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METEORITE AND ASTEROID REFLECTANCE SPECTROSCOPY:
Clues to Early Solar System Processes

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INTRODUCTION

Although Earth has a magnetic shield that protects it from energetic ions and a cushioning atmosphere that catches the tons of small particles (< 1 mm) that bombard it daily, solid material from extraterrestrial sources nevertheless reaches the surface of Earth many times a year (Dodd 1981). When the largest of these bodies impact the surface with great velocity, they release immense energy, usually form a crater, and often disrupt the terrestrial biosphere. Fortunately, such events occur relatively infrequently, although individual impacts are currently unpredictable beyond a statistical accounting (Shoemaker et al 1979, Grieve 1982). Cosmic material between the size of small dust particles and the larger crater-forming bodies is slowed by the terrestrial atmosphere upon entry. The outermost portion of these objects is melted and ablated during passage forming a fusion crust which protects the interior, and they land

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as solid objects on the surface. These are the meteorites, our free samples of other parts of the solar system.

A handful of well-documented meteorites are now known to have originated from the Moon and probably Mars. The vast majority of these extraterrestrial samples, however, have been shown to have originated on the smaller bodies of the solar system—i.e. asteroids. These meteorites all have ancient radiometric ages ~4.5 Aeons indicating that their principal formation age is that of the solar system as a whole. Study of the major, minor, and isotope element chemistry of meteorites provides a wealth of information related to their starting composition and subsequent processes involved in their chemical evolution. The petrographic texture documents the thermal and physical processes through which the samples have evolved. These clues form the basis of our understanding of the pre-planet forming stages of the solar system and the subsequent evolution of small bodies. While the meteorites provide invaluable compositional information, they do not provide a full inventory of small bodies in the solar system, nor do they provide information about their heritage and the regions of the asteroid belt, or the solar system in general, which they represent. Gaffey et al (1993a) describe the meteorites as solar system "float," aptly employing geologic terminology for scattered rock fragments not found in direct association with their source regions or outcrops.

When one takes an astronomical perspective, there are thousands of small bodies located predominantly between Mars and Jupiter which comprise the main asteroid belt. The instantaneous distribution of these small bodies is shown in Figure 1. Also easily seen in the plane view of the solar system are the inner planet-crossing asteroids and the Trojan asteroids at the leading (L4) and trailing (L5) lagrangian points of Jupiter's orbit. In addition, a growing number of small bodies have been recently discovered beyond the orbit of Jupiter and even Pluto (e.g. Steel et al 1992, Jewitt & Luu 1993). The other primary structural components of the asteroid belt are its resonances, regions where perturbations have resulted in zones of depletion of planetary materials. Commensurate resonances with Jupiter (e.g. 3:1 and 2:1) form some of the most prominent low-density zones in the main asteroid belt, called the Kirkwood gaps (e.g. Froeschle & Greenberg 1989). Secular resonances that form from the perturbations of all planets (e.g. ν_6, ν_{16}) are more complex but are also clearly evident in the structure of the main belt. The theory and simulations of the dynamics of secular resonances were reviewed by Scholl et al (1989) and later by Milani & Knežević (1992). Both types of resonances are notable features of the asteroid belt and are zones that are dynamically unstable for planetary materials.

In the past few decades the combined studies of meteorite composition

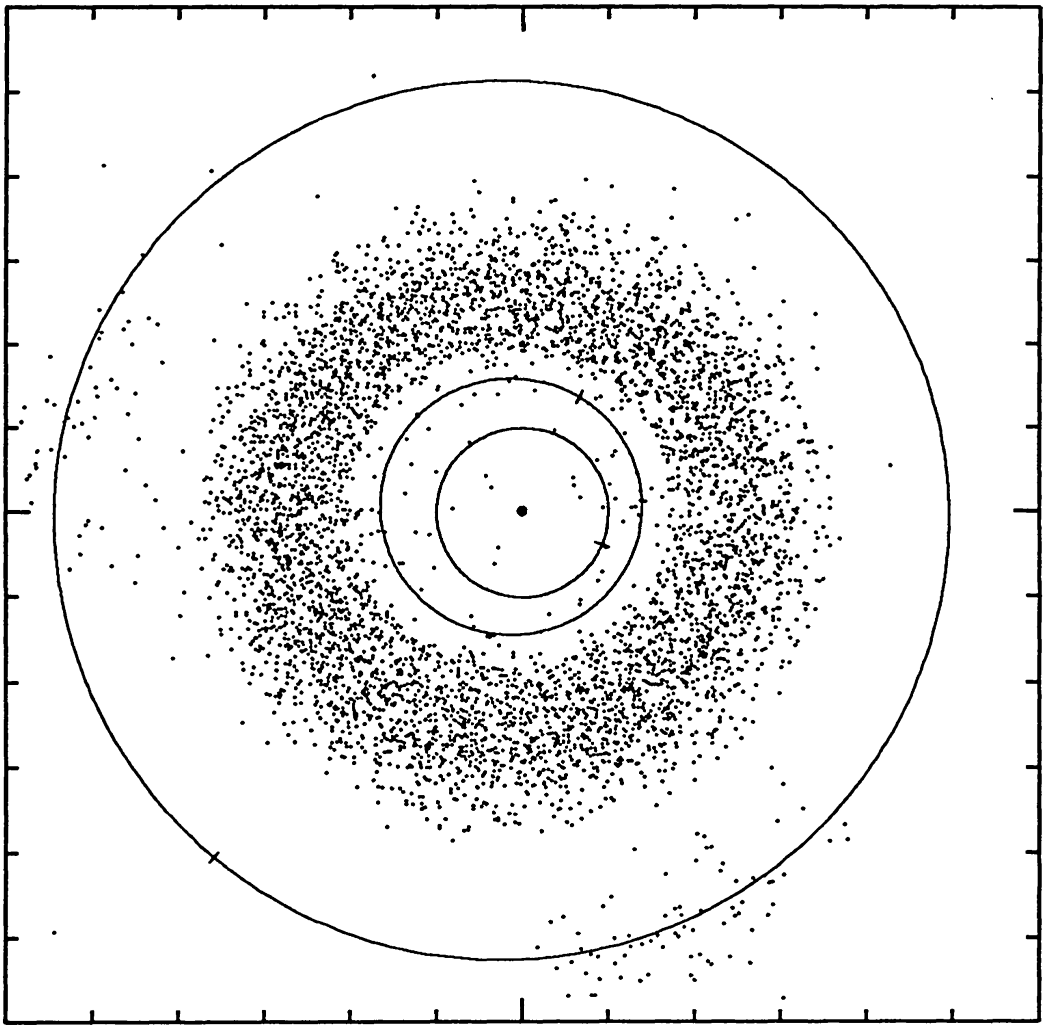

Figure 1 Plane view of the solar system on August 31, 1994, the scheduled date of asteroid 1620 Geographos flyby by the *Clementine* spacecraft. The Sun is the larger dot at one focus of the solar system. Concentric circles represent the orbits of Earth, Mars, and Jupiter from the focus outward. Each dot represents the location of one of 5531 numbered asteroids on the above date.

and petrology, the physical properties of asteroids, and the dynamical evolution of the asteroids, have documented several fundamental links between specific meteorite and asteroid classes. A more detailed understanding of the relation of meteorites to asteroids and derived information on the composition, structure, and evolution of the solar system focuses on two basic questions. First, which asteroids are the parent bodies of the different types of meteorites studied in terrestrial laboratories and what is the spatial distribution and abundance of such asteroids? A related fundamental question is: To what extent does the meteorite collection represent extraterrestrial material in the asteroid belt and the solar system? Second, what are the composition and basic physical properties of small bodies in the solar system which are not represented in the meteorite collection and how abundant are such bodies? As reviewed here, significant progress has been made addressing these issues, and the physical processes which produced the asteroid belt as it exists today are better understood. The same fundamental questions remain for many of the meteorite and asteroid classes, and it is the task of the next several decades to accurately survey and identify the composition and physical characteristics of materials formed at the very beginning of solar system evolution.

Spacecraft encounters with several selected asteroids will clearly play a central role in this endeavor, but because of the great diversity of asteroids and meteorites, remote sensing approaches from the Earth or Earth orbit must necessarily provide the baseline information. This review summarizes the current capabilities of, advances in, and issues surrounding reflectance spectroscopy and its use as a tool to evaluate the mineralogy of meteorites and asteroids.

Meteoriticists and asteroid scientists have developed independent (and largely unrelated) classification schemes for meteorites and asteroids. These classification schemes provide an overview of the diversity of both groups of materials. The primary classes of meteorites are summarized in Table 1. This classification is based principally on compositional distinctions between meteorites. Petrographic texture of the silicates is often used for subclasses, and both aqueous and metamorphic alteration is recognized (McSween 1979, Scott et al 1989). The abundance of specific meteorite types is normally evaluated through the statistics of observed meteorite falls (and recovery). Since stony meteorites weather more readily than iron meteorites in the terrestrial environment, the use of fall statistics eliminates the bias that weathering imparts on the statistics of meteorites that are simply found in a field long after their arrival.

The most commonly used classification scheme for asteroid taxonomy is summarized in Table 2. The basic unit of classification is a spectral class identified by a letter designation (D,P,C, . . .). Members of a class are often referred to as having a characteristic spectral type. Determination of a class designation is well defined in fields such as botanical taxonomy and requires that specific boundaries between classes can be defined and that variations between classes are discontinuous. The analogue to an asteroid class in botanical taxonomy, for example, is the species (Jeffrey 1982). The most frequently used class designation adopted for asteroids is defined by a statistical minimal tree algorithm using 8-color extended visible data and albedo information developed by Tholen (1984) and discussed in Tholen

Table 1 Summary of meteorite classes, their mineralogy, and fall statistics

Class*	Mineralogy[a]	Falls[b]	Antarctic[c]
Chondrites (containing chondrules)			
Carbonaceous—roughly solar composition; abundant Carbon			
CI	hydrous; sheet silicates, no chondrules, no Fe^0	5	0
CM	hydrous; sheet silicates, no Fe^0	18	14
CO	mafic minerals; small chondrules, minor Fe^0	5	4
CV	mafic minerals; Ca-Al-inclusions, minor Fe^0	7	5
Ordinary—olivine + low-Ca Pyroxene + feldspar + metal			
H	high in total Fe; $>50\%$ Fe^0	276	904
L	low in total Fe; $\sim 1/3$ Fe^0	319	490
LL	low in total Fe, most oxidized	66	83
Enstatite—Enstatite mineralogy + metal			
E	iron highly reduced, mostly Fe^0	13	9
Achondrites (melted; differentiated)			
Howardites	breccias of Eucrite-, Diogenite-like material	18	4
Eucrites	Low-Ca pyroxene + plagioclase	25	18
Diogenites	Mg-pyroxene	9	9
Urelites	C-rich; olivine + pyroxene + volatiles	4	11
Aubrites	Enstatite	9	2
SNC[d]	basaltic, olivine	4	3
Lunar[e]	anorthositic breccia	0	(9)
Primitive[f]	olivine + pyroxene + metal + troilite ± plagioclase	(4)	(14)
Stony-irons (metal + silicates)			
Mesosiderites	Fe-Ni + HED achondrites	6	3
Pallasites	network of Fe-Ni + olivine	3	0
Irons	Fe-Ni (kamacite and taenite) + triolite	42	21

* There are also several unclassified or unusual meteorites.

