REVIEW OF ASTEROID COMPOSITIONS

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Asteroids are a potentially rich source of a variety of materials in the solar system. Some of them are also relatively easy to access because they have been perturbed into near-Earth orbits. Most of our information on asteroid surface compositions comes from telescopic reflectance spectroscopy, and most of our information on asteroid bulk compositions has been determined from the study of meteorites. In this chapter, we summarize the current state of knowledge of asteroid compositions, using the information from both these sources. We conclude with a discussion of some of the remaining controversies.

I. INTRODUCTION

Asteroids were the last class of objects to be discovered in the solar system. However, most astronomers did not consider asteroids as subjects worthy of study in their own right, therefore very little was learned about them until the latter half of this century. Now much has been learned about the brighter, main belt asteroids, and improvements in instrumentation have made detailed investigations of the faint asteroids feasible. Several dedicated asteroid search programs (see, e.g. Shoemaker and Shoemaker 1988; Helin and Dunbar 1991; Gehrels 1991) have significantly increased the number of known asteroids in recent years. The growing interest among astronomers in asteroids essentially coincided with a growing realization among meteoriticists that the vast majority of the meteorites in our collections have been derived from the asteroids. Astronomers and meteoriticists have been debating which classes of meteorites are derived from which classes of asteroids ever since.

It is sometimes difficult to determine which asteroids and meteorites are similar for several reasons. Telescopic reflectance spectroscopy gives compositional information only about the surfaces of the asteroids, and those surfaces are subject to alteration by a variety of irradiation and collisional processes. These processes can cause changes in the surface which obscure the diagnostic absorption features of component minerals in the reflectance spectra. There are a few meteorites in the collections which have been identified as surface material (the gas-rich chondrites), but the majority of the meteorites are derived from asteroid interiors, which have not been subject to the same alteration processes. These differences can make it extremely difficult to determine compositional similarities for some of the asteroid and meteorite classes. It is even more complicated to attempt to identify the parent body of a specific meteorite, because there is no guarantee that the asteroid was not destroyed in the collision which created the meteoroid. It will probably not be possible for most meteorites, without detailed chemical comparisons from asteroid sample return missions.

There are several reasons for continuing to try to make these correlations. Interpretations of telescopic reflectance spectra, without meteorite analogs, are limited to discussions of the spectrally distinguishable minerals such as olivine, pyroxene, plagioclase and water. The presence of metal can sometimes be inferred from spectral slope, but it cannot be confirmed due to the lack of diagnostic absorption features. Meteorite analogs make it possible to apply the extensive mineralogic information derived from meteorites to the compositional interpretation of spectrally similar asteroids. These correlations are also essential for models of the origin of the solar system. They make it possible to place the information derived from the meteorites on conditions in the solar nebula in the correct spatial context.

Asteroids are also potentially rich sources of ores for space mining. The near-Earth asteroids are particularly attractive because they are in favorable orbits. In the chapters by Nichols and by Lewis and Hutson, the types of materials which could be mined from asteroids with compositions similar to the various meteorite types are discussed. These chapters can be combined with the discussion in this chapter to identify potential targets for future exploration.

Two recent review articles have discussed asteroids from a spectroscopic perspective (M. J. Gaffey et al. 1989,1992). When combined with the McFadden et al. (1989) review of the near-Earth asteroids, these papers give a complete review of the published asteroid spectral literature up to the time of their submittal. We refer the reader to these papers for detailed summaries of the compositional analyses of individual asteroids. In our section on asteroid spectroscopy, we have focused on the compositional similarities and differences represented within the different asteroid classes. We then discuss meteorite compositions, and identify analogs for the asteroid classes when applicable. We conclude with a discussion of the remaining problems and controversies in the field.

II. DISTRIBUTION AND CLASSIFICATION

The majority of the asteroids are believed to be material which never accreted to form planets (Wetherill 1989). Most of them are probably collisional fragments of the original planetesimals, but at least one asteroid, 4 Vesta, is believed to be intact because it still possesses a basaltic crust (Davis et al. 1989). Figure 1 shows the distribution of known asteroids as a function of

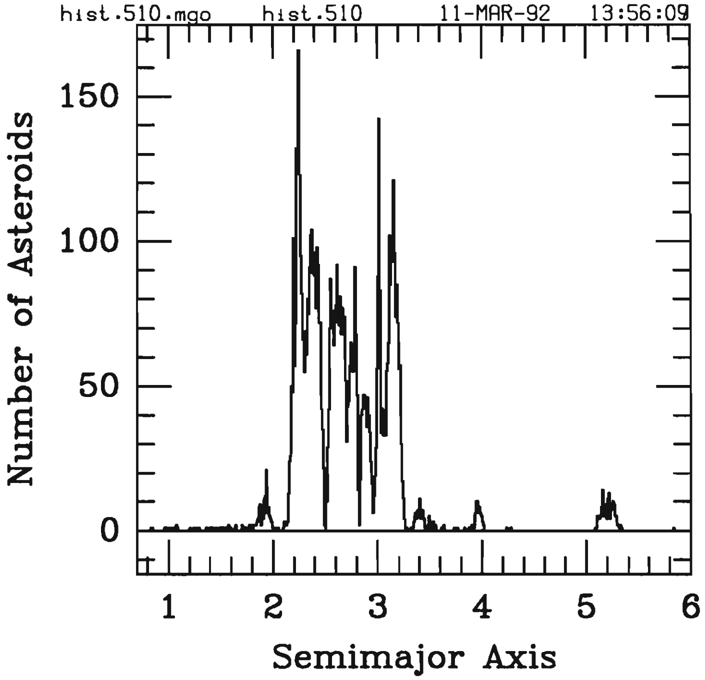
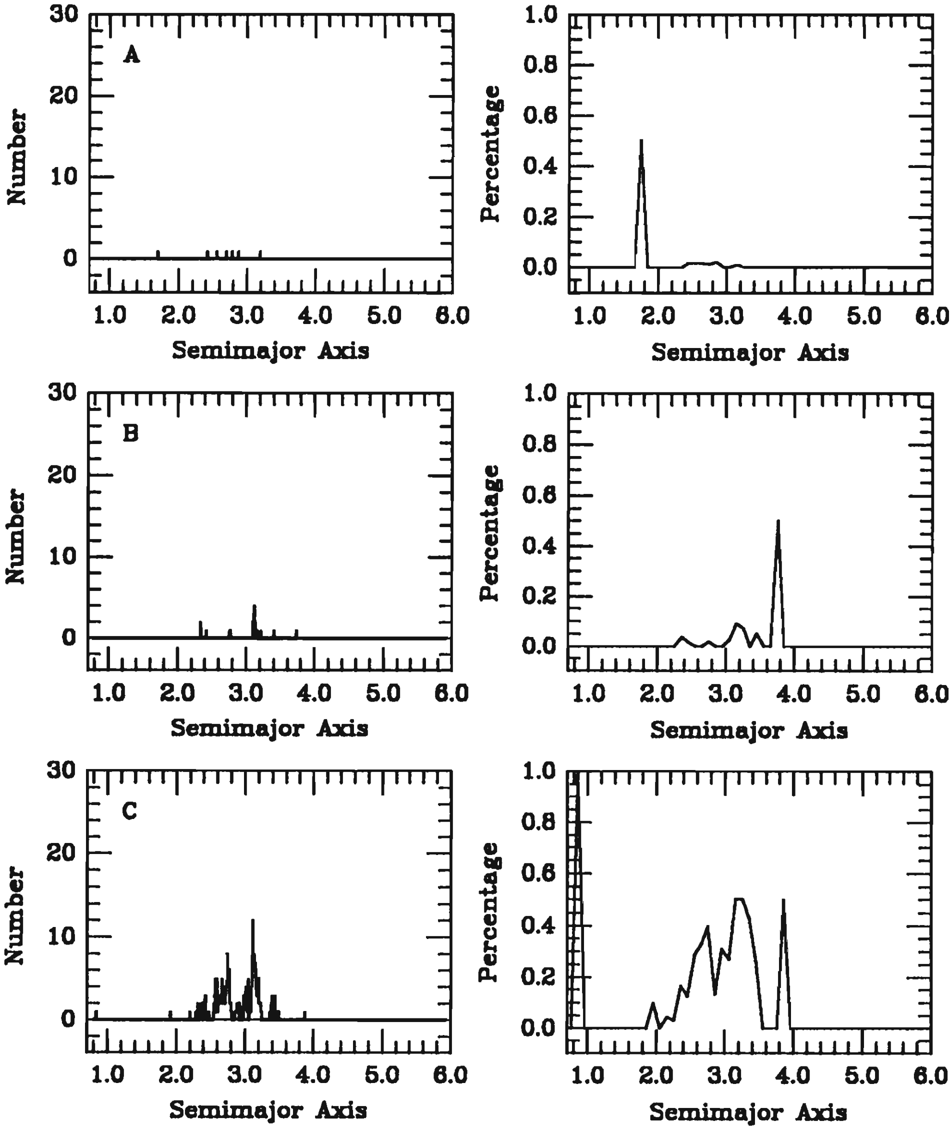
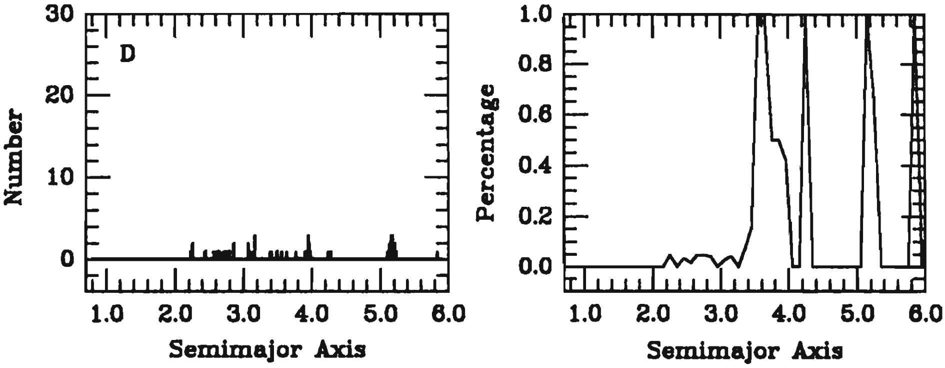


