Bidirectional Reflectance Properties of Iron-Nickel Meteorites

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Spectral reflectance studies have suggested that elemental iron is a major component of the surface mineralogy of M- and S-type asteroids. Both asteroid types exhibit a red sloped continuum (increasing reflectance with increasing wavelength) that has been interpreted as characteristic of the presence of large amounts of elemental iron. The effects of viewing geometry and small-scale (<1 mm) surface roughness on the bidirectional reflectance spectra of iron-nickel meteorites have been investigated using NASA's RELAB facility. The spectra of metallic surfaces can be divided into three general groups on the basis of surface roughness. Group I consists of surfaces with surface features in the range of 10 μm to 1 mm. This group is characterized by spectra that are similar to diffuse reflectance spectra and show no dependence on viewing geometry. Group II covers the roughness range from 10 μm to 0.7 μm. The surface features in this group are in the same size range as the wavelengths of infrared light and the reflectance spectra are very complex. Group III consists of surfaces smoother than 0.7 μm and is characterized by a two-component reflectance that is strongly dependent on viewing geometry. Group III spectra taken in the specular geometry are very bright and strongly red sloped, while the spectra taken in the nonspecular geometry are dark and flat. The diffuse reflectance spectra of Group I surfaces can be modeled as linear combinations of Group III reflectance components. Published spectra of M-type asteroids exhibit good agreement with Group I spectra, suggesting that the regoliths of these objects act as a diffuse reflector with surface features larger than the wavelength of light.

INTRODUCTION

Using laboratory measurements of metallic meteorites as spectral analogs for asteroidal parent bodies, spectral reflectance studies suggest that elemental iron is a major component of the surface mineralogy of M- and S-type asteroids (Gaffey and McCord, 1978; Zellner, 1979). Both asteroid types exhibit a red sloped continuum (reflectance increasing with wavelength) characteristic of the iron meteorites and the presence of significant amounts of elemental iron. The actual abundance and nature of the metallic component on asteroidal surfaces is the subject of considerable controversy, particularly for the S-type asteroids (Feierberg et al., 1982; Gaffey, 1984, 1986). As asteroids increasingly become targets of remote-sensing observations, both from ground-based telescopes and spacecraft, it is important to understand the bidirectional reflectance properties of naturally occurring metallic surfaces. Knowledge of these reflectance properties is necessary for the interpretation of remotely-sensed spectra and for the understanding of surface processes on metal-rich bodies.

Iron-nickel meteorites are considered to be good spectral analogs for M-type asteroids (Gaffey and McCord, 1978) and account for 4.38% of observed meteorite falls (Graham et al., 1985). Geochemical and petrographic studies (Dodd, 1981) suggest that many iron-nickel meteorites are samples of the large metallic cores formed by differentiated planetesimals. The M-type asteroids, because of their red sloped but featureless spectra, could be composed largely of iron and nickel (Gaffey and McCord, 1978) and may be remnants of these differentiated cores. The main-belt M-type asteroid (16) Psyche has a radar albedo that strongly indicates a surface with an almost completely metallic composition (Ostro et al., 1985). Two M-type asteroids, 1986 DA and 1986 EB, have recently been identified in the Earth-crossing asteroid population (Gradie and Tedesco, 1987). Independent radar measurements of 1986 DA strongly suggest a metallic composition (Ostro et al., 1986).

Visible and near-infrared bidirectional reflectance spectroscopy is currently considered to be the best available technique for the remote characterization of the surface mineralogy and petrology of solar system objects. Interpretation of reflectance spectra is based on recognition of electronic and vibrational absorption features that are diagnostic of minerals on the surfaces of remote objects (e.g., Adams, 1975). The interpretation of asteroid spectra is greatly enhanced by the study of the spectral properties of meteorites (Gaffey and McCord, 1978; Gaffey, 1976). Meteorites provide reasonable constraints for the mineralogy of asteroids and the spectra of meteorites provide valuable laboratory analogs for remotely obtained spectra.