[a] After Sears & Dodd (1988).

[b] After Sears & Dodd (1988), Graham et al (1985).

[c] After Lipschutz et al (1989).

[d] Shergottites, Nakhlites, Chassignites; probable Mars parent body (McSween 1985).

[e] Lindstrom et al (1991).

[f] McCoy et al (1993). Acapulcoites and Lodranites: achondritic texture, chondritic composition. (Numbers in parentheses were tabulated later and are derived from larger statistics.)

& Barucci (1989). The minimal tree analysis of these data does a good job of defining class boundaries, and as such it fulfills the principal requirement of a class. Although other asteroid classification systems have been devised [see review in Tholen (1984) for historical perspective, and Tholen & Barucci (1989) for a review of recent systems], Tholen's classification has gained the widest acceptance because it encompasses the largest asteroid data set and has been resilient as new data become available. It should be noted that this asteroid taxonomy is based on purely statistical relationships within a few sets of asteroid data (albedo and 8-color measurements).

Table 2 Taxonomy of main belt asteroids with associated albedo and spectral features

Class	Measured #	IRAS albedo	8-color photometry description	Additional features often observed
P	46	<0.04	featureless spectrum increasing with increasing wavelength	
C	227	0.04–0.06	weak UV band, flat-reddish reflectance vis-NIR	0.7, 0.6 and 0.43 μm, some have 3-μm bands
B	21	0.04–0.08	weak UV band, decreasing reflectance toward NIR	NIR variation, some have 3-μm bands
F	50	0.04–0.08	weak UV band, decreasing reflectance toward NIR	possibly broad, weak NIR feature, some have 3-μm bands
D	59	0.04–0.07	strongly increasing with increasing wavelength	possibly a band at 2.2 μm
G	16	0.09	strong UV band <0.4 mm, flat vis-NIR	0.6, 0.67, 0.7, 3.0 μm bands
T	13	<0.10	weak, broad UV-vis absorption flat NIR	significant variation in NIR reflectance
M	42	0.12–0.22	flat-slightly reddish vis-NIR flat vis-NIR	significant NIR variation, high radar albedo broad band >1.6 μm
S	347	0.14–0.17	UV band <0.7 μm, 1.0 μm band, red slope vis-NIR	2.0 μm band, significant variations
A	7	0.12–0.39	strong UV and 1 μm band	composite olivine band, no 2.0 μm band
Q	1	0.16–0.21*	strong UV, 1.0 μm band no red slope	2.0 μm band no IR red slope
R	1	0.34	strong UV and 1.0 μm band red slope	strong 2.0 μm band IR red slope
V	1	0.38	strong UV and 1 μm band	strong 2.0 μm, weak 1.25 μm inflection
E	13	0.38	slightly increasing reflectance with increasing wavelength	weak features NIR; variability

From PDS data base of 844 asteroids contributed by Tholen, with no observational bias correction. [PDS Small Bodies Node, 8/93.]

* Upper range is from ground-based observation of 1862 Apollo, a near-Earth asteroid.

The relevance of the classification scheme to the scientific endeavor—in this case clues to early solar system processes—is dependent on the degree to which the taxa represent discrete compositional groups. Although composition affects the 8-color data, it is not a unique relation. As will be seen in subsequent sections, detailed spectroscopic measurements that are more sensitive to compositional properties identify asteroid compositions that do not necessarily correspond directly to the taxonomy.

Excellent and relatively up-to-date broad discussions of meteorite research can be found in *Meteorites and the Early Solar System* (Kerridge & Matthews 1988). Meteorite surveys include Wasson (1985), Dodd (1981), and Lipschutz (1993). Broad overviews of asteroid research can be found in *Asteroids* (Gehrels 1979) and *Asteroids II* (Binzel et al 1989). A thoughtful interpretation of asteroid spectra and the structure of the solar system can be found in Bell et al (1989). The most recent summary of asteroid spectral measurements and integration of compositional interpretations has been prepared by Gaffey et al (1993a).

FOUNDATIONS OF REMOTE MINERALOGICAL ANALYSIS

Although asteroids and meteorites have been studied for centuries, it is only during the past several decades that analytical tools have become available with increasing sophistication to link them compositionally. Broad-band color measurements, such as the classic UBV system used in astronomy, and the later 8-color survey, allowed the asteroids to be distinguished and classified in groups. The more extensive spectroscopic measurements that encompass the visible through near-infrared, on the other hand, provide the principal diagnostic information for compositional analyses.

Historic Overview of Early Work

In the late 1960s astronomers began to use sensitive photoelectric detectors that allowed high precision measurements of solar system bodies using a large number of filters across the extended visible (0.32–1.1 μm) spectrum . Tom McCord pioneered this field with spectroscopic observations of the Moon (McCord 1968), then turned the instrument to look at the asteroid Vesta with great success (McCord et al 1970). At the same time, crystal field theory was being perfected to explain the physical principles accounting for absorptions due to transition metal ions in mineral structures (Burns & Fyfe 1967, Burns 1970a), and reflectance measurements were being made of geologic materials in the laboratory demonstrating the existence of diagnostic absorption bands (Adams & Felice 1967; Adams 1974, 1975; Hunt & Salisbury 1970; Hunt et al 1971, 1973a,b). The success of these ventures led to several major pieces of research that laid the foundation for much subsequent meteorite and asteroid spectroscopic analyses.

In the early 1970s a photoelectric assessment of the spectral properties of asteroids was driven by scientific interest and available technology. C. R. Chapman led a major asteroid survey (Chapman 1972) that resulted in a series of papers describing the spectra of asteroids based on extended visible (0.3–1.1 μm) spectra (Chapman et al 1973 a,b; Chapman 1976;

Chapman & Gaffey 1979). Chapman & Salisbury (1973) made an initial comparison between available data on asteroid and meteorite properties and showed this to be a very productive area of investigation. In the early 1970s Johnson & Fanale (1973) performed a laboratory survey of the spectral reflectance properties of low-albedo meteorites. In the mid-1970s M. J. Gaffey undertook a detailed laboratory investigation of the spectral properties of carefully selected meteorites (Gaffey 1974). The resulting manuscript (Gaffey 1976) remains one of the most complete overviews of meteorite spectral properties from the visible to the near-infrared (0.35–2.5 μm). These two fields—asteroid and meteorite spectral studies—converged to allow more detailed interpretations of the mineral character of asteroids, and also resulted in the conclusion that mineral assemblages generally similar to most meteorite types can be found in the asteroid belt, with the exception of the abundant ordinary chondrites (Gaffey & McCord 1978, 1979).

There were two additional important milestones that laid the foundation for much subsequent research linking asteroids and meteorites. The first was a survey conducted by McFadden (1983) of near-Earth asteroids, a prime source for meteorites currently falling to Earth. These asteroids have orbits that cross or are near to that of Earth. They are thus good potential sources for Earth-destined meteorites, but are dynamically short lived and cannot remain in near-Earth orbit for longer than 10^7–10^8 years (Wetherill 1974). Near-Earth asteroids need to be replenished regularly. McFadden et al (1984, 1985) showed that almost all the types of asteroids observed in the main asteroid belt are seen in the near-Earth asteroid population, thus strengthening the link between the two populations. A notable exception was 1862 Apollo, a single member of the Q class of objects, which provided a close analogue to the most abundant type of meteorites, the ordinary chondrites. 1862 Apollo provided a possible source for ordinary chondrites, but its apparent uniqueness provided little information about the significance to the structure of the solar system of this abundant meteorite type, thus underlining what remains one of the largest mysteries in asteroid/meteorite science.

A second milestone in addressing the character and structure of the main belt of asteroids was reached when a significant amount of information on asteroid colors had been compiled. This cumulative asteroid data allowed Gradie & Tedesco (1982, using data subsequently published in Zellner et al 1985) to recognize that the main belt of asteroids was not well mixed. As shown in Figure 2, each asteroid class appears to exhibit a distinct distribution as a function of distance from the Sun. This suggests that in spite of the likely reworking of asteroidal surfaces by other asteroidal material, some semblance of order of these primitive materials has been maintained throughout the age of the solar system.

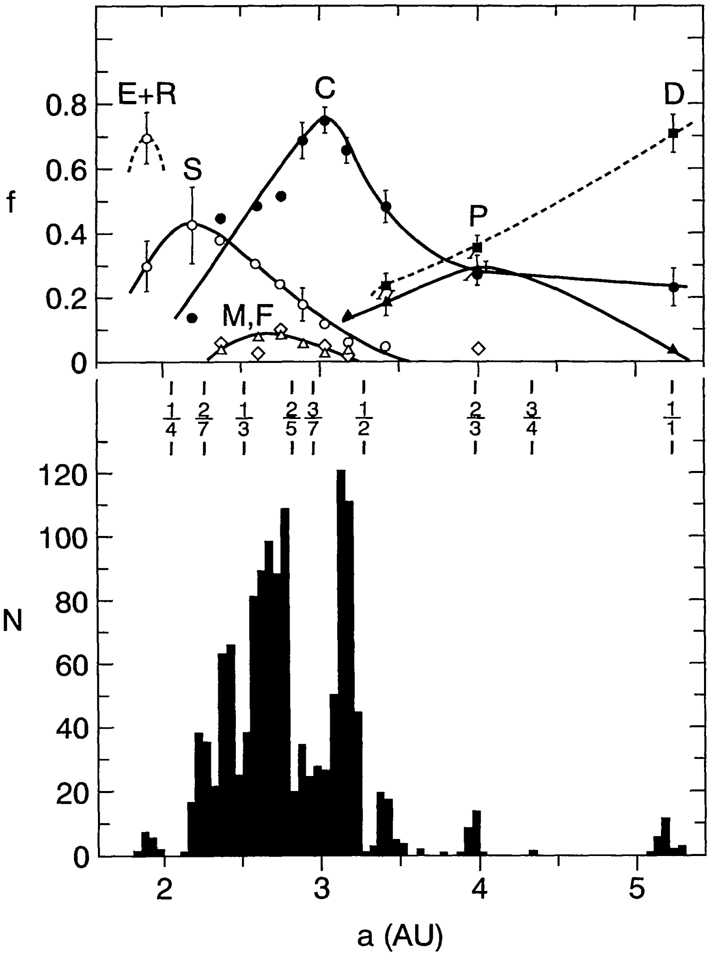

Figure 2 The distribution of major taxonomic classes with respect to heliocentric distance is shown in the top figure. Bias corrections for observation circumstances and family membership have been included. The peak occurrence of Ss in the inner belt, Cs in the mid-belt, and Ps and Ds in the outer belt have been interpreted as evidence of compositional variation across the asteroid belt. The bottom histogram shows the number distribution of 1373 asteroids and the Kirkwood gaps of the main belt. (After Gradie & Tedesco 1982).