Figure 1. Distribution of asteroids as a function of orbital semi-major axes. This figure includes all the asteroids in the Minor Planets Center database which have been observed at more than one apparition, asteroid type, at a spatial resolution of 0.01 AU. The right panels show as of February 1991.

semimajor axis. Most of the asteroids are found in the main asteroid belt between the orbits of Mars and Jupiter (with semimajor axes between 2.1 and 3.3 AU). Orbital resonances with Jupiter create the gaps in the distribution (Froeschlé and Greenberg 1989). The dominant composition of main belt asteroids changes with heliocentric distance (Gradie et al. 1989), which suggests that they have remained near their original formation regions since the origin of the solar system (Ruzmaikina et al. 1989). The Trojan asteroids are located at the L4 and L5 Legrangian points of Jupiter's orbit (with semimajor axes of 5.2 AU). They are probably a small subset of the original outer solar system planetesimal population which were trapped in these resonances (Shoemaker et al. 1989). The near-Earth asteroids have semi-major axes ranging from >1 AU to 1.5 AU. Their lifetimes against collision with one of the terrestrial planets, or ejection from the solar system, are calculated to be approximately 10^7 to 10^8 yr (Chapter by Greenberg and Nolan). The majority of the present near-Earth asteroids are believed to have been perturbed from the main belt into planet-crossing orbits (Greenberg and Nolan 1989), although these dynamical mechanisms are still poorly understood. Some of the current population of near-Earth asteroids may also be extinct comet nuclei, (Weissman et al. 1989), however no definitive identification of an extinct nucleus has been made. Recent work by Binzel et al. (1992) has shown that it is theoretically possible for up to 40% of the near-Earth asteroid population to be extinct comment nuclei.

Asteroids can be classified into groups based on orbital parameters (Valsecchi et al. 1989; Zappala et al. 1990) or on the basis of reflectance spectra (Tholen and Barucci 1989). The different orbital classifications all use different criteria to define groups of asteroids with similar orbits which are called families. Families are thought to be the pieces of disrupted bodies, but recent spectral analyses have called the validity of many of the smaller families into question (Chapman et al. 1989). There are also a number of spectral classification systems currently in use, and earlier papers use still other, older, less detailed systems. Tholen and Barruci (1989) present the

