement of NEAR is designed simultaneously to provide very high resolution multicolor imaging of the asteroid surface, and to measure both mineralogical and elemental composition using near-infrared, X-ray, and γ-ray spectrometers [Veverka et al., 1995; Trombka et al., 1995].

Prior to undertaking this first global study of an asteroid, it is necessary to understand the nature of Eros and to place it into an accurate context among other asteroids. Perhaps no other small asteroid has been so thoroughly characterized by remote sensing studies, largely by virtue of its 1975 opposition when it was at an unusually close range to earth. These include measurement of three-, five-, and eight-color spectral properties in the extended visible wavelength range [Millis et al., 1976; Wisniewski, 1976; Miner and Young, 1976; Zellner et al., 1985], moderate spectral resolution (including "24-color") measurements over the same wavelength range at different rotational phases [Wisniewski, 1976; Pieters et al., 1976], high spectral resolution CCD spectra [Vilas and McFadden, 1992], low spectral resolution near-infrared (NIR) reflectance measurements [Veeder et al., 1976], high spectral resolution NIR spectra at different rotational phases [Wisniewski, 1976; Pieters et al., 1976], high spectral resolution CCD spectra [Vilas and McFadden, 1992], low spectral resolution near-infrared (NIR) reflectance measurements [Veeder et al., 1976], high spectral resolution NIR spectra at different rotational phases [Larson et al., 1976], polarimetric observations [Zellner and Gradie, 1976], mid- and thermal-infrared observations [Morrison, 1976; Lebofsky and Rieke, 1979], and radar observations [Campbell et al., 1976; Jurgens and Goldstein, 1976; Ostro et al., 1990].

These studies show that Eros is a member of the S spectral class [Zellner et al., 1985]. Its geometric albedo at 0.56 μm has been estimated as 0.18±0.03 [Jones and Morrison, 1976; Morrison, 1976], 0.17±0.01 [Zellner and Gradie, 1976], 0.19±0.01 [Zellner, 1976], and 0.125±0.025 [Lebofsky and Rieke, 1979]. Thermal and polarimetric properties are consistent with a medium-grained regolith with a component of either larger fragments or bare rock [Zellner and Gradie, 1976; Morrison, 1976; Lebofsky and Rieke, 1979]. The dimensions of Eros have been estimated as 36x15x13 km...
Differing studies have yielded different conclusions about the presence and nature of spectral heterogeneity on the surface. Some find no evidence for spectral variations [Millis et al., 1976; Miner and Young, 1976; Veeder et al., 1976; Larson et al., 1976], while others note a shift in the band minimum of the 1-μm mafic mineral absorption with rotational phase [Wisniewski, 1976; Pieters et al., 1976]. The latter studies suggest that one face of Eros exhibits a somewhat stronger absorption at a shorter wavelength whereas the other face exhibits a shallower longer-wavelength absorption, implying differences in mineralogy on a regional or hemispheric scale. Interestingly, these studies had not previously been integrated to produce a high spectral resolution reflectance spectrum covering both extended visible and NIR wavelengths. Such data are necessary to assess the position and character of the 1-μm and 2-μm mafic mineral absorptions which are indicative of the composition and relative abundance of mafic mineral phases.

In this study we first examine the classification of S asteroids into different spectral-compositional groupings, in order to identify a sound framework for relating Eros to other S asteroids. We then combine previously acquired spectral data covering the extended visible and NIR wavelength ranges to derive a composite spectrum of Eros from 0.33 to 2.5 μm, and to examine the question of spectral variations with rotational phase. We use these data to address the questions: What is the nature of Eros? Is it compositionally homogeneous or heterogeneous? If there are heterogeneities, how are they distributed across the surface? How is Eros related to other members of the S asteroid classes? Finally, we examine the implications of our results for investigation of Eros by the NEAR mission.

Background

The S Class of Asteroids

The S class of asteroids was first defined by Chapman et al. [1975] based on albedo, spectral, and polarimetric properties. The basic spectral attributes of the class are a moderate albedo, a relatively red continuum slope (reflecting more light at longer wavelengths), and broad absorptions near 1 μm and 2 μm (Figure 1). These attributes are characteristic of mixtures of olivine, pyroxene, and probably Ni-Fe metal. S asteroids dominate the inner main belt and constitute a significant fraction of near-Earth asteroids, and are thus a huge potential reservoir of meteorite materials.

The metal-olivine-pyroxene assemblage of S asteroids is also present in meteorite types with highly divergent histories, and substantial debate has arisen regarding the connection between S asteroids and various classes of meteorites. One school of thought focuses on the relative abundances of different meteorite and asteroid types. It holds that because this mineral assemblage is shared with the most common type of meteorites, primitive undifferentiated ordinary chondrites, the most common type of nearby asteroids (S) is the logical source [e.g., Wetherill and Chapman, 1988]. However, spectrally the S asteroids exhibit a redder continuum and weaker absorption bands than do the ordinary chondrites measured in terrestrial laboratories. The difference in spectral properties is attributed to optical alteration that reddens and decreases absorption band depth in asteroidal regoliths, or "space weathering" [Pieters et al., 1993]. The other school of thought focuses on the spectral properties of the asteroids, and mineralogic interpretations that do not require space weathering effects [Bell et al., 1989; Gaffey et al., 1989]. The meteorites most closely resembling the S asteroids are stony-iron meteorites, which have undergone varying degrees of igneous melting and separation of mineral phases. Ordinary chondrites then derive either or both from a minority of S asteroids or from the very uncommon Q asteroids, which are in orbits that are dynamically favorable for delivery of impact-ejected meteoritic fragments to Earth [e.g., McFadden et al., 1984; Bell and Keil, 1988; Bell et al., 1989; Gaffey et al., 1993; Hsio et al., 1993; Bell, 1995]. The implications of either model for the origin and evolution of S asteroids and their relation to meteorite classes are profound: in the first case, S asteroids are little evolved since their accretion and are well sampled by meteorites, but in the second case the S asteroids represent fragments of relatively evolved parent bodies that are poorly sampled by meteorites.