Principles of Reflectance Spectroscopy and Mineral Interpretation

The compositional interpretation of reflectance spectra for meteorites and asteroids is based upon the principles of molecular and crystal field theories (e.g. Cotton 1971, Burns 1970a). The success of remotely sensing the composition of asteroid surfaces rests on the fact that there are well-characterized absorption bands in the visible and near-infrared regions of the electromagnetic spectrum. These absorptions are diagnostic of the presence of rock-forming minerals from which cosmochemically significant inferences can be made about the evolution of materials during and after solar system formation.

The interpretation of asteroid spectra has been made from the premise that the surface material of asteroids is composed of cosmochemically abundant minerals. Based primarily on meteorite studies, the origin of asteroid mineral assemblages were believed to be either derived from the solar nebula and survived intact, or were thermally and/or aqueously processed after formation during the first few hundred million years of solar system evolution. The most common components of asteroid surface materials that can be identified remotely include (listed in the approximate order of most to least degree of certainty based on diagnostic parameters): pyroxene, olivine, phyllosilicates, organic material, and opaques (which include metallic iron, graphite, troilite, and magnetite). Visible to near-infrared spectra of these components are shown in Figure 3. The combinations of these minerals on any particular asteroid surface reflect the formation and post-formation processing to which the asteroid has been subjected.

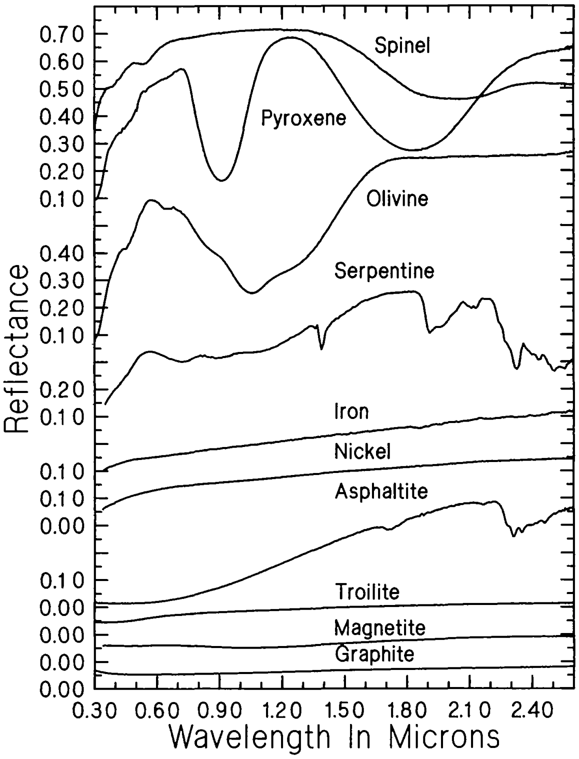

Figure 3 Representative bidirectional reflectance spectra of mineral components of asteroids and meteorites measured in the RELAB ($i = 30°$, $e = 0°$). All samples are particulate (< 500 μm). Each spectrum has been offset vertically for clarity. These data were obtained for E. Cloutis (spinel, iron, nickel, troilite, magnetite, graphite), L. Moroz (asphaltite, an organic compound), J. Mustard (serpentine, a phyllosilicate), and general RELAB collection (pyroxene, olivine).

Significant limiting factors affecting the mineralogical interpretation of meteorite and asteroid spectra include the signal to noise of the system (S/N), spectral range of the measurement, and spectral resolution. Since diagnostic mineral absorption features occur from the visible through the near-infrared (Figure 3) and mineral assemblages include several superimposed features that require deconvolution (see the next section), it is essential to acquire high spectral resolution data ($\Delta\lambda/\lambda = 1\%$) over the broadest spectral range (0.3–3.5 μm) available for reflectance measurements to maximize their interpretive value.

In the laboratory environment, the signal to noise ratio of a reflectance measurement is a combination of the S/N measured for the standard (typically 3000/1) and for the sample. For assemblages that are intrinsically bright, that is with reflectance of 10% or brighter at 0.56 μm, S/N in current laboratory measurements is nominally 1000 or better between 0.3–2.6 μm. For very dark material (reflectance $< 5\%$), which is abundant in the asteroid belt, reflectance S/N ratios of 100 can be achieved between 0.3–2.6 μm. Shown in Figure 4 are examples of laboratory reflectance measurements of particulate meteorite samples. Although the spectra are shown scaled to 0.56 μm to allow comparison with asteroid spectra, their albedos fall into two groups: (*a*) moderate to bright meteorites ($R_{0.56} = 21$ to 34%) which include basaltic achondrites and ordinary chondrites, and (*b*) dark meteorites, ($R_{0.56} = 5$–9%) including the various types of carbonaceous chondrites.

At the telescope, the observer usually has more noise to contend with than in the laboratory and the quality of the data are not as high. Available spectra of asteroids are limited by the sensitivity of detectors and the faintness of the signal from the asteroid combined with the addition of atmospheric and instrumental noise contributions. Overall, the quality of asteroid spectra is poorer than laboratory spectra and the reliability of the interpretations is less than for laboratory samples. It is always wise to obtain independent data to confirm any unusual or important spectral feature. In the past decade technological advances have resulted in the availability of instruments that provide better asteroid spectra over a wider spectral range, and in some cases have higher spectral resolution and better S/N than was available previously. Shown in Figure 5 are representative spectra for each of the major asteroid classes. These spectra were derived from composites of data acquired with different visible and near-infrared instruments (each data set should soon be available in the Planetary Data System, Spectroscopy subnode of the Geoscience node).

Major Technical Advances

Most asteroid and meteorite research has been confined to Earth-based telescopes and laboratories. There are several significant technical

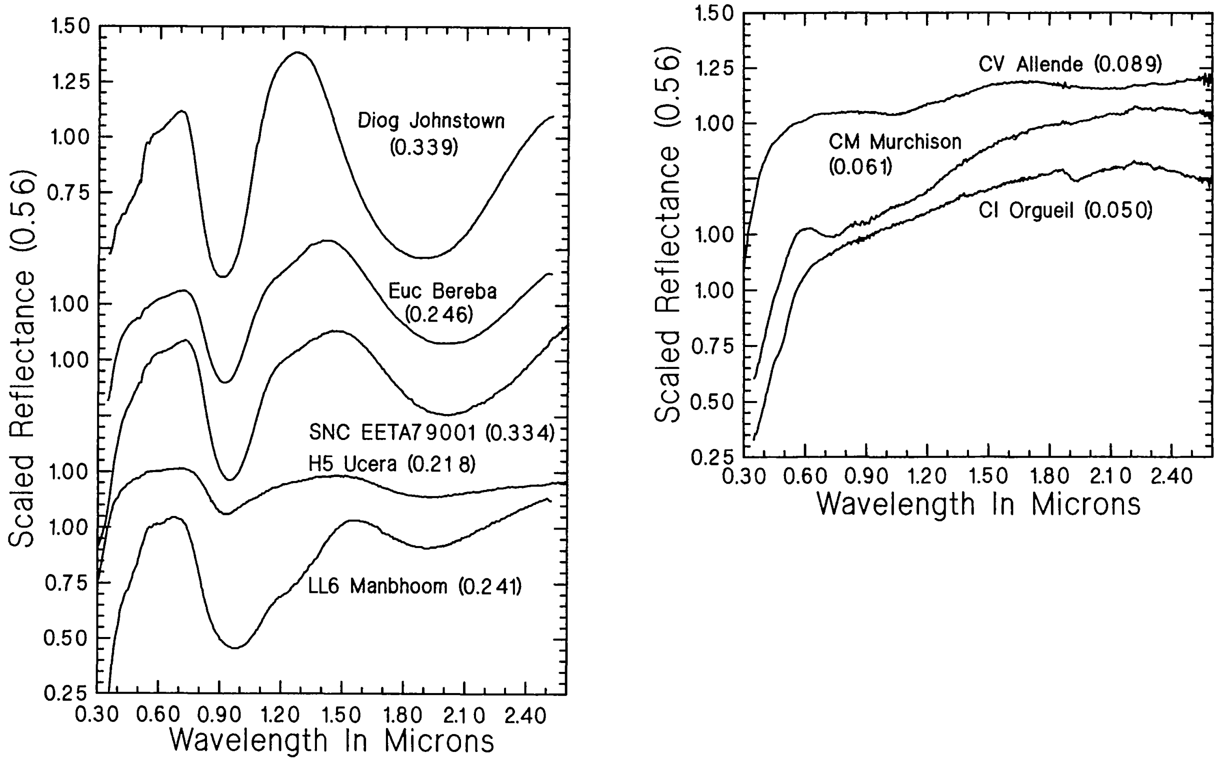

Figure 4 Representative reflectance spectra of meteorite classes. The spectra are scaled to unity at 0.56 μm and the number in parentheses is the laboratory reflectance at that wavelength. The spectra for Johnstown, Bereba, and Manbhoom are from the Gaffey collection of directional hemispheric spectra (Gaffey 1976). The remaining spectra were measured in the RELAB ($i = 30°$, $e = 0°$) for D. Britt (Ucera); L. McFadden (EETA79001), L. Moroz (Murchison, Orgueil), and T. Hiroi (Allende).

advances that have broadened the character of this research and continue to bring new discoveries and excitement to the field. These advances are summarized below and specific results are discussed in the following two sections.

SENSOR TECHNOLOGY Observations of asteroids have dramatically improved with the development of instruments with higher sensitivity, higher spectral resolution, and broader spectral range. The sensitivity allows smaller asteroids to be observed with sufficient precision for classification, thus both increasing the number of asteroids measured and expanding the data base to include small, faint asteroids. As discussed above, the higher spectral resolution and broader spectral range that includes the near-infrared is essential to progress beyond classification of asteroids based on color and albedo in order to allow mineral identification and abundance estimates of surface material based on diagnostic absorption features.