However, many laboratory spectra have been obtained under different geometric conditions than those for remotely obtained spectra. Remotely obtained spectral data are bidirectional in nature (Hapke, 1981) with the light source (the sun) oriented at a specific incidence angle (i) to the surface in question, and the observer (the telescope or spacecraft) located at a specific emission angle (e). The bidirectional reflectance spectrum of a surface material can vary significantly with changes in viewing geometry (e.g., Gradie et al., 1980). Many laboratory spectra of meteorite samples are directional-hemispherical (diffuse) spectra (Gaffey, 1976) obtained with an integrating sphere used to average the sample's reflected radiation over all geometries. By eliminating geometric effects and using all the reflected light, directional-hemispherical reflectance is often able to characterize more precisely the diagnostic absorption features of a sample. However, this method has the disadvantage that it does not mimic the bidirectional nature of remote observations.

Physical properties of a surface that can affect its spectrum are state of compaction, albedo, particle size, and surface roughness (Adams and Fränz, 1967; Hapke, 1981). For cut metallic surfaces (slabs) such as iron-nickel meteorites, the effects of compaction, porosity, and particle size are probably
not important parameters. However, changes in surface roughness are known to affect the brightness of metal surfaces (Gaffey, 1986). This study examines how viewing geometry and small-scale (<1 mm) surface roughness affect the bidirectional reflectance of iron-nickel meteorites and explores the implications of these effects on our understanding of the surface components of metal-rich (particularly M-type) asteroids.

THEORETICAL MODELS OF METALLIC REFLECTANCE

For the scope of this paper, classical electromagnetic theory based on Maxwell's equations and the Drude model is a good approximation of metallic reflectance properties and will be used in place of the more general but complex quantum theory of absorption and dispersion (Wooten, 1972). Briefly, the reflectance of metal in the classical Drude model (Bobren and Huffman, 1983) is a result of incident light inducing an electric field in a conducting material. This field penetrates the conductor, but rapidly decays with depth. The depth to which the electric field effectively penetrates, and that the photons of the incident light can sample, is called the skin depth. The skin depth can be considered to be the optically active portion of the metal. For example, a conducting metal such as copper has a skin depth of 0.016 μm for light with a wavelength of 0.19 μm (Wooten, 1972). Light that penetrates the metal interacts with the induced field and is subjected to wavelength dependent absorption or reflection. In this way the reflected light acquires information from the metal in the form of a characteristic reflectance spectrum. Metallic reflectance is determined by the relationship between the electric field, the resonance frequency of the free electrons in the metal (the plasma frequency), and the wavelength of incident light. Each metal has its characteristic plasma frequency that, in large measure, determines the reflectance of the metal. For light in the visible and near infrared regions, the Drude model predicts that iron will exhibit a steadily increasing reflectance with increasing wavelength. These results have been verified by the experimental determination of optical constants of iron.

Optical constants for metals are usually not derived from mathematical models, but are generally determined experimentally by measuring normal incidence bidirectional reflectance (1 = ε = 0) of very smooth, vapor-deposited samples (Blodgett and Spicer, 1967). Shown in Fig. 1 are the reflectance spectra for pure iron and several iron-nickel alloys calculated from published optical constants using the Fresnel equations of reflectance for dielectrics (Born and Wolf, 1965; Bolotin et al., 1969; Sosnovskaya and Noskov, 1974). As predicted by the Drude model, iron is characterized by a steadily increasing reflectance with increasing wavelength.