Key S Asteroid Spectral Properties

Objectively approaching the subject of S asteroid composition and compositional diversity requires sorting those aspects of spectroscopic data which are relatively clear in significance from those which are ambiguous. The key spectral attributes of S asteroids are illustrated in Figure 2. These include the strength and wavelength position of
Figure 2. Schematic diagram illustrating the calculation of the spectral parameters common to this study and that of Gaffey et al. [1993]. The spectrum is the composite disk-averaged spectrum of Eros.

The methodology used by Gaffey et al. [1993] to distinguish among S asteroids is summarized in Figure 3c. For each asteroid, the 52-color near-infrared data are integrated with 8-color or 24-color data covering the extended visible wavelength range to yield a composite visible-NIR spectrum. Then using the procedures illustrated in Figure 2,
Figure 3. Graphical representations of compositional variations in meteorites, S asteroids, and laboratory mixtures of mafic minerals (olivine, orthopyroxene, clinopyroxene). Symbols represent the 39 S asteroids belonging to the seven taxa of Gaffey et al. [1993], or the same asteroids as classified into the three taxa of Howell et al. [1994]. Average Eros is shown with a large solid square; the olivine-rich face is shown with a large solid circle; and the pyroxene-rich face is shown with a large solid triangle. (a) Band I center versus Band II center, after Adams [1974] and Cloutis and Gaffey [1991]. For pyroxene the band centers vary over a narrow admissible range related to composition. Addition of olivine leaves the Band II center unaffected but shifts Band I to longer wavelengths. The asteroids have band centers consistent with a pyroxene fraction dominated by orthopyroxene and varying proportions of olivine. Asteroid taxa are those of Gaffey et al. [1993]. Six of the seven taxa group nearly separately; subgroup S(IV) overlaps several other subgroups. Average Eros overlaps subgroups S(III), S(IV) and S(V). The olivine-rich face is transitional to S(II), and falls well outside the pyroxene field indicating a significant component of olivine. The pyroxene-rich face falls in the pyroxene field and groups most closely with S(V). (b) Same type of diagram as Figure 3a, showing the three asteroid taxa of Howell et al. [1994]. Half of the Sp asteroids plot within the orthopyroxene domain; S and So asteroids exhibit comparable scatter between this and the olivine-rich regions of the diagram. (c) Band I center versus Band I/Band II area ratio, after Galley et al. [1993]. The band area ratio is zero for olivine and becomes larger with progressively greater fractions of pyroxene. Band I center is near 0.9 µm for orthopyroxene and approaches 1.05 µm for pure olivine or clinopyroxene. The heavy shaded line is the result of mixing varying proportions of olivine and orthopyroxene; the arrow shows the effect of adding clinopyroxene to this mixture. Dashed regions outline the fields occupied by major meteorite types. The letters show the portions of the ordinary chondrite domain occupied by H, L, and LL ordinary chondrites. Asteroid taxa are those of Gaffey et al. [1993]. The asteroids plot close to the trend expected for compositional variations within a mixture of olivine and orthopyroxene. All Eros spectra fall within the domain of S(IV) asteroids, but the olivine-rich face is transitional to S(II) and the pyroxene-rich face is transitional to S(VI).
the spectra are parameterized. Gaffey et al. found that a diagram of Band I center plotted against Band II/Band I area ratio is particularly useful for discerning the spectral variations indicative of mafic mineralogy.

The same procedure can be carried out using analogous data for mineral mixtures or meteorite powders measured in the laboratory. In Figure 3c, the heavy gray line shows the variations of these parameters for mixtures of olivine and orthopyroxene. Pure olivine, with Band I near 1.05 µm and no Band II absorption, plots in the upper left of the diagram. Pure orthopyroxene, with a relative large Band II/Band I area ratio and a Band I center near 0.90 µm, plots on the lower right. Mixtures of the two minerals plot along a curvilinear trend. Incorporation of clinopyroxene into such a mixture offsets the plot of the spectrum above that trend, by virtue of the long wavelength of Band I. Laboratory spectra of powders trend. Incorporation of clinopyroxene into such a mixture offsets the plot of the spectrum above that trend, by virtue of the long wavelength of Band I. Laboratory spectra of powders of several meteorite classes plot close to the olivine-orthopyroxene trend; the olivine component of olivine-rich meteorites such as pallasites plots in the rectangular domain in the upper left; pyroxene-rich basaltic achondrites (e.g., eucrites) plot in the rectangular domain in the lower right, near orthopyroxene; and H, L, and LL ordinary chondrites, which have mixed olivine-pyroxene mafic mineral compositions, plot in the intervening polygonal domain.