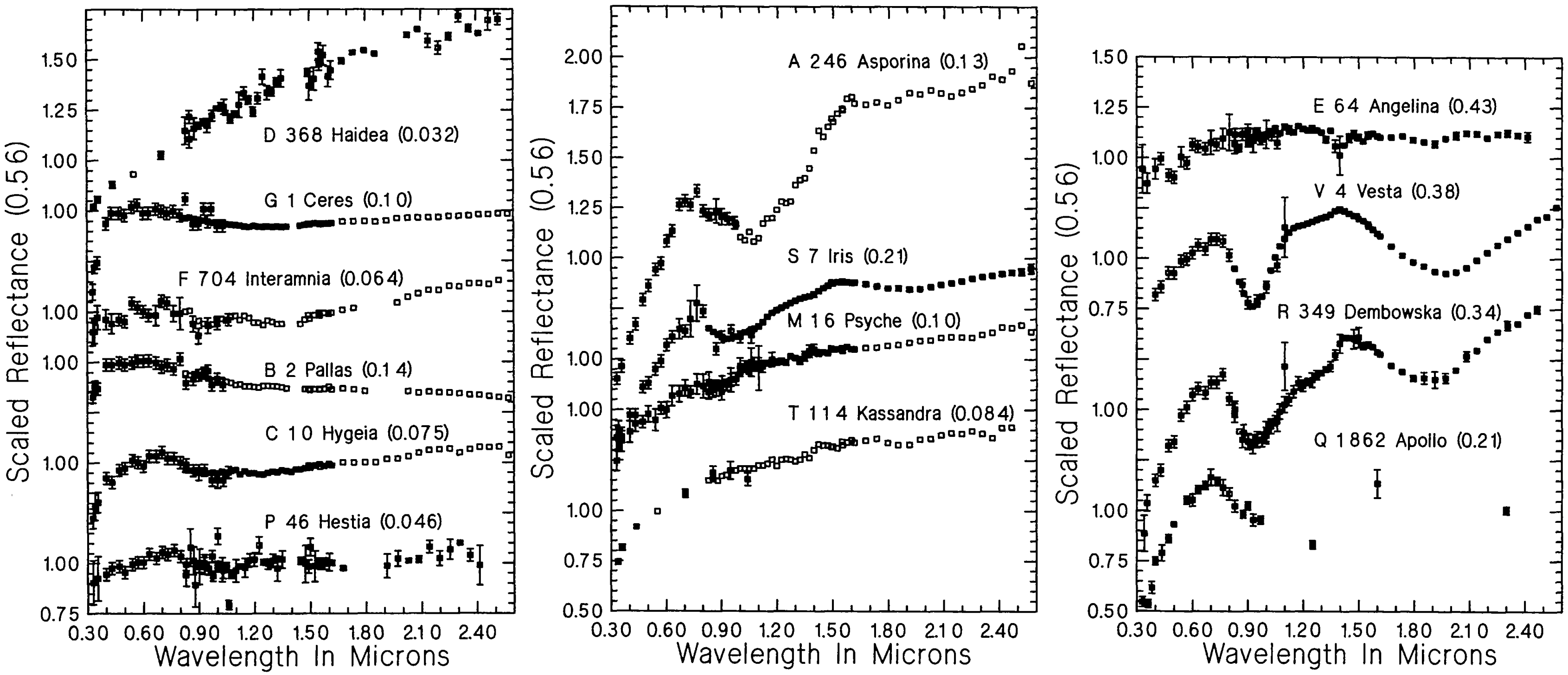

Figure 5 Representative reflectance spectra of asteroid taxonomic classes from 0.3 to 2.6 μm and scaled to unity at 0.56 μm. These composite spectra are derived from collections by Chapman & Gaffey (1979), Zellner et al (1985), and Bell et al (1988). Taxonomy is derived from Tholen (1989). Albedos (indicated in parentheses) are from *IRAS* measurements (Tedesco 1989), except for that of 1862 Apollo, which is from Lefofsky et al (1981b) ground-based radiometry.

ANTARCTIC METEORITES A multinational effort has recovered thousands of meteorites from the ice sheets of Antarctica, almost tripling the number of well-preserved meteorites available for study (see review by Dennison et al 1986). Since there has been very little opportunity for significant macroscopic degradation of the Antarctic meteorites, they are believed to be statistically representative of the falls in that part of the world over a several million year period. As can be seen in Table 1, the ordinary chondrites still dominate the population, but the proportion of specific groups is somewhat different, possibly suggesting an evolving population of meteorites that fall to Earth. When the first lunar meteorite, ALHA81005, was recognized in the Antarctic collection, it was a bit of a surprise. The geophysicists had long argued the lack of meteorites from the Moon to be evidence that the SNC meteorites (shergottites, nakhlites, and Chassigny) could not have originated on Mars since it would be harder to launch material from Mars than from the Moon. The existence of lunar meteorites in the Antarctic collection stimulated further review of ejection mechanisms during an impact event (e.g. Melosh 1984, 1985) and helped soften a principal argument against meteorites from Mars.

ANALYTICAL APPROACHES The interpretive base for evaluating the composition of asteroidal surfaces and linking them to meteorite assemblages has been improved through both empirical and quantitative approaches. A larger number and wider representation of high quality spectra of meteorites, their analogues, and possible primitive material measured in the laboratory has set bounds on the range of possible mineral assemblages present on asteroids. Perhaps equally important, the development and testing of models that accurately characterize mixtures of materials as well as models that quantitatively assess individual absorption bands has been re-evaluated and significantly expanded.

ADVANCES IN INTERPRETIVE CAPABILITIES

There are several approaches to compositional interpretations of asteroid reflectance spectra, all of which have merit, but some of which have progressed more extensively than others. Initially, the objective was simply to identify the type of minerals present or possibly present on an asteroid surface and to compare the results to the known mineral assemblages of meteorites. As mentioned above, this approach was successfully used to identify the type of pyroxene for Vesta (McCord et al 1970, McFadden et al 1977) and continues to be very productive if diagnostic absorption bands are observed in a remotely measured spectrum (e.g. identification of organics on Pholus by Cruikshank et al 1993, discussed in a later section).

Recognizing that laboratory samples of meteorites may not fully reproduce all the characteristics of unsampled asteroid surfaces, much recent effort has focused on limiting the range of possible interpretations through experimental, theoretical, and analytical approaches. The combined results of the improved interpretive capabilities discussed below coupled with better and more abundant asteroid observations discussed in the next section are summarized in Table 3.

Table 3a Weighted mineralogical interpretations of asteroid classes*

Class	Presence certain	Probable	Consistent/possible
P	—	anhydrous silicates	organics
C#	hydrated silicates, phyllosilicates	—	?
B	hydrated silicates	—	?
F	hydrated silicates	—	?
D	—	anhydrous silicates, organics	?
G	hydrated silicates, phyllosilicates	—	?
T	—	—	troilite, metal
M#	metal	—	enstatite
S#	low-Ca pyroxene + olivine	metal	(spinel)
A	olivine	—	metal
Q	low-Ca pyroxene + olivine	—	?
R	low-Ca pyroxene	olivine	?
V	low-Ca pyroxene	plagioclase	?
E	—	enstatite	metal

Table 3b Weighted meteorite analogue interpretations of asteroid classes*

Class	Certain	Probable	Consistent/possible
P	—	—	
C#	CM	CI	shock darkened OC, metamorphosed
B	—	—	metamorphosed CC
F	—	—	metamorphosed CC
D	—	—	—
G	—	—	metamorphosed CC
T	—	—	—
M#	Fe-Ni metal	enstatite	—
S#	—	primitive achondrites	pallasites, OC regolish, urelites
A	—	olivine achondrites, pallasites	—
Q	ordinary chondrites	—	—
R	—	—	—
V	HED	—	—
E	—	enstatite C, aubrites	—

HED = Howardites, Eucrites, Diogenites; OC = ordinary chondrites; CC = carbonaceous chondrites.
* For at least some members.
# Groups quite diverse; M class may not all contain metal.

Empirical methods have been used extensively and rely on spectroscopic surveys of materials measured in the laboratory and systematic manipulation of spectral parameters. Compositional inferences are made by comparing observed systematic relations within the laboratory data (e.g. chemistry vs spectral parameters) with measured properties of asteroids. This approach, of course, is limited to the range of materials analyzed in the laboratory and assumes singularity of diagnostic criteria. With the computer capabilities now available, several quantitative approaches have also evolved that model artificial mixtures of meteorite and analogue materials to reproduce observed characteristics of asteroids. In addition, quantitative deconvolution of individual absorption features is now possible and this analytical capability allows features in a remotely acquired spectrum to be characterized without actually having a sample of the same assemblage. A certain degree of humility, however, must be superimposed on all interpretive approaches since our knowledge of the space environment is limited and Nature may be able to alter a normally well-characterized material beyond recognition or our starting assumptions (such as laws that govern the evolution of the solar system) may be inaccurate.

Empirical Mineralogy

In addition to an understanding of the physical causes of diagnostic absorptions, all mineralogical interpretations of reflectance spectra are based in part on a library of laboratory spectroscopic data of relevant materials. After the initial survey of meteorite spectra by Johnson & Fanale (1973) and by Gaffey (1976), several researchers began to document the spectral properties of a number of meteorites and analogue materials that comprise meteorite assemblages. The most commonly used or referenced laboratory studies relevant to asteroids and meteorites are summarized below. A recent review by S. J. Gaffey et al (1993) provides a broader summary of laboratory analyses.

MAFIC SILICATES The landmark investigation of the reflectance properties of pyroxenes by Adams in 1974 demonstrated that not only do (anhydrous) pyroxenes exhibit two very diagnostic ferrous absorptions (near 1 and 2 μm; see Figure 3), but that the wavelength minimum of both of these absorptions varies systematically with composition (relative amounts of Mg, Fe, Ca). This study was later refined by Cloutis & Gaffey (1991) using a more diverse set of pyroxene compositions. A similar analysis of the reflectance properties of a suite of chemically well-characterized olivines of different compositions was undertaken by King & Ridley (1987), after initial work by Burns (1970b) using transmission data. King & Ridley showed that the minimum of the broad ferrous composite olivine band (see Figure 3) varies with Fe-Mg composition between 1.05 and 1.08 μm. A more detailed characterization of olivine compositional properties is discussed below in the section entitled Quantitative Diagnostic Absorptions.

A number of laboratory studies were also performed to investigate systematic variations of absorption features when known proportions of mafic minerals were mixed with other minerals (e.g. Nash & Conel 1974, Singer 1981, Crown & Pieters 1987). One of the studies most relevant to asteroid/meteorite spectral analysis was the measurement of mixtures of a low-Ca pyroxene (orthopyroxene) and an olivine (Singer 1981, Cloutis et al 1986). Olivine exhibits a composite band near 1.05 μm but no features near 2 μm, and orthopyroxenes exhibit two diagnostic absorptions near 0.9 and 1.80 μm (see Figure 3). Singer showed that for a material containing both these minerals, the relative strength (band area) of absorptions near 1 and 2 μm varied systematically, and this relation should allow the relative abundance of the two minerals to be predicted. Cloutis et al (1986) later derived a laboratory calibration of the relationship between band area ratios and relative proportion of olivine and orthopyroxene. Although particles <63 μm in size were not included in the Cloutis et al analysis, the relationship appears to hold consistently for a range of large particle sizes. This empirical calibration has been used, for example, to estimate the olivine/orthopyroxene ratio for S-class asteroids (Gaffey 1984; Gaffey et al 1989, 1993b). It should be noted that this relationship is only strictly applicable for the binary system involving olivine and orthopyroxene. Since clinopyroxenes exhibit a much broader range of compositions and site preferences, the Cloutis et al (1986) empirical relations cannot be used to predict olivine/clinopyroxene mixtures. In addition, the presence of opaques such as metal appears to add a nonlinearity to the band ratio method (see subsection on iron metal).

While much research has focused on the characteristics of olivines and pyroxenes which have been readily identified in asteroid and meteorite spectra, the diagnostic properties of less optically active minerals received less attention. Fortunately, detailed studies of several sheet silicates (King & Clark 1989, Clark et al 1990) were concluded about the same time telescopic instruments were available to detect more subtle features in asteroid spectra (see next section). Of particular importance to asteroid analyses were the measurements of King & Clark who documented the ~0.7 μm iron absorption in serpentines and chlorites (Figure 3) and showed this feature to be increasingly prominent in finer size fractions. As shown in Figure 4, this phyllosilicate feature is clearly observed in most CM meteorites (Johnson & Fanale 1973, Gaffey & McCord 1979, Moroz & Pieters 1991, Hiroi et al 1993c).