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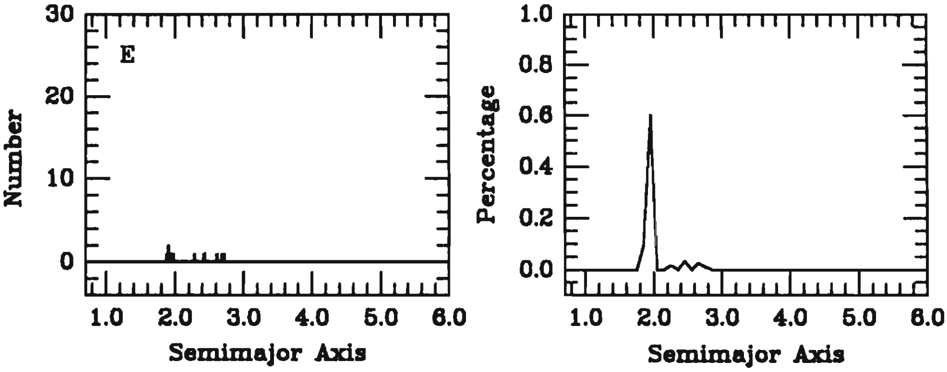
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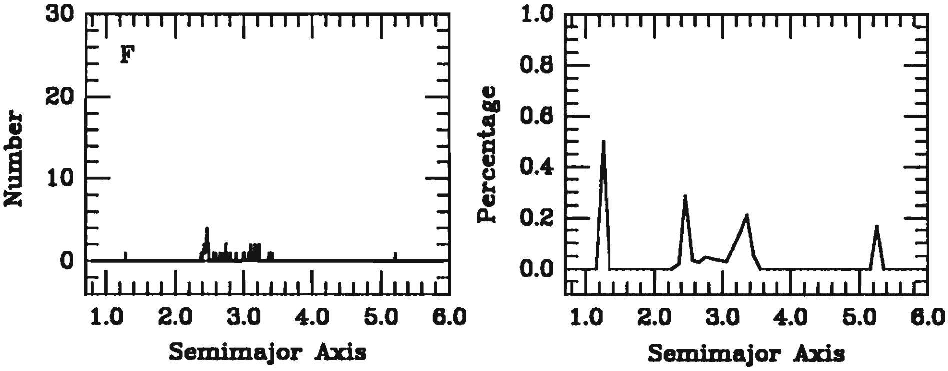
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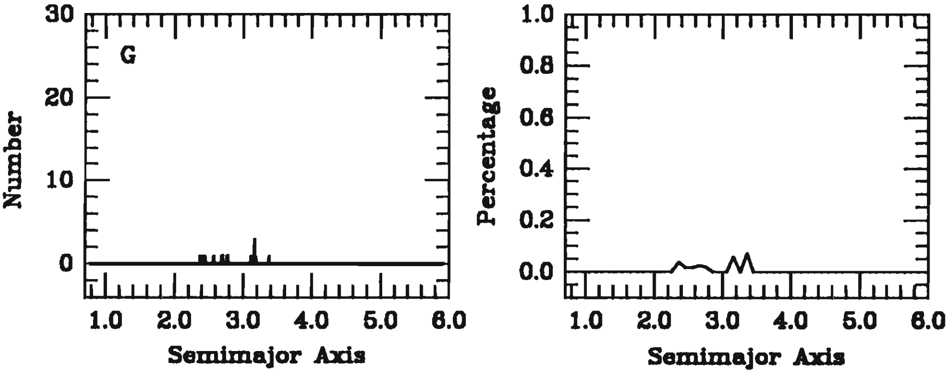
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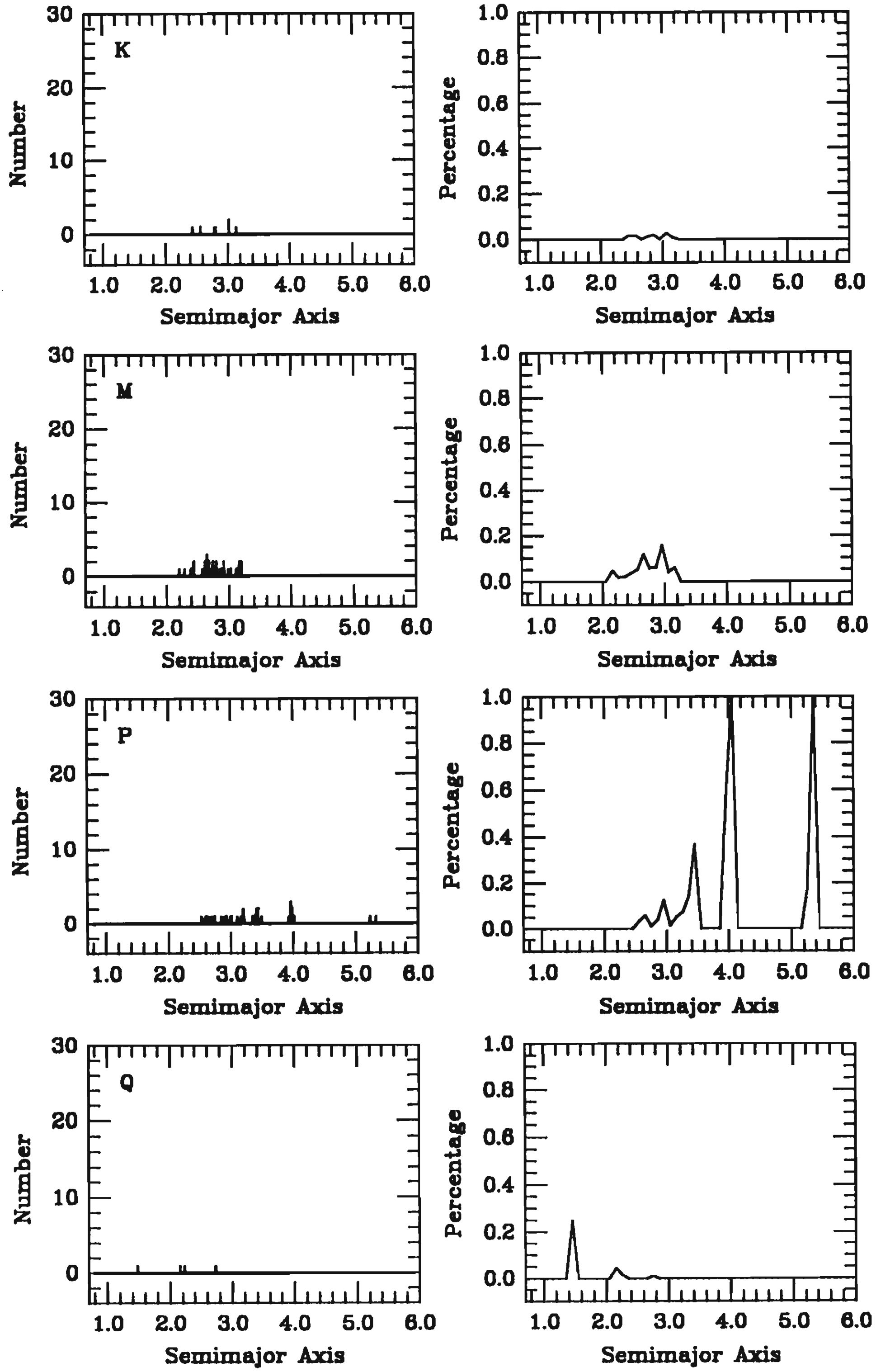
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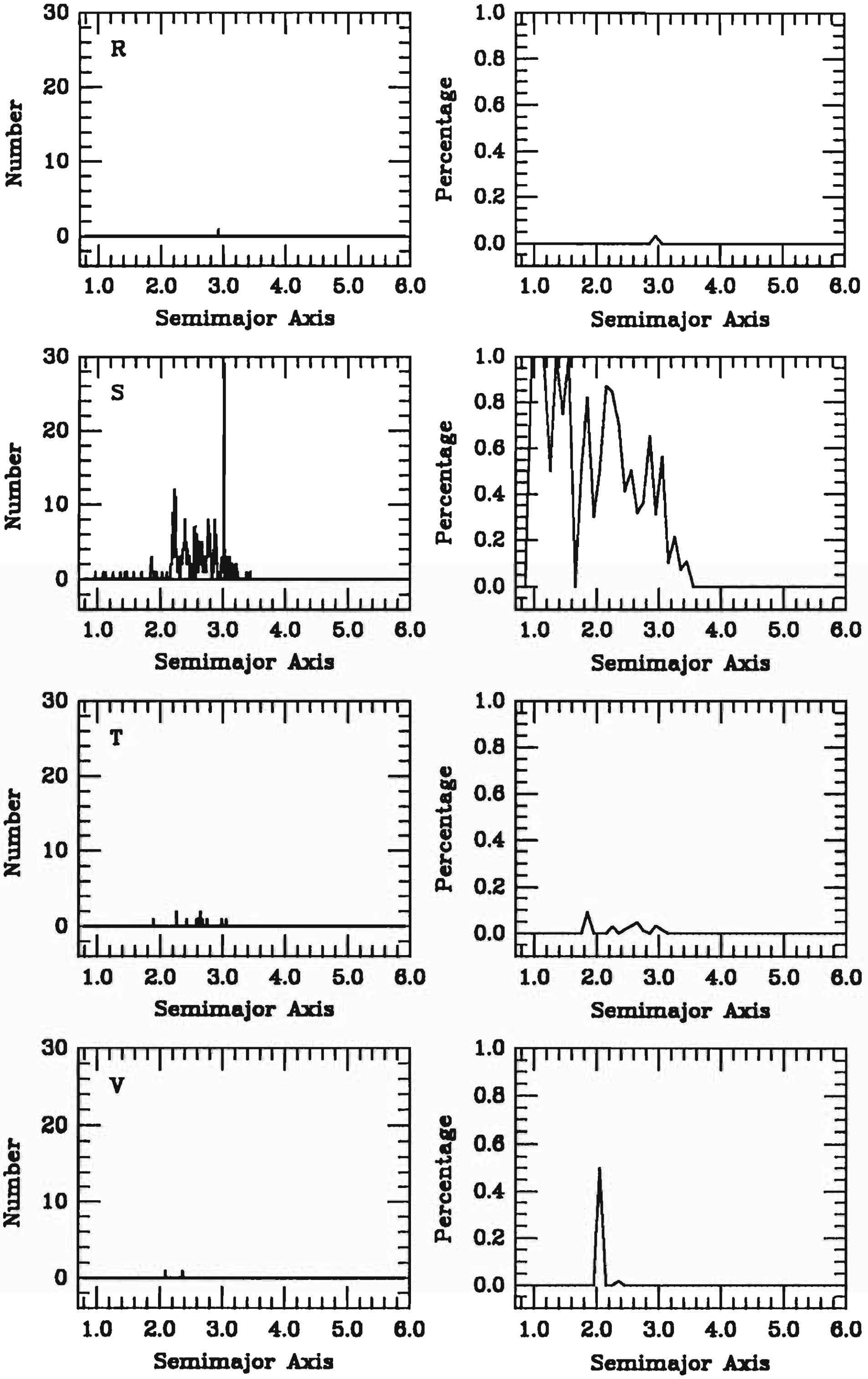

Figures 2a–d. Distribution of classified asteroids, as a function of orbital semi-major axis. The left panels show histograms for each asteroid class, at spatial resolution of 0.01 AU. The right panel shows the fractional distribution of each type, at a spatial resolution of 0.1 AU. Only the typed asteroids were used in determining the fractions.

best summary of the different systems, illustrating some of the differences in the criteria used, and the results obtained. This chapter will use the Tholen classification, which is based on the analysis of Eight Color Asteroid Survey (ECAS) spectra (0.3–1.1 μm) of 405 asteroids (Zellner et al. 1985). The classification uses principal components analysis to define asteroids with similar spectral properties (Tholen and Barucci 1989).

Figure 2 shows the spatial distribution of each taxonomic class of the asteroids. The left panels show histograms for the individual types, and the right panels show the fractional abundance of each type as a function of semimajor axis. It is obvious from this figure that the abundance of the different asteroid classes varies with heliocentric distance. If the near-Earth asteroids are ignored (all asteroids with semimajor axes $\leq$1.5 AU) the variations are highly systematic. This is the best evidence that the main belt and Trojan asteroids have not been perturbed far from their original formation orbits (Gradie et al. 1989). The near-Earth asteroids are a heterogeneous group, including most of the taxonomic types found in the main asteroid belt, as well as one, (Q), which has not yet been found in the main belt. This may be a real difference in populations, although it is more likely to be an observational bias. It is possible to detect much smaller objects in the near-Earth population than in the main-belt population, and if the distribution of taxonomic classes varies as a function of size, some classes might not be detectable in the main belt with current technology (Bell et al. 1989).

Our Fig. 2 differs from many published figures of distribution by type because it shows only the known asteroids. The true population of asteroids is much larger than the observed population, due to limitations on the number of hours available on telescopes to observe, and to the instrument limitations which define the darkest, and therefore the smallest object which can be detected. Many of the published figures, such as those in Gradie et al. (1989) have made attempts to extrapolate to the actual number of asteroids by correcting for the observational bias against dark objects. All of these extrapolations depend on the taxonomy and the assumptions used, therefore no two are alike.