Spectra of the S asteroids plot near the olivine-orthopyroxene mixing line in Figure 3c. Gaffey et al. [1993] divided the S asteroids into seven subgroups, the details of which they discuss at length. The most salient aspects of these grouping are summarized here, making reference to representative spectra from each subgroup in Figure 4. Subgroup S(I) is the most olivine rich, with an insignificant Band II and a composite Band I centered near 1.05 µm. S(II) asteroids exhibit a broad, rounded Band I due to contributions from both orthopyroxene and olivine. S(VI) and S(VII) asteroids have the greatest Band II/Band I area ratio and are the most pyroxene-rich. S(III), S(IV), and S(V) asteroids all exhibit spectra indicative of a mixed olivine-orthopyroxene composition. Subgroup S(IV) is defined as the portion of those asteroids with mixed olivine-pyroxene composition which overlap the field occupied on this diagram by ordinary chondrites. As such its separation from subgroups S(III) and S(V) is somewhat arbitrary. Two of the subgroups, S(II) and S(V), cluster furthest above the olivine-orthopyroxene mixing line in a manner consistent with occurrence of a significant clinopyroxene component. Gaffey et al. concluded that if there are in fact ordinary chondrite parent bodies among the S asteroids, they probably reside in the S(IV) subgroup whose spectra indicate an olivine-orthopyroxene ratio and low clinopyroxene abundance consistent with those meteorites.

Data and Procedures

Validation of Asteroid Taxonomy

As a first step in our study, we reexamined the Gaffey et al. [1993] and Howell et al. [1994] taxonomies of S asteroids, to ascertain whether one (or both) provides a suitable, reproducible framework for relating Eros to other S asteroids. We did this using the S asteroid spectral parameters compiled and published by Gaffey et al., by plotting the parameterized spectra on the pyroxene band center/band center diagram used by Adams [1974] and Cloutis and Gaffey [1991]. If either taxonomy is independently reproducible, then (1) its subgroups should remain moderately distinct, (2) the subgroups interpreted as progressively more olivine-rich should plot progressively further from the pyroxene domain, and (3) Gaffey et al.'s subgroups interpreted as more clinopyroxene-rich should have Band II centers consistent with a clinopyroxene-rich pyroxene fraction. The major caveat to this test is that, because of the weakness of Band II in many of the S-asteroid spectra, determination of its center will inherently be uncertain so that some "blurring" of the properties of different subgroups may be expected.

Analysis of Eros

Several excellent data sets exist which could provide the basis for assembling a composite visible-NIR spectrum of Eros. The most appropriate data to combine should (1) have high spectral resolution, (2) resolve different rotational aspects of Eros, and (3) be acquired at closely similar phase angles to minimize differences in continuum due to phase reddening [cf. Gradie and Veverka, 1986].

The most appropriate NIR data were acquired by Larson et al. [1976] on 25 January 1975 using a Fourier transform infrared radiometer (FTIR). Twenty spectra were acquired over slightly greater than one rotation of Eros, spaced nearly equally in time, at a phase angle of 10°. The highest quality data cover the wavelength range 1.0-2.5 µm, though noisier data extend to shorter wavelengths. All spectra are measured relative to an average of three solar-type stars.

Two candidate data sets cover the extended visible wavelength range. High spectral resolution CCD data from Vilas and McFadden [1992] were acquired at a phase angle of 32°, and 24-color data were acquired by Pieters et al. [1976] at a phase angle of 12°-14°. We use the latter data because of the close similarity in phase angle to the NIR data. They consist of seven groups of spectra acquired over short intervals at different portions of Eros's light curve during 28-30 January 1975, and cover the wavelength range 0.33-1.06 µm. The data were measured with a 2-beam, 24-filter photometer relative to
the star g Geminorum and were converted to reflectance relative to the Sun.

The Pieters et al. and Larson et al. data sets were merged by scaling the NIR data to the extended visible wavelength data, using the overlapping wavelength range 1.00-1.06 \( \mu \text{m} \). (Shorter-wavelength NIR data were not used because of their noisiness.) Wavelengths inside the strong 1.4- and 1.9-\( \mu \text{m} \) terrestrial atmospheric absorptions were ignored because of the much greater uncertainty in asteroid reflectance. For estimation of Band II properties, reflectances at wavelengths near 2 \( \mu \text{m} \) were estimated using a fourth-order polynomial fit to data at wavelengths longer than 1.6 \( \mu \text{m} \). All data were scaled to unity at 0.56 \( \mu \text{m} \). Geometric albedos at different wavelengths were estimated by multiplying the scaled reflectances at different wavelengths by a geometric albedo at 0.56 \( \mu \text{m} \) \( p_v \) of 0.17, which is an average of earlier estimates.

Two sets of composite spectra were produced: (1) a disk-averaged spectrum in which both the visible and NIR data were averaged before merging, and (2) spectra of different rotational aspects of Eros, in which data covering corresponding portions of the light curve were averaged before merging. Selection of the spectra to average was made based upon rotational variations in the extended visible wavelength range, as discussed below. Spectra of two nearly opposite faces of Eros were thus derived, covering 170\(^\circ\)-320\(^\circ\) rotational phase and 320\(^\circ\)-170\(^\circ\) rotational phase, where 0\(^\circ\) is the minimum in the light curve occurring just prior to the primary maximum.

The composite spectra were parameterized following the conventions of Gaffey et al. [1993]. A linear continuum was fitted across Band I between tangent points on the spectrum. In fitting a linear continuum for Band II, the long-wavelength end was assumed to be at the longest wavelength of useful data (2.44 \( \mu \text{m} \)), and the short-wavelength end was the tangent point on the opposite side of the absorption. (Figure 2 illustrates the actual continua fitted to the disk-averaged spectrum.) Each band area was calculated as the summed area between the reflectance spectrum and the continuum. Each band center was calculated as the wavelength of the maximum difference between the continuum and a fit to the data made using either a smooth curve or a polynomial of degree 4-8 that maximized correlation with the data. Uncertainties were estimated from the error bars in the composite spectra, the effects of using slightly different continua, and (where appropriate) the effects of using different fitting techniques to the spectra.