IRON METAL The original survey of meteorite spectral properties by Gaffey (1976) showed Fe-Ni metal to exhibit a featureless red-sloped spectrum (increasing reflectance with wavelength). These diffuse reflectance spectra were acquired using an integrating sphere. Subsequent analysis of the bidirectional properties of metal and surface roughness (Britt & Pieters 1988) showed that it is the strong specular component of reflectance that provides the red slope in iron reflectance. Nonspecular geometries of measurements from iron surfaces are characterized by less intense and relatively flat spectra. If a surface consists of randomly oriented metallic particles, the specular component still dominates the reflectance spectrum and a red continuum is evident. Particulate samples of Fe-Ni metal were prepared and measured by Cloutis et al (1990a) and the spectral properties of mixtures of 45–90 μm particulate iron with olivine and pyroxenes were documented (Cloutis et al 1990b). In these studies the continuum for Fe-metal bearing samples was consistently red sloped. The presence of particulate metal was also shown to affect band area ratios of metal/pyroxene mixtures, requiring independent criteria to be developed to distinguish between the presence of metal and the relative abundance of pyroxene in olivine/pyroxene mixtures.

One of the more perplexing laboratory results is that of Gaffey (1986) who measured the spectral properties of separates of the metal component in ordinary chondrites. Gaffey showed that, instead of the expected red-sloped continuum, the chondritic metal separates exhibit a flat featureless spectrum, and a laboratory spectrum of particulate ordinary chondritic material containing metal shows no red slope. Gaffey hypothesizes that the metal grains in ordinary chondrites are coated with an optically thick layer that masks the normal features of Fe-Ni. Since metal is a significant component in ordinary chondrites, a principal issue in identifying a potential parent body for these abundant meteorites is therefore whether such iron coatings exist and are maintained during regolith formation. As discussed below, the effect of Ni-Fe and reduced Fe in asteroidal regoliths is currently ambiguous, but regolith processes is an area of active research.

OPAQUES The early work of Nash & Conel (1974) and Pieters (1974) showed the nonlinear, disproportionately large effect opaques have on a reflectance spectrum of an intimate mixture. This is of particular interest to asteroid analyses since a large fraction of asteroids are exceptionally dark by any terrestrial standard (Tedesco et al 1989a. A series of detailed studies by R. N. Clark (Clark 1981a,b, 1983; Clark & Lucey 1984) evaluated the dramatic effect even a fraction of a percent opaques could have on suppressing spectral features of semitransparent silicates or ices. Much depends on the size of the opaque (smaller, micrometer sized, are very efficient absorbers) and whether it is dispersed (making a more effective absorber) or concentrated (making a less effective absorber) in the matrix material. The general effects of typical meteoritic opaques, carbon and magnetite, were documented in laboratory experiments with mafic minerals by Cloutis et al (1990b) and Miyamoto et al (1982).

Mixture Systematics

Conceptually, one should be able to mix together the diagnostic spectra for various minerals shown in Figure 3 to form the spectrum of an assemblage of minerals. A mixture of two or more materials should exhibit weighted properties of each, thus allowing not only the identification of individual components but also an estimation of their abundance. There are, however, both linear and nonlinear mixing approaches for combining spectra of materials to form a reflectance spectrum. Linear mixing occurs when the components are widely separated and each material contributes to the bulk spectrum in proportion to its areal extent (e.g. Singer & McCord 1979, Adams et al 1993). An analogous situation for an asteroid is when there are compositional and/or physical variations across the surface and different regions contribute different spectra to the integrated whole. The size of these regions could be anywhere from centimeters to several kilometers in scale.

Nonlinear mixing is more difficult to accurately model (Hapke 1981; Clark & Roush 1984, Mustard & Pieters 1987, 1989; Johnson et al 1992; Hiroi & Pieters 1992) and occurs when grains are intimately mixed so that radiation can interact with multiple components before being scattered from the surface. These models have been shown to accurately predict mineral abundances in a mixture to about 5%, provided photometrically accurate measurements of individual components (endmembers) are available. Although appropriate for many environments, nonlinear intimate mixture models are often difficult to use in asteroid studies because detailed photometric information for all required endmembers is not available. It has been shown (e.g. J. F. Mustard. in preparation) that using the simpler linear mixture approach for materials that are intimately mixed nevertheless produces very useful results that are accurate for *relative* comparisons of similar materials (but not accurate for absolute abundances). In other words, even if it is not known whether materials are spatially separate or intimately mixed, comparisons of relative abundances of similar materials derived with a linear mixing approach is valid, but the derived abundance values may not be accurate.

Linear mixing models have been frequently used when modeling asteroid spectra with mixtures of meteorite spectra. In a typical approach, a series of meteorite spectra is selected for mixing and some limiting goodness of fit criteria are defined. Different proportions of the meteorite spectra (endmembers) are combined together to form a composite spectrum which is then compared to the asteroid spectrum. Computer algorithms then iterate until a minimum error is produced between the asteroid spectrum and the composite meteorite spectrum. The results typically provide information about which meteorite assemblages might contribute to the observable properties of an asteroid and in what relative abundance. Examples of this approach can be found in Hiroi & Takeda (1991) and Hiroi et al (1993a,b). These studies have shown that some (but not all) olivine-rich asteroids (A class) can be modeled with spectra from the metal and the silicate portion of pallasites and that some (but not all) S-class asteroids can be modeled with various proportions of primitive achondrites and metal.

A number of applications using intimate mixture modeling have also recently been evaluated. B. E. Clark et al (1993) used a Hapke mixing model to try to reproduce near-infrared spectra for 36 S-class asteroids from the Bell et al (1988) survey with endmembers such as low-Ca orthopyroxene, clinopyroxene, olivine, plagioclase, iron metal, and a generic flat absorbing material. Preliminary results showed all but two of the asteroid spectra could be reasonably modeled with different proportions of the endmembers, but that mineral assemblage solutions were nonunique. These results underscore a primary limitation of any form of mixture modeling, namely that an independent criterion for uniqueness often remains unidentified.

A different intimate mixture model was used by Hiroi et al (1993d) to compare visible to near-infrared spectra of C, G, B, and F asteroids with spectra of a variety of carbonaceous chondrites and thermally metamorphosed samples of Murchison (CM). It has been recognized since the early work by Johnson & Fanale (1973) that the location of the ultraviolet absorption edge in spectra of these dark asteroids is at a much shorter wavelength than that observed for carbonaceous chondrites in the laboratory (compare the ultraviolet properties of the C, G, and F asteroids in Figure 5 with the CV, CM, and CI meteorites of Figure 4). Until spectra of three unusual thermally metamorphosed meteorites from the Antarctic collection were measured, no carbonaceous chondrites exhibited the same ultraviolet spectral characteristics as that observed in the asteroids (Hiroi et al 1993c). The results of the Hiroi et al mixture modeling indicate that the surfaces of these dark asteroids are best modeled with a mixture that contains a significant amount ($> 50\%$) of materials similar to the thermally metamorphosed carbonaceous chondrites. The same unusual spectral properties of these thermally metamorphosed meteorites is closely mimicked by portions of the Murchison CM meteorite that were thermally processed in the laboratory (Hiroi et al 1993c,d). This strengthens the case for thermal metamorphism on many of the dark asteroids.

Quantitative Diagnostic Absorptions

A complementary approach to characterizing components in an intimate mixture involves quantitatively modeling individual mineral absorptions as combinations of modified Gaussian functions (e.g. Sunshine et al 1990), including those that form composite absorption bands (e.g. the three bands of the broad composite band in olivine, Figure 3). This approach is very powerful in that it provides quantitative band information (band center, width, strength) that is directly associated with the physical process of absorption. The procedure, the modified Gaussian model (MGM), requires high spectral resolution and high-precision data, and simultaneously fits multiple absorption features (see Sunshine et al 1990 for algorithm details).

An example of an MGM application is demonstrated in Figure 6 (from Sunshine et al 1993) for the EETA79001 shergottite spectrum shown in Figure 4. EETA79001 exhibits two non-brecciated basaltic lithologies (McSween & Jarosewich 1983). The predominance of pyroxene is evident in the EETA79001 spectrum by the two diagnostic absorption bands near 0.95 and 2.05 μm. Petrographic analyses reveal the presence of significant proportions of both a high-Ca pyroxene and a low-Ca pyroxene in this sample (McSween & Jarosewich 1983). Without more detailed analysis of the spectrum, however, it would appear that the two pyroxene bands observed near 0.95 and 2.05 μm represent the presence of an intermediate composition pyroxene. Shown in Figure 6 (*top*) is an MGM analysis of the absorptions in lithology A that assumes a single pyroxene composition in the sample. Both the magnitude and the asymmetry of the residual error and the systematic deviations of the modeled spectrum to the actual spectrum indicate this meteorite spectrum is not well modeled with a single pyroxene (see discussion in Sunshine & Pieters 1993a). On the other hand, when MGM is allowed to fit bands appropriate for two pyroxenes to the EETA 79001 spectrum (Figure 6, *bottom*) the fit is accurate to within the noise of the system. Furthermore, the relative proportions of the low-Ca (large arrows) and the high-Ca (small arrows) pyroxenes derived from band strength relationships agree well with what is observed petrographically (Sunshine et al 1993).

The MGM approach has also been used in analysis of olivine reflectance spectra to quantify the systematic variations of the absorptions with Mg-Fe composition (Sunshine & Pieters 1990, and in preparation). The band centers and strength of the three olivine bands that form the composite feature near 1.05 μm are shown to vary with composition, but the band