Similar red sloped spectra are seen in laboratory measurements of the spectra of iron-nickel meteorites. Shown in Figs. 2a,b are directional-hemispherical (diffuse) spectra from clean, cut faces of four iron-nickel meteorites (Gaffey, 1976). Gaffey found that iron-nickel meteorites exhibit red sloped but featureless spectra. With increasing nickel content the continuum may become less red sloped. Included in Figs. 2a,b is the calculated average spectrum of these four meteorites (shown as an X-ed line). This “average diffuse iron meteorite"
reflectance for source, sample, and observer. The “specular”
direction, shown in Fig. 3a, is defined as a reflection geometry
for which the angle of incidence equals the angle of reflection.
The normal incidence reflection used to experimentally obtain
optical constants is a specular geometry. The specular direction
can be considered as a narrow cone of light reflecting from
a surface in the direction e as illustrated in Fig. 3b. The first
one or two degrees in solid angle around the specular geometry
(1 = e) is included in the specular cone. The angular size
of the specular cone is dependent on surface roughness; narrow
for smoother surfaces, wider for rougher surfaces. The next
bidirectional reflectance zone is the “near-specular” direction.
The near-specular includes a cone of light approximately 10
degrees in solid angle around the specular cone. Finally, the
geometry describing the remainder of the reflected light is the
“nonspecular” direction. This is light for which the angle
of incidence is different from the angle of reflection by more
than 10 degrees.

In the following discussion, the specular, near-specular, and
nonspecular directions will be referred to as components of
reflection. In diffuse spectra all the components of reflection
are measured simultaneously and integrated into one value.
With bidirectional spectra, individual components of reflection
can be measured separately. A natural surface reflects some
incident light in all directions and therefore into all components, but it is the position of the observer with respect
to the incident light and the surface that determines which
component of reflection is observed.

Samples of the Gibeon and Canyon Diablo meteorites were
used in this study. Gibeon is a fine octahedrite, class IVA, with
7.68% nickel (Schaudy et al., 1972). Canyon Diablo is a coarse
octahedrite, class IA, with 6.98% nickel (Wasson, 1974). Several
cut surfaces on both meteorites were polished with aluminum
oxide and diamond abrasive grits to controlled surface
roughness. All samples were checked for corrosion and
polishing imperfections with a reflected light microscope. After
polishing, each sample was immediately washed in ethyl-alcohol
and dried to prevent corrosion. A series of bidirectional
reflectance spectra were taken at a variety of viewing geometries
using NASA's RELAB facility located at Brown University (Pieters,
1983).

RESULTS

Overview of Roughness Groups

For this study a wide range of surface textures were
examined. Analysis of the resulting measurements suggests that
the spectra of metallic surfaces can be divided into three general
groups on the basis of surface roughness. These groups are
listed in Table 1. Photomicrographs of representative surfaces
of each roughness group are shown in Figs. 4a,b,c. Figure 4a
is a photomicrograph of the Canyon Diablo meteorite polished
with 400 grit aluminum oxide. Surface features average about
40 μm in size. This sample belongs to Group I, which is
characterized by macroscopically rough surfaces with features
ranging from 10 μm to 1 mm. Because the surface roughness
is much greater than the wavelength of light in the visible

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and near infrared, these surfaces are shown to be effectively diffuse reflectors. Shown in Fig. 4b is another face of the Canyon Diablo sample polished with 1200 grit aluminum oxide to produce surface relief in the range of 1-5 μm. This is an example of Group II surfaces, which are characterized by microscopically rough surfaces with feature sizes ranging from approximately 0.7 μm to 10 μm, the same size range as the wavelength of infrared light. This group can be considered as a transition zone between rough (Group I) and smooth (Group III) surfaces and tend to be characterized optically by complex scattering behavior. Figure 4c is a Canyon Diablo face polished with 1-μm diamond paste. This level of polish produces features less than 0.4 μm in size that are too small to be resolved with a visible light microscope. Group III consists of surfaces that are smooth relative to the wavelength of infrared light. Feature sizes are generally less than 0.7 μm. The reflectance components of Group III surfaces are distinctly different. The specular component is shown to be very bright and red sloped, while the nonspecular component is dark and flat.