III. ASTEROID SPECTROPHOTOMETRY

Much of what we know about the asteroids has been learned from telescopic spectrophotometry. The principal is very simple; different minerals absorb light at different wavelengths, producing reflectance spectra with characteristic, wavelength-dependent absorption features (see, e.g. S. J. Gaffey et al. 1992). The reflectance spectra of asteroids can be analyzed by comparing the features observed telescopically with the extensive data base of laboratory reflectance spectra of minerals and meteorites (M. J. Gaffey et al. 1989). Figure 3 shows typical reflectance spectra of some of the common minerals found in meteorites. Pyroxene and olivine are present in most meteorite types. They are readily identified by their distinctive absorption features in the near

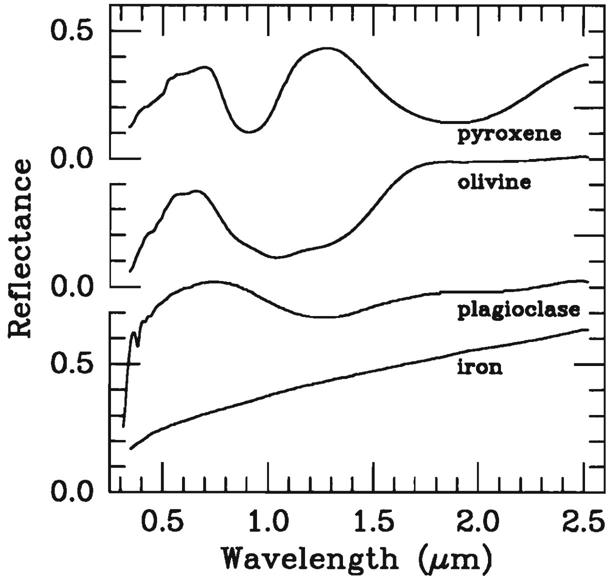

Figure 3. Reflectance spectra of pure minerals. The pyroxene is hypersthene from the Johnstown diogenite meteorite. The olivine is from the Chassigny meteorite. The plagioclase is a lunar anorthite. The metal is an iron meteorite. All of these spectra are directional hemispherical reflectance. The three meteorite spectra are from M. J. Gaffey (1976) and the lunar anorthite is an unpublished spectrum from J. Adams.

infrared. Olivine has an asymmetric absorption feature at 1 μm. Most pyroxenes have two absorption features at 1 μm and 2 μm. Laboratory studies have shown that the positions of these absorption features vary as a function of mineral chemistry (King and Ridley 1987; Cloutis and Gaffey 1991). Plagioclase is found mainly in the chondrite meteorites, the eucrite/diogenite/howardite meteorites, and in silicate inclusions in iron meteorites. It is more difficult to detect spectroscopically because of the weakness of its 1.25 μm absorption feature. Opaque components such as metal and troilite are found in most meteorite types. These compounds are difficult to detect spectroscopically because they do not produce distinct absorption features. Their presence in a mineral mixture can often be deduced from an overall lowering of the albedo and decrease in the spectral contrast. The lack of distinctive absorption features makes it impossible to determine which opaques are present from the spectra alone.

Interpretation of telescopic spectra is complicated by two factors, grain size and intimate mineral mixtures. Figure 4 illustrates the effect that grain size has on both the albedo and the depth of absorption features. These features are functions of the pathlength of the light through the mineral grains (M. J. Gaffey et al. 1992). Light is scattered out of small grains very rapidly, so the

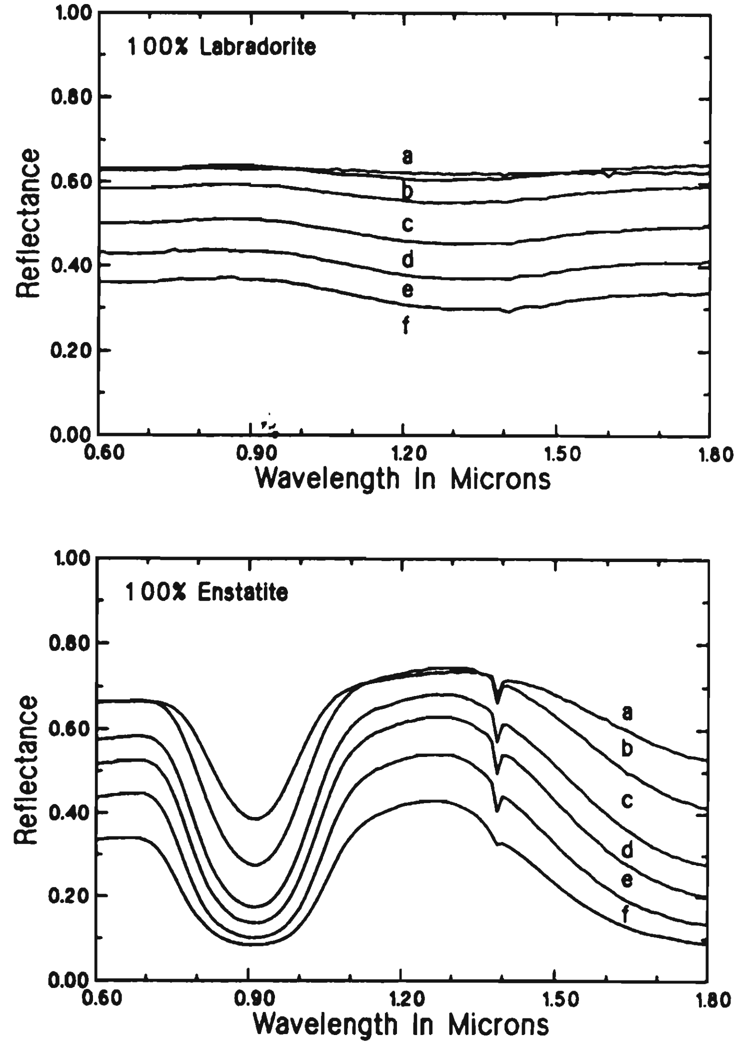

Figure 4. Bidirectional reflectance spectra (0.60 to 1.80 μm) of particle size separates of labradorite and enstatite. Particle sizes are (a) <25 μm; (b) 25–45 μm; (c) 45–75 μm, (d) 75–125 μm; (e) 125–250 μm; and (f) 250–500 μm (figure from Crown and Pieters 1987).

path lengths are short, which minimizes absorption. The path lengths in large grains are long, which maximizes absorption at all wavelengths. In addition, most natural surfaces are intimate mixtures of several minerals. The spectra of mixtures are dominated by the spectrum of the darkest component at a given wavelength, so the resultant mixture spectrum is a non-linear combination of the spectra of the individual components, as seen in Fig. 5 (S. J. Gaffey et al. 1992). Adams (1974) describes the basic approach for analyzing spectra of intimate mineral mixtures, and M. J. Gaffey et al. (1989) review most of the quantitative interpretive techniques which have been developed; they also discuss the logic involved in the application of reflectance spectroscopic

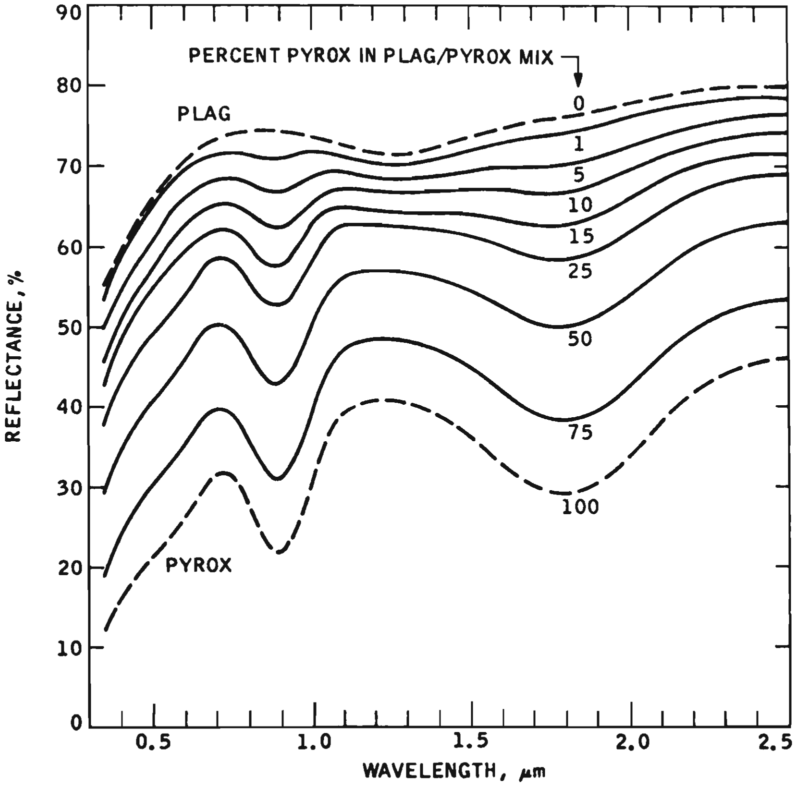

Figure 5. Reflectance spectra of a series of mixtures of labradorite (plagioclase) and hypersthene (pyroxene) (figure from Nash and Conel 1974).

techniques specifically to asteroids.

Mean (ECAS) reflectance spectra of the various Tholen asteroid classes are shown in Fig. 6. In general, these spectra lack the spectral resolution and wavelength coverage to really make compositional interpretations, but it is useful to show them because this is the dataset that was used to define the classes. The classes identify objects with similar spectra over this wavelength range, but they do not necessarily define actual compositional classes (M. J. Gaffey et al. 1989). Longer wavelength infrared data has shown that several of the classes must contain members with significantly different compositions (see, e.g., Lebofsky et al. 1990). Britt (1991) and Britt and Pieters (1991) have raised the additional possibilities that asteroids with different compositions may actually look very similar, and those with similar compositions may look very different. This will be discussed in more detail in the following section.