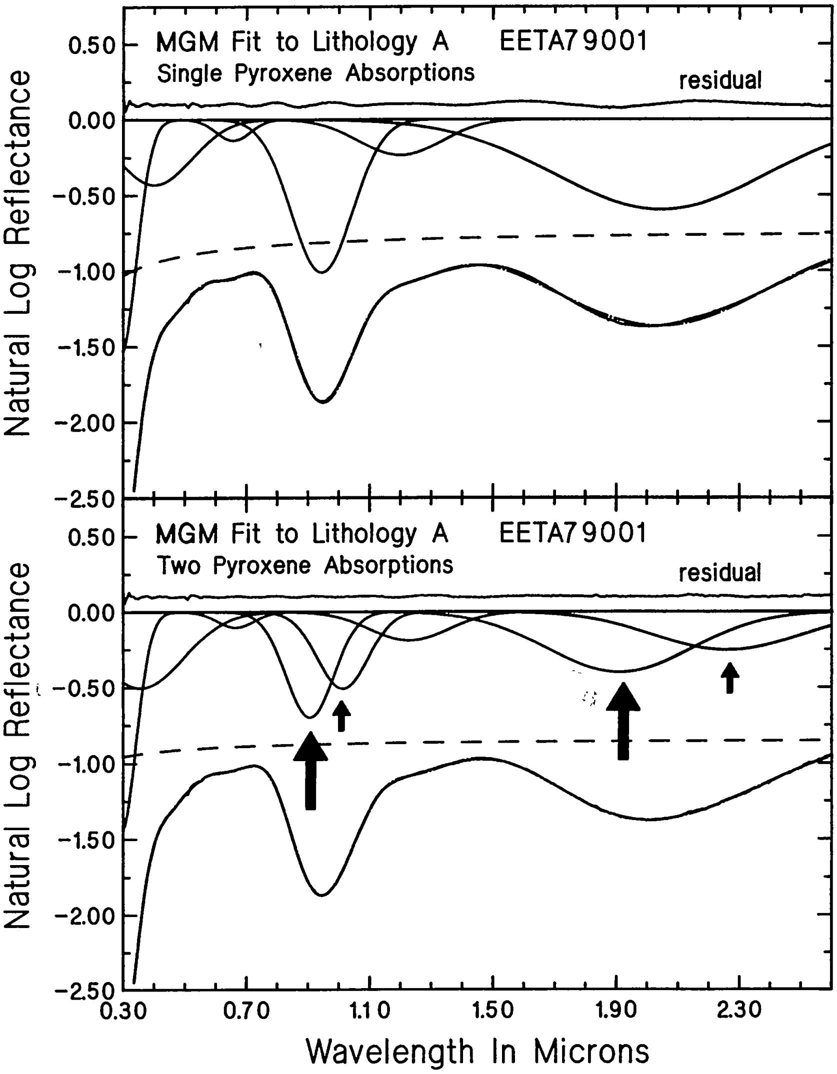

Figure 6 MGM analysis of shergottite EETA79001 lithology A (after Sunshine et al 1993). The four components of the analysis include (from top to bottom in each figure): the residual error between the log of the modeled spectrum and the log of the actual spectrum (offset 10% for clarity), the individual modified Gaussian distributions representing absorption bands, the continuum or baseline onto which these distributions are added (*dashed line*), and the modeled spectrum superimposed onto the actual spectrum. The upper figure contains MGM fits to EETA79001 using absorption bands in the 1 and 2 μm region representing a single pyroxene composition. Note the systematic pattern of the residual errors and that the peaks of the residual errors are uncorrelated with characteristics of the derived absorption bands. This is diagnostic of a fit that requires additional absorption bands (see Sunshine & Pieters 1993a). The lower figure contains MGM fits to the same spectrum using absorption bands in the 1 and 2 μm region representing two pyroxenes of different composition. Large arrows indicate absorption bands from the low-calcium component, and small arrows indicate the absorption bands from the high-calcium (clinopyroxene) component.

widths remain constant. The observed systematic variation of band centers allows a determination of olivine composition from an accurate deconvolution of a reflectance spectrum of a material with an unknown composition. This approach has been used to show that the olivine composition of A-class asteroid 246 Asporina is fosteritic, or Mg-rich (Sunshine & Pieters 1993b).

Space Weathering

Although there are obvious spectral similarities between meteorites measured in the laboratory and asteroids observed using remote sensors (spectra of Figures 4 and 5), the optical properties of the two types of materials do not exactly correspond (with the notable exception of 4 Vesta and basaltic achondrites). Principal component analyses of the two populations sampled to the 8-color standard show that the statistical measurement of spectral variability for prominent asteroid types do not readily overlay those for meteorite classes (Britt et al 1992). Individual or composite features can be identified in spectra of each that are readily interpreted (olivine, pyroxene, phyllosilicate), but there are unaccounted differences between asteroid spectra and meteorite spectra in such characteristics as strength and shape of absorption features, near-infrared continuum, nature of the spectrum below 0.5 μm, and overall albedo.

These differences could, and probably do, have several causes. Physical preparation of a meteorite for measurement in the laboratory may not accurately reproduce the physical form of material on an asteroid surface. In addition, a meteorite several centimeters in size may not represent its parent body due to the 10^6–10^7 difference in scale between meteorites and asteroids. Furthermore, there are most certainly asteroids that have not contributed to our meteorite collection and may thus not correspond to any meteorite class. There may be a selection process such that the solid material removed from an asteroid to become a meteorite does not represent surface material. And most worrisome, the only documented samples from an extraterrestrial body exposed to the space environment (the Moon) have shown that solid rocks and soil are quite different optically. Significant optical alteration occurs as a fine-grained regolith develops from local lithologies. Below, we summarize various aspects of the research concerning space weathering of surface materials.

Space weathering processes active in the lunar environment result in a lower albedo, weaker absorptions, and a red-sloped continuum. It is important to note, however, that although diagnostic mineral absorptions may be altered by such effects, they are not eliminated (e.g. Pieters 1993). Although the optical effects of space weathering were thought to be due to glass and/or agglutinate formation, more detailed evaluation of glass

(Bell et al 1976, Wells & Hapke 1977) and agglutinates (Pieters et al 1993) showed that neither exhibited the required optical effects. Recent analyses of lunar soil separates have shown that it is only the finest fraction of naturally developed lunar soils (which constitute <25‰) that accounts for the red-sloped continuum characteristic of lunar alteration, and that the processes producing optical alteration in the space environment appear to be surface correlated (Pieters et al 1993). A leading hypothesis of the physical cause of lunar optical alteration is linked to small particles of reduced iron such as those recently produced experimentally by Allen et al (1993) and the submicroscopic single-domain iron measured by ferromagnetic resonance (Morris 1977, 1980) that preferentially accumulates in the finest fraction. Understanding the properties of this reduced iron, the conditions of formation, and the optical effects on soil products are areas of active research. Since the finest fraction appears to be most strongly affected by space weathering, the degree to which small particles accumulate in asteroid regolith must be evaluated. In particular, the relative effects of gravitational, magnetic, and molecular forces on small particles adhering to surfaces may produce quite different results depending on the size of the asteroid and the physical characteristics of its surface (composition, texture, impact history).

The effects of irradiation is an additional important topic that requires controlled experiments. The solar wind is likely to play a pivotal role in space weathering, but its effect on geologic materials is poorly known. Hapke et al (1975) showed that there is a differential retention of elements sputtered using 2 keV hydrogen ions. Enrichment ratios of sputtered deposits appeared to follow atomic weight with Fe > Ca > Al > O. Preliminary experiments have been performed by Benedix (1993) in which silicates such as olivine were irradiated with 10 keV hydrogen ions in a vacuum environment. Minor optical effects were observed for the irradiated samples, but the active physical processes require further investigation.

Two recent laboratory experiments were performed to independently evaluate the optical effects of glass formation during regolith development. In the simulation by Clark et al (1992) chondritic meteorites were ground, a portion melted, and a pulverized fraction of the quenched material remixed with the original chondritic powder. In the experiments of Cloutis & Gaffey (1993) synthetic glasses of varying compositions were prepared and mixed with a variety of mafic silicates. In both cases the glass lowered the albedo and weakened the original absorption features. Both experimenters found it difficult to produce glass free of microcrystals. The results are useful in a qualitative sense, but since the effects of the low oxygen fugacity of the space environment on glasses (Bell et al 1976) was not reproduced, they cannot be directly compared to space weathering.

Some meteorites may provide clues to the processes active on the surface of meteorite parent bodies. Bell & Keil (1988) attempted to evaluate the spectral properties of gas-rich meteorite breccias, which are believed to contain components that have accumulated exposure to the space environment. They observed minor spectral variations between the gas-rich matrix and clasts across a cut slab of the meteorite. Because spectra of nonparticulate samples (slabs) are strongly dominated by the specular reflection component (Fresnel reflection) and less light is able to interact with and scatter from individual grains, direct comparison of these experiments with particulate samples and the effects of space weathering on regoliths can not be made.

Shock-darkened ordinary chondrites ("black chondrites") are another type of meteorite that have clearly undergone alteration effects that occurred either on the surface of the meteorite parent body or as the meteorite was ejected from the parent body. Britt & Pieters (1991) showed that these altered meteorites constitute 14–17% of the ordinary chondrite falls. Britt later documented that it is the finely dispersed metal and opaques ($\sim 2\ \mu$m in diameter) in the matrix of these shocked meteorites that causes the notable darkening (Britt & Pieters 1993). These shock-darkened meteorites exhibit a lower albedo and weaker absorption bands than their unshocked counterparts of the same composition, but, unlike the lunar case, they exhibit a flat continuum. The physical conditions necessary to transform an ordinary chondrite into a black chondrite are currently not well constrained.

Although the details of both the causes and effects of space weathering remain unclear, the multispectral observations of the S-class asteroid Gaspra by the *Galileo* spacecraft clearly show spectral differences across the surface (Belton et al 1992). Small bright craters are less red than their surroundings and exhibit stronger 1 μm absorptions—the very characteristics expected for space weathering from the lunar experience. It is thus likely that some form of space weathering has been observed on an asteroid, but the magnitude of these effects is clearly less on an asteroid like Gaspra than it is on the Moon.

ANTARCTIC METEORITES

The collection of Antarctic meteorites has dramatically increased the number of well-preserved meteorites available for analysis. Spectral reflectance studies of the Antarctic meteorites were initially carried out to search for spectral types that might be rare among the meteorites but at the same time similar to some asteroid spectral types. McFadden et al (1980) examined a suite of eight Yamato meteorites that were texturally different from existing members of their meteorite classes, basaltic achondrites, ureilites, and carbonaceous chondrites. While the variations in the spectral features of these Antarctic meteorites were mineralogically and petrologically significant, this first search did not yield any major new meteorite spectral types. More recently, successful examples of identifying and using unique properties of the Antarctic collection include the studies by Hiroi and associates mentioned in the previous section. Most primitive achondrites (Lodranites, Acapulcoites) come principally from the Antarctic collection. The thermally metamorphosed carbonaceous chondrites, which best mimic the ultraviolet properties of C-class asteroids, are unique to the Antarctic collection.

Among the significant discoveries from Antarctica are meteorites originating from the Moon (Lindstrom et al 1991). Spectral reflectance studies of the first recognized lunar meteorite ALHA81005 (Pieters et al 1983) was carried out in an effort to constrain the source region on the Moon from where the meteorite was ejected. The assemblage brought to Earth and named ALHA81005 exhibited features diagnostic of low-Ca pyroxene and olivine, characteristics which at that time had not been observed for craters on the Moon which had been studied from ground-based reflectance spectroscopy and which could serve as possible source craters. Based on the known compositional properties of nearside lunar units, the meteorite most likely was ejected from the nearside limb or the far side of the Moon. A small crater on the limb near Mare Crisium was in fact later found to have the required spectral characteristics (Pieters 1986, 1993). Spectral studies of a second lunar meteorite, Y791197 (McFadden et al 1986), showed it also to have a highland composition, but to probably originate from a separate ejection event. Spectroscopic studies have been initiated for a third lunar meteorite, A881757 Asuka 31, an unusual gabbroic sample. Preliminary studies of mineral separates from this sample have provided the first spectroscopic analysis of uncontaminated maskelynite, shocked plagioclase (Pieters & Rode 1993). Maskelynite was shown to exhibit the spectral properties of glass, but with an exceptionally strong ultraviolet absorption below 0.4 μm.

The suite of meteorites called the Shergottites-Nakhlites-Chassignites (SNCs), which are believed to have been ejected from Mars (McSween 1985), was significantly enlarged as a result of the Antarctic meteorite expeditions. Spectral reflectance measurements of these meteorites may provide constraints on their source regions when there are spectral reflectance data of Mars with sufficiently high spatial resolution to provide meaningful constraints. Singer & McSween (1991) and Mustard et al (1993) have discussed the constraints on the composition of the martian crust based on remote measurements of the surface and on reflectance studies of SNC meteorites by McFadden (1987) and McFadden & Pratt (1989). While there is evidence for pyroxene-bearing material (like shergottite) on the martian surface from telescopic and spacecraft investigations, no surface exposures of the cumulate phases of the SNCs, the nakhlites or chassignites, have been observed remotely.