**Group I Surfaces**

Group I surfaces are the roughest of the three groups with features that range in size from 10 μm to 1 mm. Since these features are much larger than the wavelength of incident light, samples can be considered a collection of randomly oriented reflecting surfaces or facets. Shown in Fig. 5 are scaled spectra measured at a number of viewing geometries of the surface illustrated in Fig. 4a, a face of the Canyon Diablo meteorite polished to 40-μm roughness. This group consists of macroscopically rough surfaces that are, as shown in Fig. 5, characterized by the classic red sloped continuum of iron, but exhibit little or no geometric dependence on reflectance (albedo range 0.20 to 0.29 at a wavelength of 0.6 μm). All spectra, including both specular and nonspecular geometries, show basically the same spectral shape. The spectrum of the average iron meteorite is included in Fig. 5 for comparison. In this roughness range bidirectional spectra agree well with the diffuse spectral reflectance measurements of iron-nickel meteorites.

Similar results are obtained for a number of different surfaces and samples in this roughness range. Shown in Fig. 6 are spectra of fresh filings from the Canyon Diablo meteorite with a wide particle size range of 10 μm to 1 mm. Once again, the spectrum of this metallic surface is characterized by a classic red slope, no geometric dependence on reflection, and close agreement with the average iron meteorite diffuse spectrum (albedo range 0.14 to 0.18 at 0.6 μm).

<table>
<thead>
<tr>
<th>Group</th>
<th>Roughness range</th>
<th>Reflectance characteristics</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>10 μm - 1 mm</td>
<td>diffuse</td>
</tr>
<tr>
<td>II</td>
<td>0.7 μm - 10 μm</td>
<td>complex scattering</td>
</tr>
<tr>
<td>III</td>
<td>&lt;0.7 μm</td>
<td>two-component</td>
</tr>
</tbody>
</table>

**Fig. 4a.** Photomicrograph of a sample of the Canyon Diablo meteorite polished with 400 grit aluminum oxide to produce surface roughness of 40 μm (Group I). Field of view is approximately 600 μm.

**Fig. 4b.** Photomicrograph of a sample of the Canyon Diablo meteorite polished with 1200 grit aluminum oxide to produce surface roughness of 1-5 μm (Group II). Field of view is approximately 600 μm.

**Fig. 4c.** Photomicrograph of a sample of the Canyon Diablo meteorite polished with 1-μm diamond paste to produce surface roughness of <0.4 μm (Group III). Field of view is approximately 600 μm.
Cratering is an important process on planetary bodies and these craters may represent possible surface processes on metal-rich asteroids. Projectile velocity for these experiments was approximately 5 km/sec, which is the average collisional velocity in the asteroid belt (Davis et al., 1979). One crater was created by an aluminum projectile, the other by a basalt projectile. Shown in Fig. 7b are scaled spectra of all Fig. 7a complex surfaces and the average iron meteorite. The different surfaces and samples show a similar red sloped spectrum, little geometric dependence on reflection, and good agreement with the diffuse iron meteorite spectrum (albedo range 0.04 to 0.32 at 0.6 µm).

These data suggest that in this roughness range (10 µm to 1 mm) bidirectional reflectance spectra of metallic surfaces is comparable to diffuse reflectance spectra. The surface textures of macroscopically rough surfaces make them effectively diffuse reflectors.

Fig. 5. Bidirectional reflectance spectra of the Canyon Diablo meteorite polished with 400 grit aluminum oxide (Group I surface). Surface roughness is approximately 40 µm. Viewing geometry is indicated as i/e representing “angle of incidence/angle of emission.” Also shown is the spectrum of the average iron meteorite (AIM).

An interesting aspect of spectra from the filings sample is the close agreement of all the spectra at different viewing geometries, much tighter than spectra for the 40-µm roughness sample (e.g., Fig. 5). Although both samples belong to the same roughness group and have similar spectral characteristics, the 40-µm sample has a much smaller range of surface roughness than the filings with a 10-µm to 1-mm particle size range. The tight distribution of spectra produced by the filings sample suggests that a wide distribution of particle sizes will tend to homogenize the spectra, perhaps by providing a more random distribution of facets to act as reflecting surfaces. The effect is to reduce further the geometric dependence of the sample’s reflectance.