### Results

#### Asteroid Taxonomy

The band centers of the S asteroid spectra examined by Gaffey et al. [1993] are compared with those observed for pyroxene in Figure 3a. Three aspects of this diagram are particularly noteworthy. First, spectra for six of their seven subgroups (S(I), S(II), S(III), S(V), S(VI), and S(VII)) cluster separately or nearly so. Thus the distinctiveness of these subgroups is largely maintained, consistent with Gaffey et al. actually having identified different compositional groupings. However, the space occupied by subgroup S(IV) overlaps that occupied by subgroups S(III), S(V), S(VI) and S(VII). S(IV) asteroids appear to be more heterogeneous than other groups, consistent with the arbitrary definition of that subgroup as overlapping ordinary chondrites on the band center/band area ratio diagram.

Second, the subgroups interpreted by Gaffey et al. as most pyroxene-rich, S(VI) and S(VII), fall on the pyroxene trend in the orthopyroxene domain. Lower-numbered, putatively more olivine-rich subgroups plot progressively further from that domain. The most olivine-rich subgroups, S(I) and S(II), plot well above the pyroxene field. S(III) asteroids plot closer but still well above the pyroxene field. Subgroups S(IV) and S(V) are dominantly outside the pyroxene domain, but individual asteroids within those groups overlap the pyroxene field. These trends generally validate Gaffey et al.'s interpretation of variations in the olivine-orthopyroxene mixing ratio among S asteroids.

Third, the subgroups S(II) and S(V) were interpreted by Gaffey et al. to be richest in clinopyroxene. Although Figure 3a does not reveal these groups consistently to be clinopyroxene-enriched, individual members of the groups have the longest wavelength Band II centers, consistent with at least some clinopyroxene enrichment.

Locations on the band center/band center diagram of asteroids belonging to the S\(_0\), S, and S\(_p\) taxa of Howell et al. [1994] are shown in Figure 3b. About half of the "pyroxene-rich" (S\(_p\)) asteroids plot within the orthopyroxene domain, but several plot well outside. The "olivine-rich" (S\(_0\)) and intermediate (S) asteroids range approximately equally from within the orthopyroxene domain to the region of the diagram indicating olivine enrichment. Overall that taxonomy appears less indicative of mineralogy as determined using the methods of Adams [1974] and Cloutis and Gaffey [1991].

Taken together, this work shows that the S asteroid taxonomy of Gaffey et al. is generally reproducible using the methodology of Adams [1974] and Cloutis and Gaffey [1991], and that most details about mineralogic variations between subgroups are corroborated. In this paper we will use that taxonomy as a vehicle for classifying Eros and relating it to other bodies, for three reasons. First, the method is based on aspects of NIR spectra that have clear compositional significance. Second, different groups of S asteroids distinguished by this method have the potential for being related to different rock types. That is, based on these parameters, some bodies are clearly pyroxene-rich whereas others are clearly olivine-rich, but at present uniquely matching asteroids with rock (i.e., meteorite) types may be hampered by the inability to separate the spectral effects of space weathering and incorporation of Fe-Ni metal. Third, most of the S asteroid groups identified by Gaffey et al. appear to exhibit particular systematics between diameter, albedo, and/or spectral parameters such as band depth and continuum. These relationships provide clues to the nature of surface processes and their effects on the asteroid materials, and suggest a basis for testing the consistency of the spectrum of a given asteroid (e.g., Eros) with the overall properties of a particular spectral grouping.

#### Disk Averaged Spectrum of Eros

The disk-averaged composite spectrum of Eros is shown in Figure 5. Superficially, it strongly resembles "intermediate" S asteroid spectra such as 7 Iris in Figure 1. Disk-averaged Eros has a Band I center of 0.96+0.015, a Band II center of 2.0+0.1 \( \mu \text{m} \), a Band I depth of 0.19+0.01, and a Band II/Band I area ratio of 0.62+0.12, listed in Table 1.
the light curve. Near the primary maximum there is a strongly

reliable. The thin solid line is interpolated, except in the gap
terrestrial atmospheric absorptions where the data are less

Before proceeding further, it is instructive to place the disk-integrated spectrum into the taxonomy of Gaffey et al. Figure 3c shows how "average Eros" compares with other S asteroids on a Band I center versus Band II/Band I area ratio plot. Eros plots with subgroup S(IV) and has mafic mineral absorptions consistent with the olivine-pyroxene assemblage in ordinary chondrites. It does not overlap the regions of the plot occupied by the adjacent groups S(II), S(III), or S(V). Figure 3a shows a band center/band center plot. Here average Eros overlaps the fields occupied by classes S(III), S(IV), and S(V). The Band II center is longer in wavelength than for most other S asteroids, suggesting relatively more clinopyroxene; however, the large error bars on this parameter could also accommodate only an orthopyroxene component. Taken at face value, these results would indicate that Eros is a typical S(IV) asteroid.