ADVANCES IN ASTEROID OBSERVATIONS

Photoelectric detectors were used for the 8-color asteroid survey which forms the basis for asteroid taxonomy. Since the initial productive age of photoelectric photometry using a series of filters, most advances in asteroid observations have resulted from the use of more sensitive and efficient sensors which cover a much larger spectral range.

Extended Spectral Range of Near-IR Spectroscopy

As the 25-filter two-beam photoelectric photometer was being retired, circular variable filters (CVFs) with 1.5% wavelength resolution and InSb detectors were coming on-line. Near-infrared measurements covering 0.8–2.6 μm (52-color) were made, first of the larger asteroids (McFadden et al 1981, Gaffey 1984) and then as a survey of all asteroid types with $V_{mag} < 13$ (Bell et al 1985). Inner belt asteroids near the 3:1 Kirkwood gap were targeted in a study by McFadden & Chamberlin (1992) using a cooled grating InSb array at the Infrared Telescope Facility (IRTF). Data from the expanding Bell et al survey provide a mother lode of information that continues to form the basis for new ideas related to asteroid surface composition.

MAFIC SILICATE MINERALOGY AND CHEMISTRY One of the first major discoveries enabled by the technical advances of near-infrared spectrometers and the IRTF was the discovery of olivine-rich asteroids in the main asteroid belt (Cruikshank & Hartmann 1984), predicted from cosmochemical principles. These asteroids (A class) exhibit well-defined olivine absorption features (e.g. 246 Asporina in Figure 5) and are believed to represent the subcrustal, mantle region of bodies which have undergone chemical differentiation.

Using the same instrumentation augmented by visible and infrared measurements, Cruikshank et al (1991a) discovered three additional basaltic achondrite meteorite analogues among the near-Earth asteroids. The orbits of these near-Earth V-class asteroids are remarkably similar, indicating that if they have a similar origin, the disruption event must have occurred recently. This discovery brought to four the number of possible basaltic achondrite parent bodies among the dynamically short-lived near-Earth asteroids.

Other near-Earth asteroids have been the subject of further study as well. Gaffey et al (1992) present visible and near-infrared evidence confirming that the Apollo asteroid 3103 1982 BB is an E-class asteroid. Unlike the V-class near-Earth asteroids studied by Cruikshank et al, 1982BB is in a relatively long-lived orbit with an orbital resonance (3:5) with the Earth. Gaffey et al (1992) suggest that this asteroid is the principal source of the enstatite achondrite meteorites (Aubrites).

Asteroids with previously unidentified mineralogies have also been discovered as a result of the 52-color IR survey. A few S-class main belt asteroids which do not have a 1.0 micron band were observed to exhibit a prominent broad feature near 2 μm. The lack of a prominent feature near 1.0 μm in an asteroid with moderate to high albedo implies that ferrous silicates are low in abundance or absent. Very few materials, except for various forms of spinel, exhibit a singular 2 μm absorption. The observed unusual spectral character of these asteroids led to an interpretation that they contain spinel-bearing assemblages, perhaps similar to the Ca-Al inclusions in CV meteorites (Burbine et al 1992).

The near-infrared properties of S-class asteroids has been under study for over a decade and two very different, but equally important, hypotheses on their origin remain open for discussion. From the character of the absorption features near 1 and 2 μm (see Figure 5) the surfaces of S-class asteroids are known to contain a mineral assemblage consisting of orthopyroxene and olivine. S-class asteroids also exhibit a red-sloped near-infrared continuum which normally indicates the presence of a metallic component (although there are exceptions such as the red continuum of lunar soils which may or may not be linked to fine-grained metal and, conversely, laboratory spectra of metal-bearing ordinary chondrites which do not exhibit a red continuum). This basic information is consistent with at least two types of material: a stony iron assemblage and an ordinary chondrite assemblage. The literature is full of arguments for and against each possibility. Most of the unresolved issues concern 1. the character and effects of alteration processes and regolith development active on an asteroid surface (e.g. Pieters et al 1976, 1993) and 2. the degree to which compositional components derived from laboratory spectra of meteorites and meteorite analogues (see previous section) can be used to interpret spectral properties measured for an asteroid surface (e.g. Gaffey & McCord 1978, Gaffey 1984, Gaffey et al 1993b). This is obviously an important dilemma to resolve since the S-class asteroids are abundant in the inner part of the main belt (see Figure 2 and Table 2) and the stony iron interpretation implies that pervasive differentiation and igneous processes affected the inner belt, while the chondrite interpretation suggests the opposite.

The most complete survey of visible and near-infrared spectral properties of 39 S-class asteroids has been compiled by Gaffey et al (1993b). In this investigation Gaffey et al divide the S-class asteroids into eight different groups based on wavelength of the composite 1 μm band and a band area ratio parameter (2 μm band to that of the 1 μm band). Using empirically derived interpretive algorithms Gaffey et al characterize the compositions of these groups as ranging from undifferentiated to fully differentiated bodies. They also present comparisons of spectral parameters with asteroid size. Assuming smaller asteroids would be less affected by optical alteration, they argue that the size information refutes most regolith alteration processes. One of the most important results unveiled from Gaffey et al's discussion is that the S class of asteroids are not one type of material, but are quite compositionally diverse. [It is interesting to note a bit of convergence of the two hypotheses for S-class asteroids in this discussion. Gaffey originally proposed the stony iron hypothesis (Gaffey 1984), but with more detailed and expanded data and analyses Gaffey et al (1993b) recognize that one of their eight groups of S-class asteroids is "not inconsistent with" ordinary chondrites.]

ORGANICS An excellent overview of organic compounds in carbonaceous chondrites can be found in Cronin et al (1988). Several investigators (e g. Gradie & Veverka 1980; Vilas & Smith 1985; Cruikshank et al 1991b; Moroz et al 1991, 1992) have suggested that organics could be the cause of the low albedo and red coloration of the P and D outer solar system asteroids, but until recently no conclusive spectroscopic evidence for organics had been observed. The high sensitivity of several current spectroscopic instruments has resulted in the confirming evidence. Cruikshank et al (1993) integrated new telescopic and laboratory data identifying an absorption feature at 1.7 μm and a stronger absorption at 2.27 μm for the small planetesimal 5145 Pholus (which has a perihelion inside the orbit of Saturn and a aphelion outside the orbit of Neptune). Because Pholus is also one of the reddest objects in the solar system (Mueller et al 1992, Fink et al 1992, Binzel 1992) Cruikshank et al were able to convincingly show that the surface of Pholus contains aliphatic-rich and high H/C solid asphaltite-like organics. They also suggested that Pholus may represent an endmember body containing unaltered primitive materials, and that comparable materials on asteroids closer to the Sun have been transformed to more closely resemble organics seen in meteorites.

Observations in the 3 μm Region

In the mid-1980s a cooled grating array infrared spectrometer became available permitting measurements of asteroids in the 3.0 μm spectral region with greater sensitivity and spectral resolution than in the previous decade. This spectral region is particularly difficult observationally due to an extremely strong atmospheric water absorption. For comparison, the spectral characteristics of a suite of meteorites in this spectral region can be found in Salisbury et al (1991). Lebofsky et al (1981a) first interpreted the 3.0 μm absorption band as a water of hydration feature observed in large C-class asteroids. Jones (1988) measured 19 low-albedo asteroids using the cooled-grating infrared array spectrometer at the IRTF at Mauna Kea, Hawaii to search for and characterize the 3.0 μm water of hydration band. Examples of such spectra are shown in Figure 7. Of the 32 asteroids available for analysis (Jones et al 1990), 66% of the C class (and their subsets) contain 3-μm absorption bands, diagnostic of the presence of hydrated silicates. Of the P and D class, which populate the Trojan and Cybele regions of the asteroid belt, only 1 (324 Bamberga) has a water of hydration band.

A significant result from the work of Jones et al (1990) is the cosmochemical implication that the distribution of asteroids with water of hydration bands peaks in the middle of the main asteroid belt, and decreases both inward and outward from there. The P- and D-class asteroids which dominate the outer belt apparently do not contain any form of water. This result is somewhat counter-intuitive as there is ample water ice among the satellites of Jupiter and Saturn. The explanation proposed by Jones et al (1990) is that the temperatures were too low for aqueous alteration, and over the age of the solar system volatiles have not been retained on the surface for bodies the size of outer belt asteroids (100s of km in diameter). Additional measurements obtained in the 3 μm region will provide important information on the spatial distribution of hydrated materials and will help constrain the processes that have created and/or destroyed them.

A recent intriguing result is the interpretation of King et al (1992) that a 3.07 μm absorption band in the largest main belt asteroid, 1 Ceres, is due to an ammoniated form of phyllosilicate rather than water frost as interpreted by Lebofsky et al (1981a). Their interpretation uses new, high resolution spectra in the 3–5 μm region as well as laboratory studies of the ammoniated form of a saponite clay mineral. Their argument is primarily based on the difference in band widths between the observed band in the Ceres spectrum and laboratory spectra of water frost. Mixing analyses combining an opaque material with phyllosilicate produces a spectrum

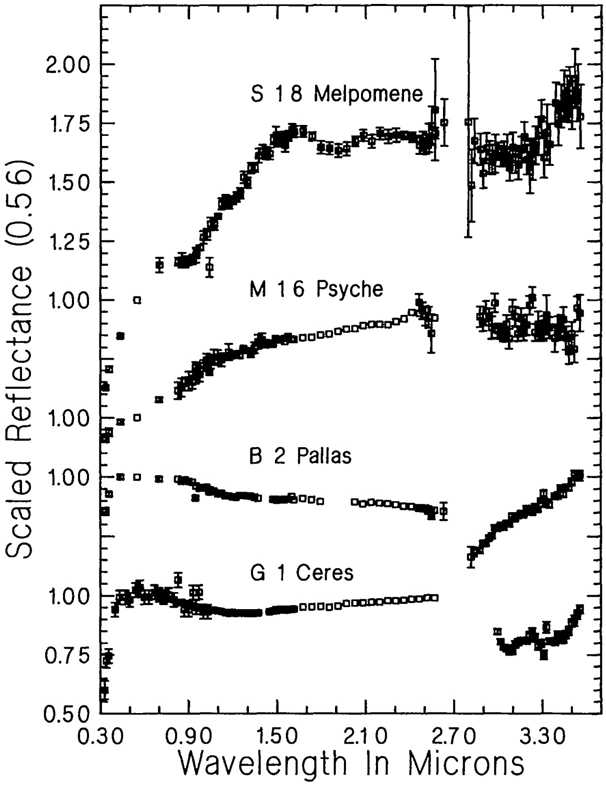

Figure 7 Examples of composite asteroid reflectance spectra from the visible through 3.6 μm. The long wavelength data (2.6–3.6 μm) are from Jones et al (1990). The 3 μm region is an important part of the spectrum for identifying fundamental vibrational modes of such volatile species as OH, H_2O and H_2O frost. Main belt asteroids exhibit diverse characteristics and the presence of these bands in asteroid spectra (Pallas and Ceres) demonstrates the existence of hydrated species which could indicate either a primary accretion composition or a secondary alteration product.

reasonably similar to Ceres. If this interpretation is correct and other ammoniated assemblages are found in the main belt, it implies that secondary heating processes have not exceeded 400 K in the asteroid belt since this ammoniated assemblage was formed. This result, however, must be reconciled with independent evidence for the presence of water from ultraviolet spectra showing OH emission, presumably formed from dissociation of water vapor (A'Hearn & Feldman 1992).