Spectra of additional complex metallic surfaces in Group I are shown in Figs. 7a,b. These surfaces include craters on the Gibeon meteorite created by experimental hypervelocity impacts using the NASA-Ames vertical gun (Matsui and Schultz, 1984).
Fig. 8a. Bidirectional reflectance spectra of surfaces of the Canyon Diablo meteorite polished with diamond paste to roughness of <0.7 μm and <0.4 μm (Group III surfaces). All spectra were obtained at a specular geometry (i = e). Reflectance is measured relative to an aluminum mirror standard and is three to four orders of magnitude brighter than the nonspecular component measured relative to halon. Also shown is the spectrum of iron-nickel alloy calculated from optical constants measured at normal incidence.

Fig. 8b. Bidirectional reflectance spectra of the Canyon Diablo meteorite polished with diamond paste to roughness of <0.7 μm (Group III surface). All spectra were obtained at a nonspecular geometry (i ≠ e).

Group III Surfaces

Group III surfaces represent the roughness range of less than 0.7 μm, which is as smooth or smoother than the wavelength of visible light. Under high-power optical microscopes these surfaces appear completely featureless. Figure 4c illustrates a smooth Group III surface on a sample of the Canyon Diablo meteorite. Reflectance from these smooth surfaces is strongly dependent on viewing geometry and two components of bidirectional reflectance exhibit very different spectra. The specular component of reflectance exhibits a very bright and red sloped spectrum, while the nonspecular component shows a dark and flat spectrum. The specular component was measured relative to an aluminum mirror standard. The aluminum mirror was calibrated relative to a fresh, vapor-deposited gold mirror and corrected to absolute reflectance using published, experimentally-determined optical constants for gold (Johnson and Christy, 1972). Shown in Fig. 8a is the specular component of two Group III surfaces of the Canyon Diablo meteorite measured at a number of specular geometries. All spectra tend to be very bright and exhibit a red sloped continuum. For comparison, the reflectance of an iron-nickel alloy calculated from optical constants is also shown. The specular component of the Canyon Diablo Group III surface measured in RELAB agrees well with the theoretical reflectance of an iron-nickel alloy calculated from optical constants derived from normal incidence reflection.

The specular component of reflectance tends to be three to four orders of magnitude brighter than the nonspecular component at all measured wavelengths. The spectral character of the nonspecular component of reflectance is shown in Fig. 8b for the <0.7-μm Group III surface. These spectra were measured relative to a halon standard (halon approximates a diffuse Lambertian reflector) and show a dark, flat spectral shape that exhibits none of iron's characteristic red sloped continuum. These flat reflectance spectra are not predicted by mathematical models of iron reflectance based on classical or quantum mechanics. The source of this flat nonspecular spectrum is currently unknown. The near-specular reflectance component of the <0.7-μm sample exhibits a blue sloped spectrum at short wavelengths. This interesting phenomenon will be discussed further in the next section.

These data for Group III surfaces suggest that the bidirectional reflectance spectra of optically smooth metallic surfaces is strongly dependent on viewing geometry and is characterized by a two-component reflectance model with a bright, red sloped specular component and a dark, flat nonspecular component. Iron's characteristic red sloped continuum is only found in the specular component. In a latter section we will use these components to model the diffuse reflectance of metallic surfaces.

Group II Surfaces

Group II surfaces represent the roughness range between 0.7 and 10 μm and can be considered to be a transition zone between optically smooth and rough surfaces. Surface features are in the same general size range as the wavelength of the incident light. Figure 4b illustrates a face of the Canyon Diablo meteorite polished with 1200 grit aluminum oxide to produce surface features in the 1- to 5-μm range. Bidirectional spectra of this surface are shown in Fig. 9. Group II spectra exhibit similarities and differences with both Group I and Group III spectra. The first and perhaps most striking similarity is that, like Group III, Group II reflectance is strongly dependent on viewing geometry. Group II spectra measured in specular and near-specular geometries (top four spectra) exhibit a more strongly red sloped continuum than those for nonspecular geometries (bottom four spectra). Also, like Group III spectra, these two components of Group II reflectance exhibit different spectral shapes. The specular component is relatively bright and red sloped while the nonspecular component tends to
be darker and flatter than the specular. A significant difference between Group II and Group III is that the nonspecular component, while being darker and flatter than the specular component, still exhibits a red sloped continuum in most viewing geometries. The slope of this continuum, however, shows a strong dependence on viewing geometry. For Group II nonspecular geometries where $i = 0$, reflectance and slope of the continuum decrease steadily with increasing phase angle. Also, the intensity difference between the specular and nonspecular components is much reduced in Group II spectra from Group III. In Group III the intensity difference between the brightest and darkest spectra was approximately three to four orders of magnitude, while the difference in Group II spectra is about a factor of 10. An important distinction is the complexity of the Group II spectral character. The classic iron red sloped continuum that was ubiquitous in Group I reflectance and the Group III specular component is not readily evident from Group II spectra. The specular component shows a strong red slope only for a portion of the wavelength range; at longer wavelengths the spectra flatten and, in the case of the 45/45 geometry, exhibit a blue slope.