Comprehensive reviews of asteroid spectrophotometry have recently been published by M. J. Gaffey et al. (1989,1992). We have summarized the main points here for each Tholen asteroid class. The figures used in the rest of this section illustrate the spectral variability within each class. They include spectra from Bell et al. (1992, in preparation), and Lebofsky et al. (1990), which survey the asteriods at longer wavelengths than those used to

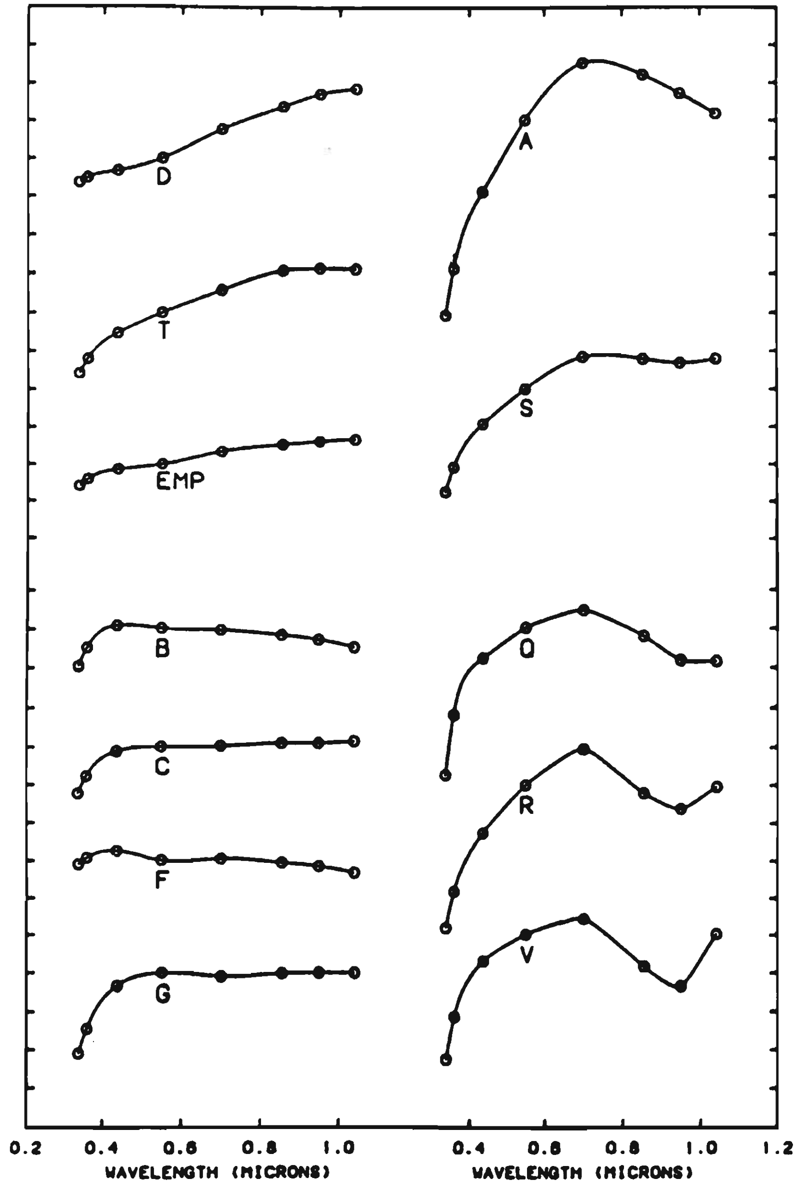

Figure 6. Mean reflectance spectra for the Tholen asteroid classes. Tick marks on the ordinate are spaced 0.2 magnitudes apart (figure from Tholen and Barucci 1989).

define the spectral classes.

A. A-Type Asteroids

Spectra of the A asteroids show an asymmetric absorption band with a minimum near 1 μm, which is characteristic of olivine (Fig. 7). The surface composition has been interpreted to be either pure olivine, or a mixture of olivine and metal, depending on the actual grain sizes and surface textures. A-type asteroids are relatively rare in the main asteroid belt, although there is some indication that they are more abundant in the population of small

(<10 km) asteroids (R. Binzel, personal communication). One A-type asteroid has been found in the near-Earth asteroid population.

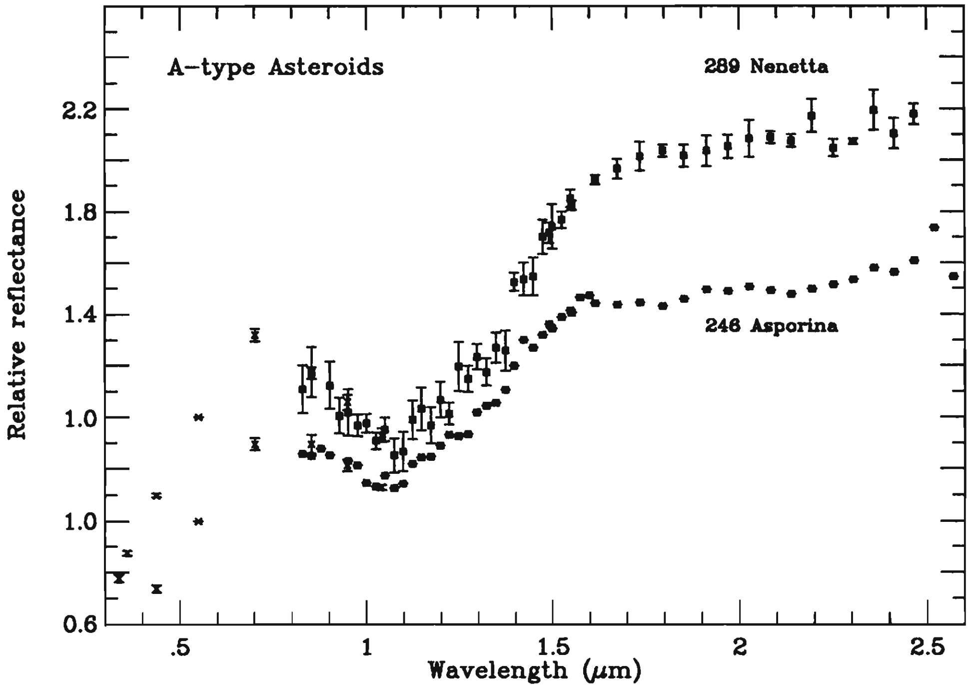

Figure 7. Reflectance spectra of two A-type asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

B. B-, C-, F-, and G-Type Asteroids

The spectra of B, C, F, and G asteroids are generally relatively flat and featureless, with an ultraviolet drop-off (Figs. 8 and 9). The types are distinguished by differences in the ultraviolet absorption. Comparison with meteorite spectra and various laboratory analogs has led to a compositional interpretation of silicate chondrules (composed of olivine and pyroxene), in a matrix of phyllosilicates mixed with carbon, organics, and opaques. Cruikshank and Brown (1987) may have spectrally detected organics on one G-type asteroid, but the observation is still unconfirmed. Clark et al. (1990) have also reported the presence of an ammonium-bearing component on Ceres, which is another G-type. Lebofsky and co-workers have surveyed these asteroid classes in the 3 *mu*m region looking for absorption features caused by water in the phyllosilicates. Figure 10 shows a few of their best spectra. The latest results from their survey work (Lebofsky et al. 1992) indicate that the phyllosilicates are hydrated on approximately half of the C-type asteroids and most of the B- and G-type asterids. No absorption features attributed to water have yet been identified on the F-type asterids. The differences in the 3 micrometer spectra amoung the C-type asteroids imply important compositional differences which are discussed in more detail in the next section, and in Lebofsky and Britt (1992). A new spectral classification by Howell et al. (1993), including the 52-color data identifies two additional sub-groups within the large C-class, but they point out that the dataset is still too small for at these wavelengths to fully define new classes. Figure 8. C-type asteroids are very common, but the other types are significantly less common, perhaps due to observational biases. All of these asteroid types are found primarily in the main asteroid belt. The relative abundance of C-types increases with semimajor axis through the main belt. One C- and one F-type asteroid have also been found in the near-Earth asteroid population.