High S/N CCD

In the past decade CCD spectrometers replaced most of the visible photoelectric systems bringing significant increases in sensitivity and increased spectral resolution. Several applications of this technology have brought a diversity of new results.

DARK ASTEROIDS/PHYLLOSILICATES Vilas first used CCD spectrometers to measure asteroid spectra and took advantage of the improved sensitivity to study the faint asteroids of the outer asteroid belt (Vilas & Smith 1985). In this study it was noted that there is a general spectral reddening trend as a function of heliocentric distance. This observational program was expanded by Sawyer (1991) who also studied low-albedo asteroids of the main belt. These two programs resulted in the discovery of weak absorption features in low-albedo asteroids. The most common and prominent feature is a broad weak absorption that occurs near 0.7 μm and is believed to arise from Fe^{2+}–Fe^{3+} charge transfer absorptions in phyllosilicate minerals (Vilas & Gaffey 1989, Vilas et al 1993b). Examples of this absorption are shown in Figure 8*a*. Possible additional weak features have been observed at 0.43 and 0.6 μm (Vilas et al 1993a,b). Prior to the availability of CCD spectrometers, no diagnostic absorption bands of the dark C-class asteroids were observed in the spectral region between 0.4 and 1.0 μm. The discovery of these bands increases the specificity of the mineralogical interpretation of dark asteroids.

The identification of features in C-class asteroid spectra, such as the pervasive 0.7 μm phyllosilicate band, is noteworthy not only because of the specificity of the mineralogical identification which they afford, but because these minerals are secondary products of aqueous alteration. During the next decade it is anticipated that weak features of dark asteroids in the visible will be more thoroughly documented. This will allow valuable comparisons between the visible features and the water of hydration band near 3 μm, adding an important dimension to our understanding of the compositional makeup of the asteroid belt and outer solar system.

SMALL BASALTIC ASTEROIDS Whereas CCDs were first used to target faint asteroids in the outer solar system, a recent spectroscopic survey targeting faint (and thus small) asteroids in the inner part of the asteroid belt has also been scientifically productive (Binzel & Xu 1993, Binzel et al 1993).

Until recently, only 4 Vesta, the second largest asteroid in the main belt ($\sim$500 km in diameter), and four small near-Earth asteroids were known to have surface compositions similar to the howardite, eucrite, and diogenite (HED) meteorites. The V class of asteroids in the main belt contained a single member, Vesta, until 1993 when Binzel & Xu (1993) reported their discovery of 14 small asteroids ($\leqslant$10 km in diameter) of basaltic achondrite composition forming a trail from Vesta to the 3:1 Kirkwood gap. The visible spectra of two of these small V-class main-belt asteroids are shown in Figure 8*b*. The observations of Binzel & Xu have provided a possibly significant breakthrough in solving the puzzle of how Vesta could be the parent body of the HED meteorites—a preference among geochemists (e.g. Drake 1979). Large fragments apparently ejected from Vesta during

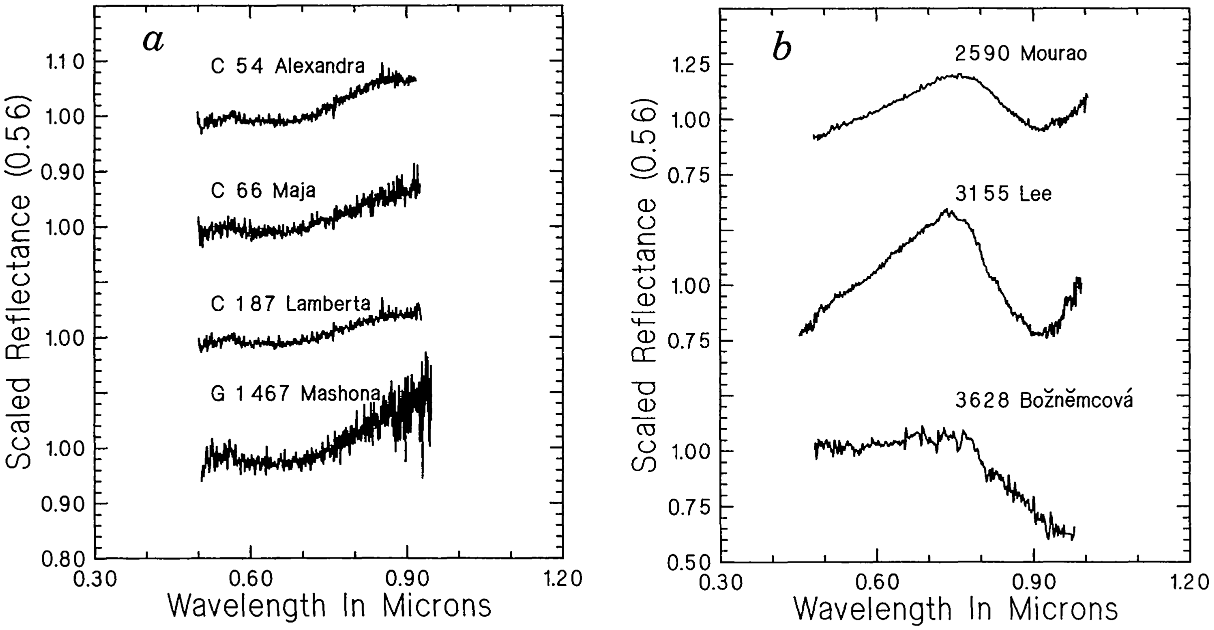

Figure 8 Examples of high spectral resolution visible CCD spectra of asteroids. (*a*) Spectra of several low albedo asteroids (Vilas et al 1993b). These dark asteroids exhibit a weak but definite 0.7 μm feature that can be attributable to the presence of phyllosilicates. (*b*) Spectra of selected small main belt asteroids. Mourao and Lee are two of the suite of small asteroids that appear to be associated with Vesta and the HED meteorites (Binzel & Xu 1993). Bŏznĕmcov̌ is currently the only small asteroid near the 3:1 Kirkwood gap that exhibits a prominent Fe^{2+} absorption centered beyond 0.9 μm and a relatively flat spectrum between 0.5 and 0.7 μm, consistent with spectral properties of ordinary chondrites (Binzel et al 1993).

a major impact event have been placed in orbits approaching the 3:1 Kirkwood Gap, where the probability of gravitational instabilities are high and from which Earth-crossing orbits can readily evolve (Wisdom 1985). From near the 3:1 Kirkwood gap, small asteroids are readily perturbed into Earth-crossing orbits becoming Apollo asteroids. Associated fragments evolve dynamically and, if they collide with Earth, become meteorites.

Conventional wisdom has previously described 4 Vesta as a compositionally unique asteroid of the main belt with a surface that exhibits little, if any space weathering (e.g. Matson et al 1977). If significant space weathering does occur on asteroidal surfaces, however, then the apparently unaltered optical properties of Vesta's current regolith indicate that material across the body has been freshly exposed by a recent event, such as a large impact. In support of this scenario are three pieces of evidence: 1. the unweathered appearance of the regolith on Vesta, 2. the existence of a family of small V-class asteroids (also with spectra indicating freshly exposed material) that string from Vesta to the 3:1 resonance, and 3. the similar (basaltic achondrite) V-class near-Earth asteroids in poorly evolved orbits (suggesting recent arrival to their current positions).

MAIN BELT ORDINARY CHONDRITE CANDIDATE In the same ongoing survey of small main belt asteroids Binzel et al (1993) discovered a small main belt asteroid with characteristics that are directly comparable to those observed for the ordinary chondrite meteorites in the laboratory. The spectrum of this asteroid, 3628 Božněmcová, is also shown in Figure 8*b*. 3628 Božněmcová is a 7 km diameter object that is located near the 3:1 Kirkwood gap. Its CCD reflectance spectrum has a strong 1 μm absorption band and, according to the available broadband near-infrared measurements, probably has a 2.0 μm band as well. What makes this an unusual spectrum are the strength of the ferrous bands and the apparent lack of optical effects of space weathering. Unlike the V-class basaltic achondrite asteroids, however, a *large* parent body has not been found for the ordinary chondrites.

To account for the abundance of ordinary chondrites in the meteorite collection, either (*a*) large parent bodies must be found to supply material to the appropriate resonance and/or near-Earth orbit, (*b*) a large number of small bodies must be located, or (*c*) cosmochemists and dynamists must accept a paucity of ordinary chondrite material in the main belt. Marti & Graf (1992) discuss evidence from cosmic rays indicating that the collisions that produced the ordinary chondrite classes were stochastic events. This suggests that there is more than one ordinary chondrite parent body. Because most large main belt asteroids have been included in the various asteroid surveys, but no ordinary chondrite-like material has been directly identified, if such large bodies exist they must exhibit a surface not directly comparable to those of ordinary chondrites. If this is the case, it is most likely a result of space weathering. On the other hand, if very small asteroids are the principal supplier of ordinary chondrites, then more must be discovered. It is significant that Binzel et al have found only one ordinary chondrite in the main belt out of the 80 thus far measured. The next phase of observations may provide the determinative answer.

CURRENT PERSPECTIVES ON THE ASTEROID-METEORITE LINK

The above discussion highlights many of the recent advances in spectroscopic observations of meteorites and asteroids and our ability to infer compositional implications from these data. Due to the limited nature of the data, the questions posed in the Introduction of this review are not fully resolved. Nevertheless, the compositional complexities of small bodies in the solar system are becoming more readily apparent and additional patterns may emerge as new investigations are pursued and more complete data are analyzed in an integrated manner. There are several points, some more obvious than others, that are important to consider at this stage of our understanding of the asteroid-meteorite link:

1. The asteroids are a more diverse group of bodies than is suggested from the suite of materials represented by the meteorites. This is simply another way of saying that the meteorites have sampled some, but not all types of asteroids. As the data for Pholus exemplifies, *we clearly have an incomplete sample of primitive solar system materials.*
2. The relative abundances of meteorites that fall to Earth are determined by processes that affect a small number of asteroids in any given time period. *Our current meteorite collection does not necessarily reflect the bulk composition of the asteroid belt, but it reflects the interplay of random collisions and dynamical forces that control delivery of material from the resonances.*
3. The general order originally observed throughout the main belt of asteroids using 8-color data appears to be an inherent part of the structure even as more complete spectroscopic data have been acquired. However, asteroids with compositional properties important to understanding solar system processes (hydrated components, organics, phyllosilicates, etc) do not necessarily correspond to the current classification of asteroids. As a more diverse range of compositional information for a larger number of asteroids accumulates, *it is clear that the original asteroid taxonomy will need to be revised to reflect the true complexity seen from compositionally related parameters.*

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