The complexity of spectra for the Group II surfaces is probably related to changes in scattering and reflectance behavior as the wavelength of incident light approaches the size of the surface features. The range of surface roughness for this sample is between 1 to 5 µm while the incident wavelength range is 0.5 to 1.8 µm. To the shorter wavelengths, some of the surface features are sufficiently large and smooth to be specular reflectors and the resulting spectrum exhibits a strong red slope, as the classical model would predict. At longer wavelengths, starting around one micrometer for these samples, the surface begins to appear rough to the incident light and the proportion of the surface that can behave as a specular reflector decreases. As the wavelength increases, a larger proportion of the incident energy is reflected into other nonspecular geometries. The decreasing flux in the specular direction with increasing wavelength causes first a decrease in the red slope of the spectra, and finally, as more energy is lost from the specular geometry, a spectrum with a blue slope.

A related effect that produces a blue sloped continuum is observed in the near-specular reflectance component of some Group II surfaces with smaller surface features. Shown in Fig. 10 are near-specular spectra for three samples: two Group III surfaces and one Group II surface. This Group II sample was first polished with 1200 grit aluminum oxide, then repolished with 0.3-µm aluminum oxide to reduce the roughness range, producing a 1- to 3-µm surface roughness. The most striking feature of this data is the strongly blue sloped spectrum that the Group II surface exhibits over the entire wavelength range. The smoothest surface, a Group III surface with a roughness of <0.4 µm, exhibits a flat spectrum over the wavelength range. The slightly rougher sample (the <0.7-µm Group III sample discussed earlier) exhibits a blue sloped spectrum to 0.7 µm before the spectrum flattens at longer wavelengths. These data suggest that as the incident wavelength increases, this surface becomes increasingly smooth relative to the wavelength of incident light, and that the portion of incident energy that is scattered into nonspecular geometries declines. Scattering continues to decrease with increasing wavelength, producing for nonspecular geometries a blue sloped spectrum that become flat when all surface features are smaller than the incident light.

These results suggest that Group II represents a transition zone between the effectively diffuse reflectance of Group I surfaces and the two-component reflectance of Group III surfaces. Reflectance is strongly dependent on viewing geometry and the size range of surface roughness. Surface features that are in the same size range as the wavelength of incident light produce complex patterns of reflectance that can change significantly as the wavelength changes. The proportions and intensity of specular and nonspecular

![Fig. 9. Bidirectional reflectance spectra of the Canyon Diablo meteorite polished with 1200 grit aluminum oxide (Group II surface).](image)

![Fig. 10. Bidirectional reflectance spectra of three surfaces of the Canyon Diablo meteorite. The top spectra was obtained from a sample polished with 1200 grit aluminum oxide and then repolished with 0.3 micrometer aluminum oxide (Group II surface). The bottom two spectra were obtained from samples polished with 6-µm and 1-µm diamond paste, respectively (Group III surfaces). All spectra were obtained at a near-specular geometry ($i = 0^\circ$, $e = 10^\circ$).](image)
components vary with wavelength and can cause unusual bidirectional reflectance results, such as a blue sloped metallic spectrum.