Rotational Spectral Variations

The spectral measurements of different sides of Eros present a far richer picture of the asteroid's surface than does the disk-integrated spectrum alone. Pieters et al. [1976] noted in their 24-color data an apparent dependence of the character of Band I on rotational phase. This is illustrated in Figure 6a, where their seven spectra are ordered by rotational phase, starting with the spectrum corresponding to the primary maximum of the light curve. Near the primary maximum there is a strongly

Table 1. Spectral Parameters for Eros

<table>
<thead>
<tr>
<th>Spectral Parameter</th>
<th>Average</th>
<th>Px-Rich face</th>
<th>Ol-Rich face</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum slope</td>
<td>0.368±0.015</td>
<td>0.396±0.025</td>
<td>0.336±0.025</td>
</tr>
<tr>
<td>Band I center</td>
<td>0.969±0.015</td>
<td>0.948±0.015</td>
<td>1.007±0.015</td>
</tr>
<tr>
<td>Band I depth</td>
<td>0.19±0.01</td>
<td>0.18±0.01</td>
<td>0.19±0.02</td>
</tr>
<tr>
<td>Band II center</td>
<td>2.0±0.1</td>
<td>2.0±0.1</td>
<td>2.0±0.1</td>
</tr>
<tr>
<td>Band II/Band I area ratio</td>
<td>0.62±0.12</td>
<td>0.81±0.20</td>
<td>0.39±0.12</td>
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<tr>
<td>px / (px+ol)</td>
<td>--</td>
<td>0.39±0.10</td>
<td>0.22±0.07</td>
</tr>
</tbody>
</table>

Possible explanations for spectral differences between the two hemispheres include uncertainty in the data, particle size differences, differences in "space weathering" effects, and compositional differences. Random errors are likely not the source of the variations, as error bars of the spectra themselves, of Band I center, and of Band II/Band I area ratio do not overlap between hemispheres. Lateral variations in average surface particle size may and probably do occur, and could affect both continuum and depth of absorption bands. However they should not greatly affect the Band II/Band I area ratio, nor should they cause strong variations in Band I center.

Figure 5. Composite disk-averaged spectrum of Eros. Squares denote data from Pieters et al. [1976], and circles denote data from Larson et al. [1976]. Gaps represent strong terrestrial atmospheric absorptions where the data are less
terrestrial atmospheric absorptions where the data are less

Figures 5 and 6 show how the NIR spectra covering the corresponding rotational phases extends the wavelength coverage to near 2.5 μm. The rotationally resolved composite spectra are displayed at the same scales (labeled on the left and right axes), offset to overlay at 1.6 μm. Examination of Figure 7b clarifies the difference between the two hemispheres of Eros. The hemisphere centered at rotational phases of 170°-170° has a Band I center of 0.948±0.015 μm, a relatively strong Band II absorption (Band II/Band I area ratio of 0.8±0.2), and a weak 0.6-μm absorption. The hemisphere centered at rotational phases of 170°-170° has a Band I center of 1.007±0.015 μm, a Band II strength only half as great as for the opposing hemisphere (a Band II/Band I area ratio of 0.4±0.12), and little or no 0.6-μm absorption. Spectral parameters for each hemisphere are listed in Table 1. The spectral measurements of different sides of Eros present a far richer picture of the asteroid's surface than does the disk-integrated spectrum alone. Pieters et al. [1976] noted in their 24-color data an apparent dependence of the character of Band I on rotational phase. This is illustrated in Figure 6a, where their seven spectra are ordered by rotational phase, starting with the spectrum corresponding to the primary maximum of the light curve. Near the primary maximum there is a strongly

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Before proceeding further, it is instructive to place the disk-integrated spectrum into the taxonomy of Gaffey et al. Figure 3c shows how "average Eros" compares with other S asteroids on a Band I center versus Band II/Band I area ratio plot. Eros plots with subgroup S(IV) and has mafic mineral absorptions consistent with the olivine-pyroxene assemblage in ordinary chondrites. It does not overlap the regions of the plot occupied by the adjacent groups S(II), S(III), or S(V). Figure 3a shows a band center/band center plot. Here average Eros overlaps the fields occupied by classes S(III), S(IV), and S(V). The Band II center is longer in wavelength than for most other S asteroids, suggesting relatively more clinopyroxene; however, the large error bars on this parameter could also accommodate only an orthopyroxene component. Taken at face value, these results would indicate that Eros is a typical S(IV) asteroid.

Rotational Spectral Variations

The spectral measurements of different sides of Eros present a far richer picture of the asteroid's surface than does the disk-integrated spectrum alone. Pieters et al. [1976] noted in their 24-color data an apparent dependence of the character of Band I on rotational phase. This is illustrated in Figure 6a, where their seven spectra are ordered by rotational phase, starting with the spectrum corresponding to the primary maximum of the light curve. Near the primary maximum there is a strongly
The simplest interpretation is that one hemisphere of Eros is richer in olivine and the other is richer in pyroxene.

This interpretation is supported strongly by plotting the two hemispheres (abbreviated hereafter as "pyroxene-rich" and "olivine-rich") on the spectral parameter diagrams in Figure 3. On the diagram of Band I center versus Band II/Band I area ratio (Figure 3c), the pyroxene-rich face plots at the H-chondrite end of the ordinary chondrite field, and at the pyroxene-rich end of the S(IV) asteroid field transitional to the S(V) field. On the band center/band center plot (Figure 3a) the pyroxene-rich face resembles S(V) asteroids, and plots squarely within the pyroxene field. In fact, despite the large uncertainty in Band II center, the band positions in the pyroxene-rich face appear consistent with a component of clinopyroxene as Gaffey et al. [1993] inferred for the S(V) asteroids. The olivine-rich face also still falls within the S(IV) field (Figure 3c), though at the olivine-rich end, and is transitional to subgroup S(II). It occupies the LL-chondrite end of the ordinary chondrite field. On the band center/band...
center plot (Figure 3a) the olivine-rich face plots well out of the pyroxene field, and again appears transitional to subgroup S(II).