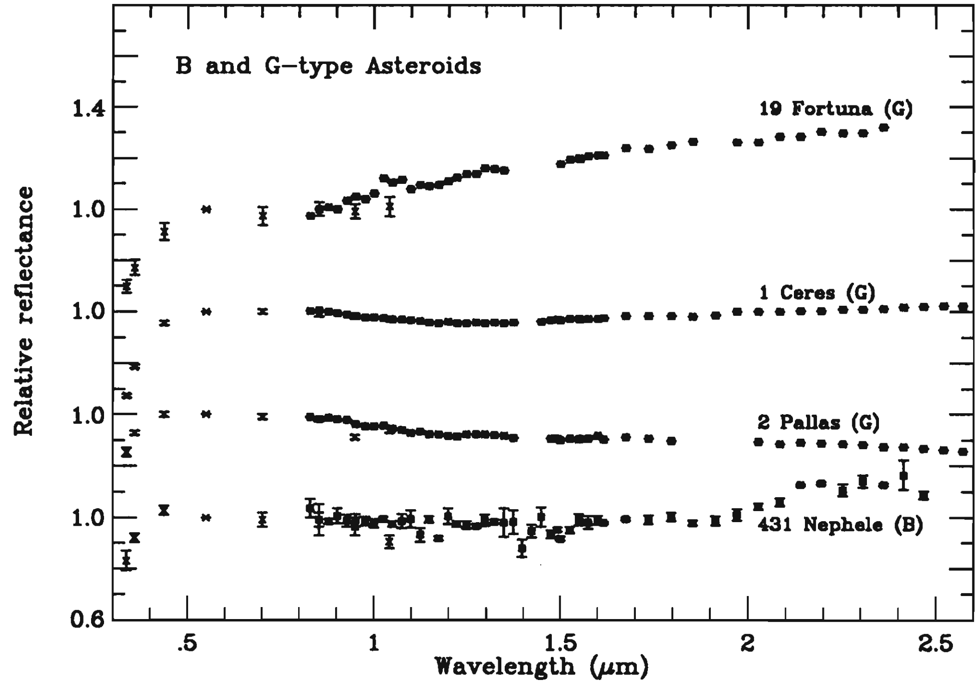

Figure 8. reflectance spectra of one B-class and three G-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

C. D-, P- and T-Type Asteroids

The spectra of D-, P-, and T-type asteroids are red sloped and featureless (Figs. 11 and 12). Lebofsky et al. (1990) observed some as yet unidentified features in the 3 μm region on asteroids of these types, but the water absorption feature has only been detected in one main-belt D-type asteroid (Lebofsky et al. 1992). These spectra are difficult to interpret, and there are no known meteorite analogs. Cosmochemical arguments have been advanced to suggest a composition of organic rich silicates, carbon, and anhydrous silicates, with

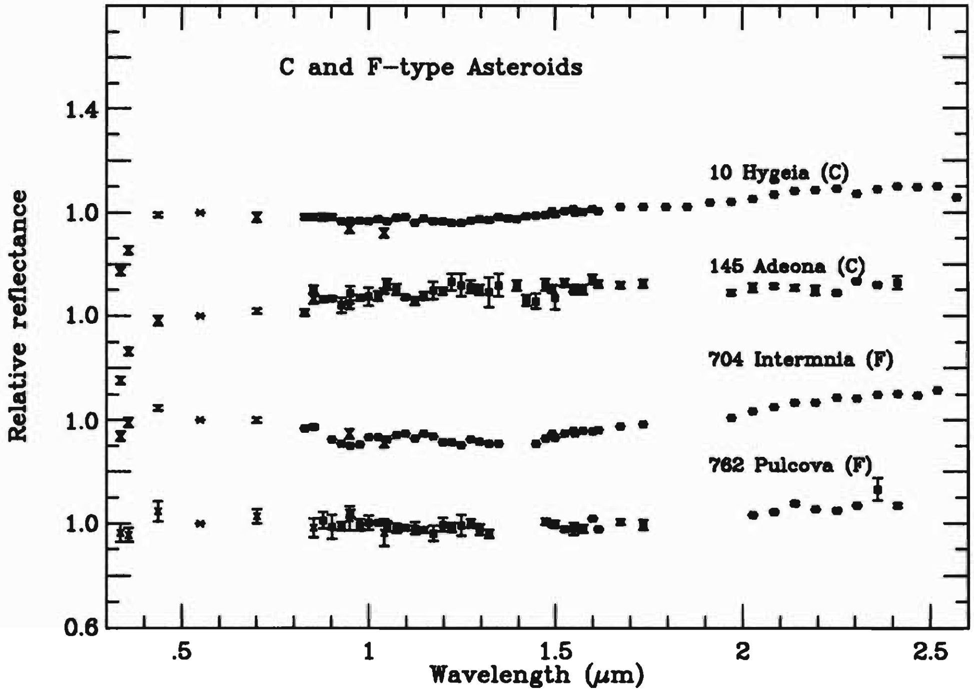

Figure 9. Reflectance spectra of two C-class and two F-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

water ice possibly preserved in the interiors (Bell et al. 1989). The D- and P-type asteroids are concentrated in the outer asteroid belt and beyond. The T-type asteroids are found in the inner main asteroid belt.

D. E-Type Asteroids

Spectra of the E asteroids are also flat and featureless (Fig. 12). They differ from those of the other spectrally similar asteroids because they have much higher albedos. Comparison with spectra of meteorites and terrestrial minerals has suggested an essentially pure enstatite composition. They are found primarily in the inner main asteroid belt.

E. M-Type Asteroids

Spectra of the M-type asteroids are also flat and featureless, with intermediate albedos (Fig. 13). Lebofsky et al. (1990) have also reported 3 μm absorption features, indicative of water on some M-type asteroids, as seen in Fig. 10. M-type asteroids have been interpreted as metal surfaces, with a possible silicate component, similar to the iron meteorites. Lupishko and Belskaya (1989) have argued based on phase functions and polarimetry that the silicates may comprise up to 50% of the surface. The water absorption feature observed in some M-types also suggests that objects with significantly different compositions may be included in this class (Lebofsky and Britt 1992). This question is still unresolved at this time. M-type asteroids are found in the main belt.

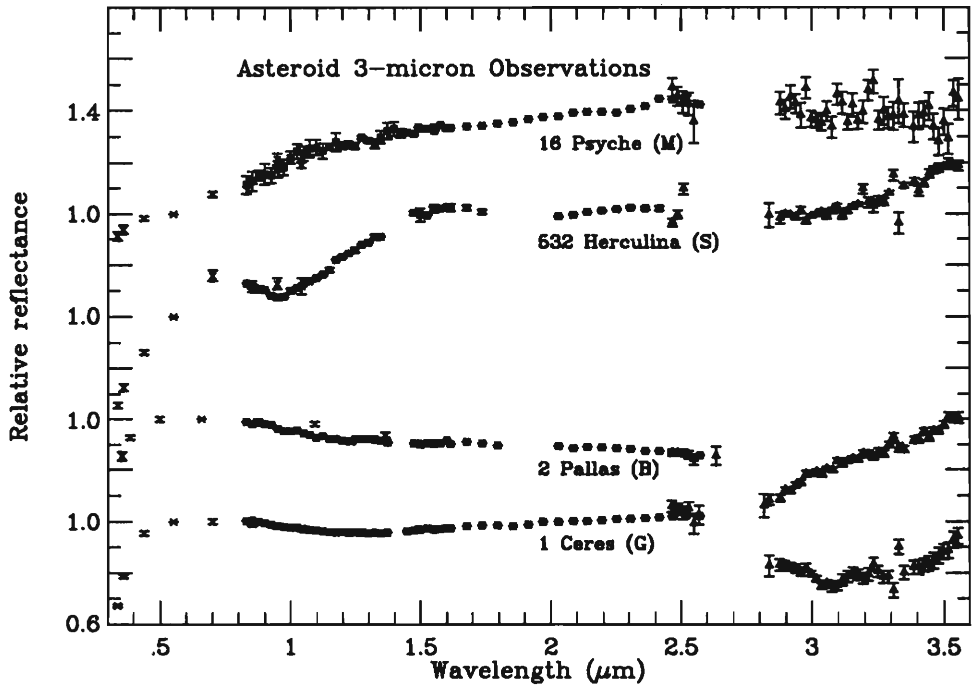

Figure 10. Reflectance spectra of two C-type and two F-type asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

F. Q-Type Asteroids

Only one Q asteroid is known to date, although three other asteroids are spectrally more similar to Q-type than any other type, so have been included in this class at this time. The significance of this class far exceeds its abundance because the Q-type asteroid is spectrally more similar to ordinary chondrite meteorites than any other asteroid type. The spectrum shows a clear 1-μm absorption feature (Fig. 6). The shape of the band indicates that both olivine and pyroxene are present, and the overall slope indicates the presence of metal. The principle Q-type asteroid is found in the near-Earth population, and the other similar asteroids are found in the inner belt.

G. R-Type Asteroids

The one R-type asteroid is spectrally very similar to the V-type (Fig. 14). The spectrum shows distinct olivine and pyroxene absorption features at 1 μm and 2 μm, with the possibility of plagioclase. The R-type asteroid is found in the main belt.