**MODELING THE BIDIRECTIONAL REFLECTANCE OF METALLIC SURFACES**

Spectral measurements of Group III surfaces suggest that the reflectance of optically smooth metallic surfaces can be described by two components with very different spectral characteristics: a bright, red sloped specular component and a dark, flat nonspecular component. Any surface with a roughness scale that is significantly larger than the wavelength of incident light, such as a diffuse Group I surface, can be thought of as a random distribution of facets. The facets on this rough surface are large relative to the wavelength of light and can produce a collection of reflective surfaces. At any given angle of incidence to the surface most facets would reflect light in a nonspecular geometry relative to the observer, but a small percentage of the facets would reflect in a specular orientation with respect to the observer. Using hemispherical geometry, it is possible to estimate the probability that a random surface facet is oriented in a specular or nonspecular geometry relative to the observer. A randomly oriented facet will produce a narrow specular cone of reflected light that is, for example, two degrees of solid angle in diameter. This specular cone will subtend an area of 0.06013 steradians, which would be 0.0957% of the area of the hemisphere. In the simplest case, the probability of the observer being in a specular orientation with respect to the facet is a direct function of the area of the hemisphere subtended by the specular cone. In this case the probability would be 0.0957%. Probability estimates for several different diameters of specular cones are detailed in Table 2.

<table>
<thead>
<tr>
<th>Diameter of specular cone (in degrees)</th>
<th>Probability of specular orientation</th>
<th>Probability of nonspecular orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0°</td>
<td>0.0038%</td>
<td>99.9962%</td>
</tr>
<tr>
<td>1.5°</td>
<td>0.0086%</td>
<td>99.9914%</td>
</tr>
<tr>
<td>2.0°</td>
<td>0.0957%</td>
<td>99.9043%</td>
</tr>
<tr>
<td>3.0°</td>
<td>0.215%</td>
<td>99.7850%</td>
</tr>
</tbody>
</table>

The diffuse reflectance of a complex Group I metallic surface can be described as a linear combination of nonspecular and specular components. Using measurements of the components of reflection from smooth surfaces and the probabilities of specular and nonspecular facet orientations estimated from hemispherical geometry, the reflectance of rough surfaces can be modeled. Spectra of the Group III <0.7-μm-roughness Canyon Diablo meteorite sample were used to calculate a spectrum consisting of a linear mix of 99.99% nonspecular component and 0.01% specular component. For these calculations the 0/20 spectrum shown in Fig. 8b was used for the nonspecular component and the 10/10 spectrum shown in Fig. 8a was used for the specular component. Shown in Fig. 11a is the calculated linear mix spectrum as well as the average iron meteorite spectrum. The linear mix of Group III components and the Group I average diffuse iron meteorite spectra show good agreement. Because the specular component is very bright and strongly red sloped, its contribution to the reflectance dominates the linear mix despite the small proportion of the surface that is in a specular geometry; the resulting spectrum exhibits a classic iron red slope. For comparison, Fig. 11b includes scaled reflectance spectra of the linear mix and several complex surfaces including the metal-on-metal crater and an average of the filings spectra. All spectra of Group I samples show good agreement with the linear mix of the Group III bidirectional laboratory spectra.

![Fig. 11a. Calculated reflectance spectrum produced by using a linear mix of Group III specular and nonspecular reflectance components (solid line) and the spectrum of the average iron meteorite (AIM).](image)

![Fig. 11b. Reflectance spectra scaled to unity at 0.56 μm for: Point a = spectrum of average iron meteorite (AIM); point b = calculated reflectance spectrum using a linear mix of Group III reflectance components; point c = bidirectional reflectance spectrum of the metal on metal crater; and point d = the average of bidirectional reflectance spectra of the Group I filings spectra.](image)
DISCUSSION AND CONCLUSIONS

The classical Drude model predicts that iron in the visible and near infrared wavelengths should exhibit an increasing reflectance with increasing wavelength. Bidirectional reflectance measurements of metallic surfaces show that only the specular component of reflectance (i.e., for optically smooth, Group III surfaces) exhibits iron’s characteristic red sloped continuum. This result suggests that only the specular component of reflectance interacts optically with the metal and has a chance to acquire spectral information. The nonspecular component of reflectance from optically smooth surfaces, which includes the bulk of viewing geometries, does not appear to interact with the optically active skin depth of the metal. As a result, nonspecular reflectance for optically smooth surfaces displays none of the characteristic and predicted reflectance properties of iron. The dark and flat spectrum of the nonspecular component shows no wavelength-dependence over the studied range.