Estimated Mineral Abundance Variations

The Band II/Band I area ratio has been measured for a variety of olivine-orthopyroxene mixtures in the laboratory [Cloutis et al., 1986], and shows a high degree of correlation with the fraction of mafic minerals consisting of orthopyroxene (opx / ol+opx). Based on the band area ratios and uncertainties listed in Table 1, this technique yields estimated mafic mineral fractions of 39±10% pyroxene and 61±10% olivine on the pyroxene-rich side of Eros, and 22±7% pyroxene and 78±7% olivine on the olivine-rich side of Eros. We emphasize, however, that these values are only estimates because (among other reasons) the work of Cloutis et al. [1986] was based on orthopyroxene, and there is evidence from Eros's band centers for a non-negligible component of clinopyroxene.

Discussion

Eros Among the S Asteroids

The most basic question arising from the work above concerns the consistency of the measured properties of Eros with the general properties of S asteroids. One of the most pronounced trends in spectral properties of S asteroids is variation in Band I depth with asteroid diameter, as shown in Figure 8 [Gaffey et al., 1993]. At diameters above 100 km, Band I depth is relatively constant; at lesser diameters it increases with decreasing asteroid diameter. This may indicate progressively greater exposure of optically "fresh," "unweathered" regolith on smaller asteroids with lesser surface gravities to retain space-weathered regoliths. Eros is smaller than the bodies included in the Gaffey et al. study, but nevertheless exhibits a strong band expected for a small asteroid which retains little altered regolith.

Heterogeneities in mafic mineral absorptions have also been observed telescopically on other S asteroids, and it is instructive to compare these with the heterogeneity seen on Eros. The best documented telescopic evidence for rotational spectral heterogeneities in mafic mineral absorptions is for the large S asteroids 8 Flora and 15 Eunomia. Flora (diameter 141 km [Tedesco, 1989]) exhibits a range in Band I center from 0.99 to 1.01 μm, and a Band II/Band I area ratio of 0.45-0.60 [Gaffey, 1984]. As with Eros, the two parameters are inversely related, but the magnitude of variation is only half or less as great as on Eros. Eunomia (diameter 272 km [Tedesco, 1989]) exhibits variations in Band I center, and variations in Band II/Band I area ratio of 0.3-0.7 [Gaffey and Ostro, 1987], the latter of the same magnitude as on Eros. These comparisons show that Eros exhibits heterogeneity in mafic mineralogy comparable to the greatest that has been well determined on any S asteroid. This is not unexpected in light of its small size, where geologic features such as igneous intrusions inherited from a parent body could occupy a large relative portion of the surface.

Eros Compared to S Asteroid Subgroups

The disk-averaged spectral properties of Eros place it as a member of the S(IV) subgroup, having mafic mineral absorptions similar to those in ordinary chondrites. However, the spectral heterogeneity recognized on the asteroid's surface suggests that Eros's affinity with specific S asteroid classes is more complicated.

According to Gaffey et al. [1993], two of the distinguishing features of the S(IV) subgroup are the correlations of continuum slope with asteroid diameter and with Band I depth. The correlation between continuum slope and diameter is illustrated in Figure 9a. The disk-averaged spectrum of Eros as well as spectra of the olivine- and pyroxene-rich hemispheres have continua consistent with that expected for a small S(IV) asteroid. The correlation between Band I depth and continuum slope is shown in Figure 9b. Here, all three spectra of Eros exhibit much stronger Band I absorptions than are expected if this relationship extends to asteroids with the small size of Eros. The inferred mineralogic dissimilarity of the two faces of Eros, similarity of the olivine-rich and pyroxene-rich faces to different asteroid classes, and the dissimilarity of Band I strength with that of subgroup S(IV) all suggest that comparisons of Eros with those other asteroid classes would be instructive.

The pyroxene-rich face of Eros appears transitional to subgroup S(V) in the diagrams in Figure 3. Gaffey et al. [1993] noted that a characteristic of S(V) bodies is a weak correlation between Band I depth and continuum slope. This is illustrated in Figure 10. In fact, except for one outlier (18 Melpomene), the correlation is quite close. This relationship differs from the similar correlation exhibited among S(IV) asteroids in that the variation in Band I depth is larger, and at red continuum slopes (like that of Eros) Band I depth is greater. Figure 10 shows that the pyroxene-rich face of Eros exhibits close affinity in this aspect with S(V) asteroids, although the disk average and olivine-rich faces do not. An additional similarity to the S(V) asteroids is the apparently clinopyroxene-rich composition characteristic of this subgroup (see especially Figure 3a).

In the diagrams in Figure 3, the olivine-rich face of Eros appears transitional to subgroups S(II) and S(III). Gaffey et al. [1993] found that S(III) is the most spectrally heterogeneous subgroup, such that clear spectral systematics are not as
Figure 9. Comparison of parameterized spectral properties of S(IV) asteroids with those of Eros. S(IV) asteroids are shown as small solid circles. Average Eros is shown with a large solid square; the olivine-rich face is shown with a large solid circle; and the pyroxene-rich face is shown with a large solid triangle. (a) Continuum slope and asteroid diameter, after Gaffey et al. [1993]. Here Eros appears consistent with a small S(IV) body. (b) Depth of the 1-µm absorption and continuum slope. Here Eros exhibits a deeper 1-µm absorption than is typical of the S(IV) asteroids.

Figure 10. Comparison of Eros's properties with the spectral systematics of S(V) asteroids. The most characteristic relationship of that group (with the exception of one outlier) is the correlation between depth of the 1-µm absorption with continuum slope. This relationship is different from that exhibited by S(IV) asteroids. The pyroxene-rich face of Eros (large solid triangle) is consistent in this respect with S(V) bodies, but the disk-average (large solid square) and the olivine-rich face (large solid circle) are not.

evident in this subgroup as in others. However, subgroup S(II) is characterized by a broad, rounded Band I not observed in the other subgroups, due to significant contributions to this feature from both olivine and pyroxene. In Figure 4 the spectrum of Eros's olivine-rich face is compared with representative spectra of the seven subgroups. The broad, rounded nature of Band I and the similarity with S(II) spectra are evident. This characteristic of the olivine-rich face of Eros is a strong indicator of some affinity with subgroup S(II).