H. S-Type Asteroids

Controversy has raged for years over the composition of the S-type asteroids, and whether or not they are the parent bodies of the ordinary chondrite meteorites. This is discussed in more detail in the next section. The spectra show

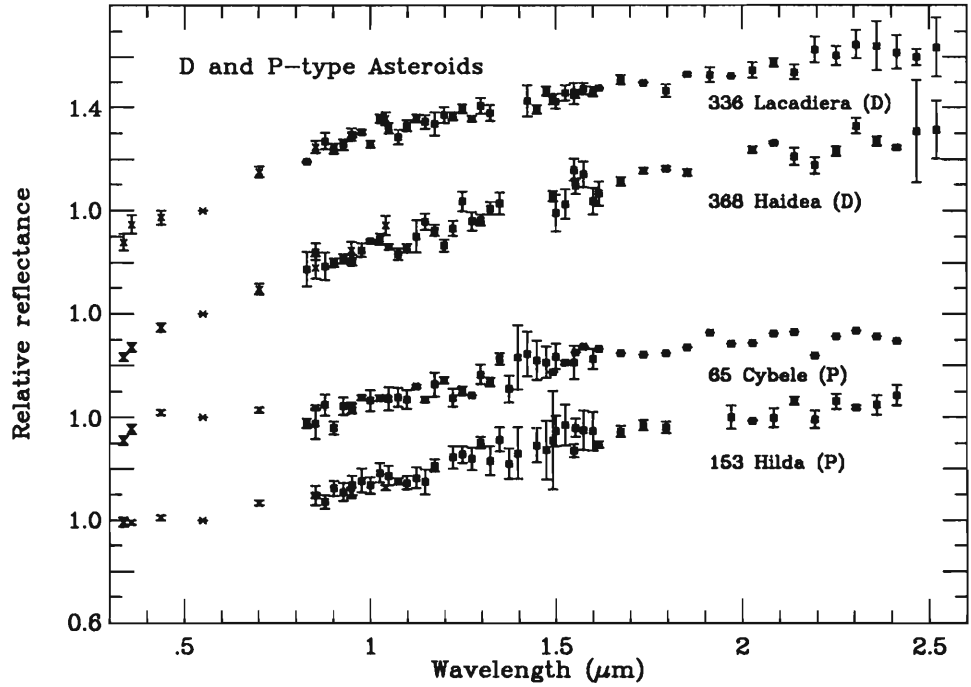

Figure 11. Reflectance spectra of two D-class and two P-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from 52-color asteroid survey (Bell et al. 1992, in preparation).

1 μm and 2 μm absorption features indicative of olivine and pyroxene, and slopes indicative of metal (Fig. 15). The spectral slopes, band shapes and band depths vary considerably within the class, which has led several authors to suggest additional subdivisions (Bell 1988; Tedesco et al. 1989; M. J. Gaffey et al. 1992; Howell et al. 1993). A consensus seems to have emerged that the S class includes asteroids with a range of compositions. S-type asteroids are found primarily in the inner main belt, and they constitute a significant fraction of the near-Earth asteroid population (Fig. 16.)

I. V-Type Asteroids

Vesta is the type example of the V-type asteroids. Until the recent discovery of several more in the near-Earth asteroid population (Cruikshank et al. 1991), it was a single member class. The spectra show clear 1 and 2 μm absorption features characteristic of olivine and pyroxene, and a weak absorption feature at approximately 1.25 μm which is indicative of plagioclase (Fig. 14). Comparison with spectra of meteorites and terrestrial analogs shows that the predominant rock type on the surfaces of the V asteroids is basalt.

IV. ASTEROID AND METEORITE RELATIONSHIPS

There are strong observational, dynamical, orbital, and spectroscopic arguments that most meteorites do indeed come from the asteroid belt and therefore

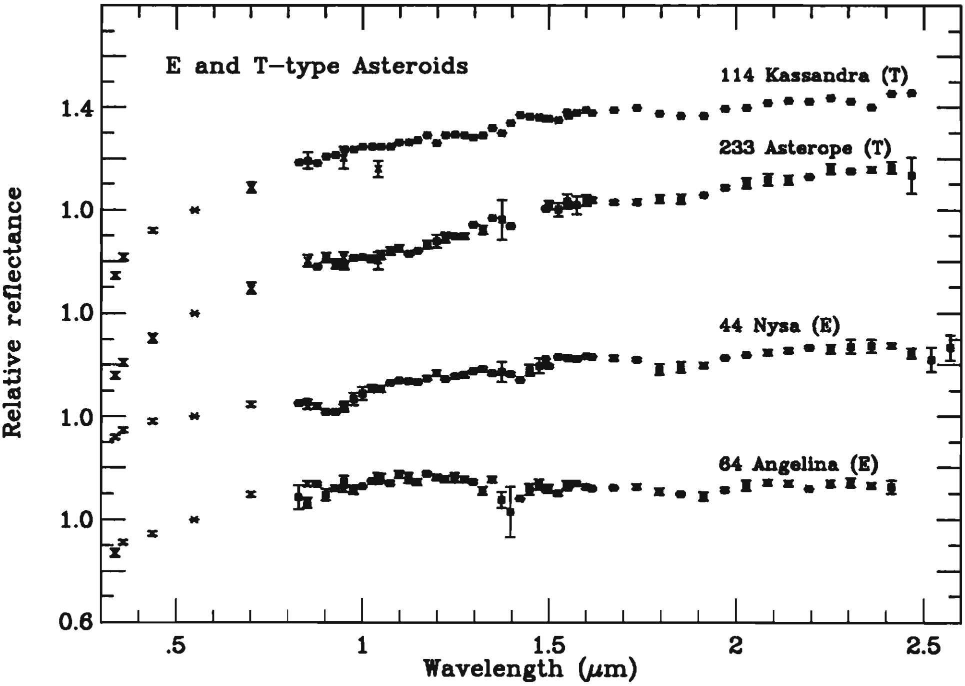

Figure 12. Reflectance spectra of two T-class and two E-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

represent samples of asteroidal material (Wetherill and Chapman 1988; Greenberg and Nolan 1989; Bell et al. 1989). These "free" samples greatly simplify the task of unraveling asteroidal mineralogy and evolution. However, even with this material, linking individual asteroid types with meteorite compositional classes is not trivial. There are several factors that combine to bias the population of meteorites arriving on Earth and therefore limit our sample of the asteroid belt. First, the dynamical processes that deliver meteorites from the asteroid belt to Earth are probably strongly biased toward sampling relatively narrow zones in the asteroid belt. Calculations suggest that the vast majority of meteorites and planet crossing asteroids originate from near the 3:1 Kirkwood gap and the ν 6 resonance (Wetherill 1985; Wisdom 1987). Both these zones are in the inner asteroid belt and probably sample primarily differentiated and relatively less primitive material (Bell et al. 1989). A second factor that introduces bias in the meteorite collection is the relative strength of the meteorites (Wasson 1985). Many meteorites begin the process of evolving into an Earth-crossing orbit by being ejected at high velocity from the parent body by a major impact (Greenberg and Nolan 1989). To survive the stress of impact and acceleration without being crushed into dust the meteorite must have substantial cohesive strength (Stoffler et al. 1988). This would strongly select against the relatively weak (and rare) carbonaceous chondrites. At the opposite extreme, the almost completely metallic

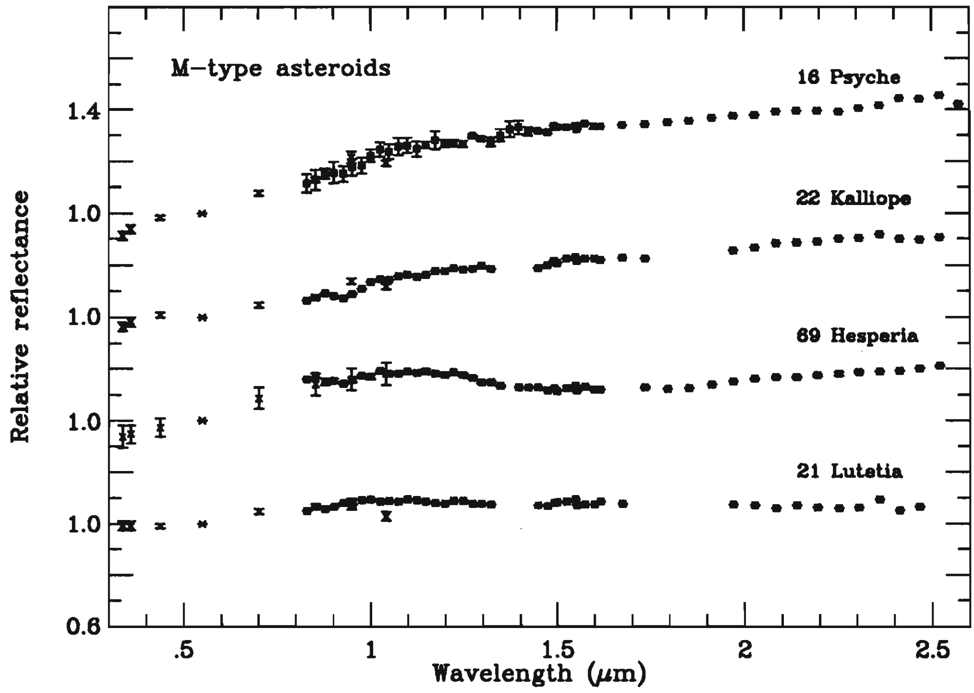

Figure 13. Reflectance spectra of four M-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

iron meteorites and the mostly metallic stony-irons have such great cohesive strength that it would be difficult to break off pieces for ejection. Cohesive strength is also an important selection factor for the meteorites that survive collisions while they are in near-Earth space and for material that survives the deceleration and heating of atmospheric entry (Wasson 1985). Data from cosmic-ray exposure ages of meteorites indicate that collisions in near-Earth space are common and that many meteorites are fragments of larger fragments that were broken up while in Earth-crossing orbits (Wetherill and Chapman 1988; Wasson 1985). Atmospheric entry usually involves a variety of thermal and dynamical stresses that typically break up most stony meteorites from one large individual into showers of much smaller stones (Wasson 1985).