Surfaces that are much rougher than the wavelength of incident light, such as Group I surfaces, can be considered to be a collection of randomly oriented facets. Each facet contributes to a given viewing geometry a specular or a nonspecular reflectance. Bidirectional reflectance from such a surface will be overwhelmingly nonspecular, but the resulting spectrum will be dominated by the small fraction of bright, red sloped, specularly reflected radiation. Spectra of these Group I diffuse surfaces exhibit iron’s characteristic red sloped continuum and can be modeled by linear combinations of facets that are oriented in specular and nonspecular geometries with respect to the observer.

Group II surfaces, with surface roughness in the same size range as the wavelength of incident light, can be considered transitional between optically smooth and rough surfaces. The reflectance characteristics of surfaces in this group vary as the wavelength of light changes and with different viewing geometries. These surfaces exhibit complex reflectance characteristics that can produce flat, red sloped, or even blue sloped metallic spectra.

These laboratory results can be used for the analysis of spectra of asteroidal surfaces that are thought to be metal-rich. Published spectra of M-type asteroids display red sloped, featureless spectra with no apparent strong geometric dependence (Gaffey and McIver, 1978). Such characteristics are in good agreement with Group I spectra, suggesting that if the surfaces of M-type asteroids are metal rich, surface particles act as a diffuse reflector, with complex surface features larger than the wavelength of light. This would imply that the surface is either rough metal or covered with a metallic regolith of fragments in the 10-μm to 1-mm size range. These results are supported by optical polarimetry measurements that suggest that the surfaces of M-type asteroids are covered with a regolith of 20-μm- to 50-μm-diameter metallic fragments (Dollfus et al., 1979).

The bidirectional reflectance characteristics of metal-rich asteroids will be determined by the morphology of metal on their surfaces. The morphology of surface particles will control the proportion of facets that are in specular and nonspecular geometries with respect to the observer. For example, a regolith of horizontally oriented flat particles will have much different spectral properties than a regolith of randomly oriented metallic fines. Furthermore, if there are large smooth areas on a metallic object’s surface, a sudden surge in reflectance could occur as these areas rotate into a specular geometry with respect to the observer, resulting in a brief percent increase in the reflectance of an asteroid. However, observation and confirmation of these reflectance surges is very unlikely. The probability of an observer being in the appropriate specular geometry to record a reflectance surge would be even lower than the probabilities listed in Table 2 since an asteroid would be into a spherical rather than hemispherical system. A review of published lightcurves of M-type asteroids shows little evidence of reflectance surges (Di Martino and Cacciatore, 1984; Harris and Young, 1979; Scardigli et al., 1978; Zappala et al., 1983; Zeigler and Florence, 1985).

The use of laboratory bidirectional spectra of iron-nickel meteorites as spectral analogs for M-type asteroids should be tempered by an appreciation of the effects of surface roughness. Polished or cut meteorite samples will be inappropriate due to the complex reflectance patterns produced by Group II and III surface features. Only rough or fragmental metallic meteorite samples with Group I roughnesses should be used as bidirectional spectral analogs for metallic asteroids.

Acknowledgments. This research would not have been possible without the help, ideas, and suggestions of Steven Pratt and William Patterson. We greatly appreciate their input as well as the funding support from NASA under grant NAGW-28. We would also like to thank M. J. Gaffey, P. Heilmen, S. L. Murcie, F. Vilas, and M. Zolensky for excellent reviews and many useful suggestions. The RELAB facility is supported under NASA grant NAGW-748.

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