These comparisons demonstrate the significance of the rotational spectral heterogeneity of Eros, but they should not be construed to mean, exactly, that half of Eros is an S(II) asteroid and that the other half is an S(V). There is simply too much overlap in the spectral properties of subgroup S(IV) with adjacent subgroups to justify such a statement (see, for example, Figure 3a). But the comparisons do show that the very S(IV)-like average spectrum of Eros results from the mixing of the properties of two distinctly different materials having affinities with the materials composing S asteroids of other subgroups. To that extent, our work underlines the fact that the Gaffey et al. subgroups are not distinct and separate, but in reality form a compositional continuum. This in no way diminishes the great utility of that taxonomy, but it does place limits on the interpretability of the subgroups.

Correspondence With Other Studies of Eros

Several previous photometric studies have examined the question of rotational spectral variations of Eros and reached differing conclusions. These are actually consistent with the results presented in this paper, once consideration is made of the wavelengths and precision of the observations. The wavelengths of these observations are listed in Table 2.

Studies covering only visible wavelengths have found no evidence for significant color heterogeneity of Eros. Millis et al. [1976] conducted UBV photometry (0.3-0.5 µm) over the course of many asteroid rotations and found no evidence for color heterogeneity. The five-color UVBGR (0.3-0.7 µm) study of Miner and Young [1976] found that any rotational color variations in this wavelength range are of the order of only 1%. Veeder et al. [1976] examined the whole wavelength region from 0.65-2.2 µm, but with low spectral resolution and

Table 2. Wavelengths of Astronomical Filters of Eros Used in Previous Studies

<table>
<thead>
<tr>
<th>Filter Name</th>
<th>Abbreviation</th>
<th>Center, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultraviolet</td>
<td>U</td>
<td>0.343</td>
</tr>
<tr>
<td>Violet</td>
<td>V</td>
<td>0.400</td>
</tr>
<tr>
<td>Blue</td>
<td>B</td>
<td>0.495</td>
</tr>
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<tr>
<td>Red</td>
<td>R</td>
<td>0.670</td>
</tr>
<tr>
<td>Infrared</td>
<td>I</td>
<td>0.9</td>
</tr>
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relatively large uncertainties in measured reflectances. They did not find convincing evidence for spectral heterogeneity, but we might have drawn the same conclusions from our own data if they had comparable precision and limited wavelength coverage. These previous results are therefore not inconsistent with our own, which show that rotational color variations at visible wavelengths are within the error bars, with the possible exception of variations in the band at 0.6 μm.

Other studies covering extended visible and NIR wavelengths with high spectral resolution agree with our results, except for differences probably related to observational geometry and the extent of data analysis. Wisniewski [1976] measured two hemispheres of Eros in the 0.4- to 1.0-μm wavelength range, and found rotational spectral differences. One hemisphere (corresponding approximately in rotational phase with the pyroxene-rich hemisphere) exhibited a short-wavelength Band I and an absorption near 0.6 μm. The other (corresponding approximately in rotational phase with the olivine-rich hemisphere) exhibited a longer-wavelength Band I and lacked the 0.6-μm absorption. These results are consistent with those presented here, but Wisniewski's Band I minima are consistently shorter than those evident in our data. This could be due in large part to the greater phase angle of his coverage (17°), which would introduce phase reddening and move band minima to shorter wavelengths. Alternatively, it could be due to calibration difficulties. Vilas and McFadden [1992] produced a very high spectral resolution CCD spectrum of Eros covering part of the wavelength range of the Pieters et al. [1976] data used here (Figure 11). Their spectrum is even redder than Wisniewski's, probably due once again to a higher phase angle of the observations (32°), introducing phase reddening effects. Larson et al. [1976], in their original analysis of data used in this paper, found no obvious rotational spectral variations. This may be due to the lower precision of the single spectra they used than the averaged spectra binned by rotational phase that we used.

Perhaps the most interesting comparison to make with the results of other studies, though, is with Ostro et al.'s [1990] radar determination of Eros's shape. That work shows one of Eros's hemispheres to be relatively flat or facet-like, and the other to be convex in shape. The general shape of Eros is depicted schematically in Figure 12. The facet-like face is the one presented at rotational phases of 0°-180°, and the convex face is the one presented at rotational phases of 180°-360°. These ranges closely match the rotational phases of the pyroxene-rich and olivine-rich faces, 320°-170° and 170°-320°, respectively. Together our work and that of Ostro et al. indicate that one face of Eros is facet-like in shape and rich in pyroxene, and that the other face is convex in shape and rich in olivine.

Implications for NEAR

Two of the most important questions to be addressed by the NEAR mission are the composition of Eros and the arrangement and geologic setting of its compositional heterogeneities. These attributes of Eros will provide some of the strongest evidence for addressing the asteroid's parentage and evolution, the holy grail of which is resolution of the S asteroid-meteorite connection. The results in this paper bear on these questions, and highlight the necessity of a spacecraft mission to answer them.

Attempting to match asteroid and meteorite spectra has a long and checkered history. The composite spectra of Eros presented here are constrained by the same limitation as most other asteroid spectral data: although rotational spectral variations are clearly evident, any particular spectrum integrates over a whole face of Eros and whatever geologic units are present there. The clearest compositional information derives from the absorption bands, so the effects of this limitation on interpretation of absorption bands warrants detailed examination. The most complete collection of spectra of relevant meteorite types is that of Gaffey [1976], who determined Band I and Band II centers for a variety of mafic-rich types. Hiroi et al. [1993] presented spectra and band centers of meteorites not included in Gaffey's compilation. Among known meteorite types, the band centers for Eros's pyroxene-rich face could be fit by pyroxene-rich meteorites such as undifferentiated H or L ordinary chondrites or partly differentiated lodranite. A differentiated, basaltic achondrite such as a eucrite also fits the band centers, though the band strengths of eucrites are incomparably larger than on Eros. The olivine-rich face has band centers consistent with the undifferentiated LL ordinary chondrites or differentiated ureilites (though the albedo is incomparably higher than for ureilites). Gaffey et al. [1993] also suggested unknown but plausible differentiated meteorite types possibly matching this spectrum, including olivine-pyroxene cumulates and pyroxene-containing pallasite. In other words, averaged spectra of Eros's two faces could match either differentiated or undifferentiated meteorite types, so our spectral results alone do not suggest a unique parentage of Eros.

The NEAR mission will improve this situation most significantly by acquiring data with high spatial resolution sufficient to ascertain the geologic setting of the compositional variations, and hence to better constrain the nature of the geologic processes involved in their formation. NEAR is equipped with a multispectral imager and a near-infrared spectrometer that will measure mafic absorption bands [Veverka et al., 1995], as well as with X-ray and γ-ray spectrometers that will measure elemental composition.
Figure 12. Schematic illustrations depicting how the spectral heterogeneities identified in this study might result either from a differentiated or an undifferentiated Eros. The outline is the actual equatorial cross-section derived by Ostro et al. [1990] from radar returns.

[Trombka et al., 1995]. The combination of both mineralogic and elemental abundance information from these instruments will allow better discrimination of possible compositions of Eros's surface than does reflectance spectroscopy alone.

To help frame questions for NEAR, Figure 12 illustrates how the spectral heterogeneity seen on Eros could result from different degrees of igneous differentiation. In general, some amount of differentiation is likely, but its form and degree are unclear. One extreme case would be that Eros is an intact fragment of a highly differentiated (Vesta-like) parent body. This "differentiated" Eros might consist of metal-bearing, olivine-rich mantle material plus pyroxene-rich, basaltic crustal material occurring as dikes, sills, or even flows that formed on the parent body of which Eros is a fragment. In such a case, planar geologic contacts from the crustal region of the parent body might define Eros's facet-like face. Mixing of the surface regolith may be expected somewhat to blur the underlying geologic contacts.

The second extreme case is that Eros is "rubble," a loosely bound collection of compositionally heterogeneous materials. This could consist of several major fragments from different regions of a disrupted, previously differentiated parent body, whose subangular shapes cluster together to form the body's overall profile. Alternatively, Eros could consist of large clasts of undifferentiated ordinary chondrite deriving from different source bodies, which have become associated on Eros by collision. Spectrally, mafic mineralogy of the pyroxene-rich material is consistent with H or L type ordinary chondrite, and that of the olivine-rich material is consistent with LL chondrite. With the latter compositions, a "space weathered" regolith would be necessary to redden the spectral continuum and weaken the mafic absorption bands.

An intermediate case is that Eros is "slightly differentiated," as previously proposed for S(IV)-like asteroids [e.g., Bell et al., 1989; Gaffey et al., 1993]. In this case the olivine-rich material is a residuum of partial melting, and the pyroxene-rich material is the partial melt which in the parent body migrated to shallower depths. This case differs from the "highly differentiated" end-member model in the degree of development of an igneous system on the parent body.

Key observations by NEAR to test these models include Eros's shape and morphology, the sharpness of mineralogic heterogeneities, and the correspondence between elements of the asteroid's shape and its mineralogic variegations. These can be addressed using NEAR's multispectral imager and near-infrared spectrometer. The imager has spectral bands specifically chosen to distinguish mafic mineralogy, and will acquire imagery with a pixel size as small as 5 m. The near-infrared spectrometer has 64 spectral channels in the range 0.8-2.7 μm, and will resolve features smaller than 300 m in size. Occurrence of pyroxene-rich material as discrete dikes or
sills would evidence a highly differentiated parent body, whereas distinct "lumps" of olivine- and pyroxene-rich materials might support an origin as compositionally heterogeneous rubble. Gradational change in mineralogy across the surface would support the slightly differentiated model.

Conclusions

Taxonomy based on mafic mineral absorption features provides a powerful reference for comparing different S asteroids. We have used the Gaffey et al. [1993] taxonomy to characterize Eros and to relate it to other S asteroids. Composite visible-NIR spectra of different rotational aspects of Eros were derived from the results of previous studies, allowing us to measure important attributes of Eros's spectrum, its mafic mineral absorptions, and the nature of its compositional heterogeneity. On average, Eros resembles the S(IV) asteroids which bear the closest resemblance to ordinary chondrites in mafic mineralogy. However, rotational spectral variations reveal two distinctly different compositional regions on the asteroid. The magnitude of the spectral heterogeneity is comparable to the greatest yet seen on an S asteroid. One region, located on the facet-like side of Eros, is rich in pyroxene, and the other region on the convex side is rich in olivine. Each side of the asteroid exhibits affinities with different spectral classes of S asteroids, demonstrating that such subdivisions of S asteroids represent different parts of a compositional continuum. Improved measurement of the mineralogic and elemental compositions and especially the geologic contexts of these different materials by NEAR will provide an enormous advance in the understanding of the origin and evolution of a candidate ordinary chondrite parent body.

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