Another major problem is the effect the space environment can have on the surface material of asteroids. Most of our knowledge of asteroid composition comes from the interpretation of remotely sensed reflectance spectra. Our studies of the lunar surface have shown that the spectral characteristics of the surface material, the regolith, can be strongly altered by its exposure to the impact, thermal, and radiation environment of space (Pieters et al. 1985). These regolith processes have been shown to also alter the spectra of some meteorite types, further complicating the identification of asteroid mineralogy (Britt and Pieters 1991). These selection and alteration effects introduce biases of unknown magnitude into the link between asteroids and meteorites that can

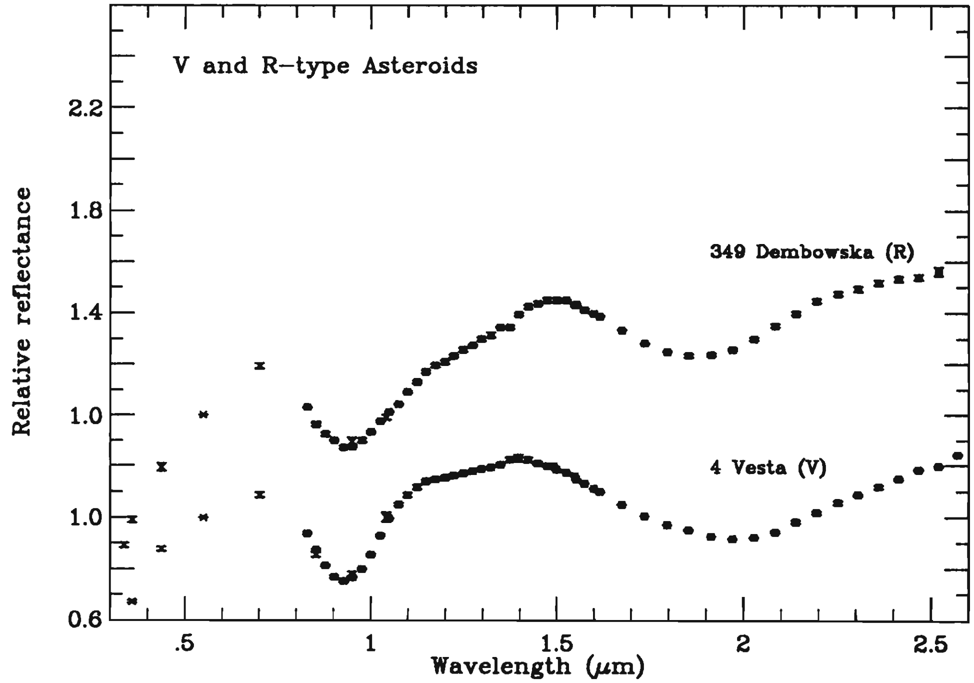

Figure 14. Reflectance spectra of one V-class and one R-class asteroid, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

limit the usefulness of the meteorite collection as a representative sample of the asteroid belt.

Any link between asteroids and meteorites must be an extrapolation of a limited and biased sample of a much larger and more complex population. With the caveats of the previous paragraphs in mind, shown in Table I are the mineralogical interpretation and possible meteoritic analogs for the Tholen (1984) asteroid classes. The organization and composition of the meteorite classes are reviewed in the chapter by Lewis and Hutson. Table I is organized in two groups, the first being asteroid types common in the inner asteroid belt (and thus more likely to have meteoritic counterparts) and the second being asteroid types common in the outer belt. The outer belt is dominated, as shown in Fig. 2, by the P and D types. The spectra of these types are dark, red to very red, generally anhydrous, and relatively featureless. No direct analogs for these asteroid types exist in the meteorite collections. The analogs most commonly cited are cosmic dust or CI carbonaceous chondrites that are enriched in organics (French et al. 1989; Lebofsky et al. 1990). However, the spectral characteristics of these asteroids are difficult to duplicate with material that is delivered to the inner solar system. Probably P and D asteroids are composed of primitive materials that have had a different geochemical evolution than cosmic dust or CI chondrites. Inner asteroid belt objects are much more spectrally varied than those of the outer belt and

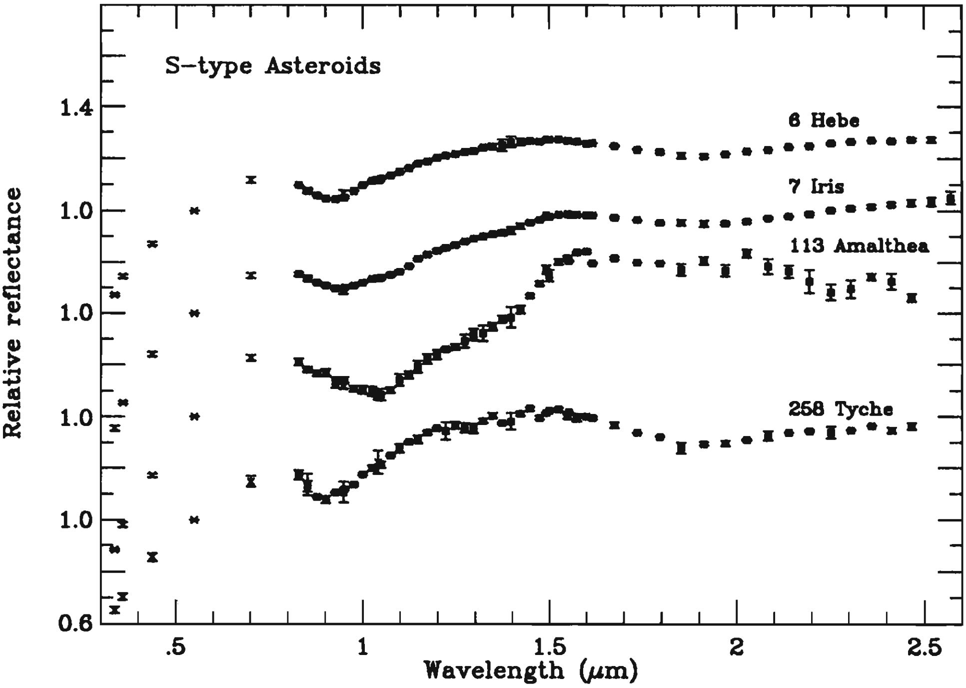

Figure 15. Reflectance spectra of four S-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

include materials which have probably been heated to some degree. This variable heating probably produced varying degrees of alteration, ranging from aqueous alteration by migrating fluids, through thermal metamorphism, to melting and differentiation. The degree of alteration is thought to be a function of composition, radius, and heliocentric distance (Bell et al. 1989).

Perhaps the best asteroid/meteorite spectral match are the V-type asteroids (Fig. 10) with the basaltic achondrite meteorites (McCord et al. 1970; Cruikshank et al. 1991). Spectrally V-types are interpreted to be a differentiated assemblage of primarily orthopyroxene with varying amounts of plagioclase (M. J. Gaffey et al. 1989), which makes them very close analogs to the basaltic howardite/eucrite/diogenite (HED) association of meteorites. The petrology of these meteorites indicate that they are basaltic partial melts originating on asteroids that underwent extensive heating and differentiation. Thus, these meteorites probably represent the surface melts and upper-crustal rocks of a differentiated asteroid (Dodd 1981). In addition, similarities in petrology, chemical trends, and oxygen isotopes suggest that all the HED meteorites are closely related and probably come from a single parent body. Fragments of what once may have been the V-type parent body may have been identified in near-Earth space. Cruikshank et al. (1991) have recently identified three V-type asteroids in Earth-crossing orbits. These objects have almost identical V-type spectra, have spectral features that suggest they are rocky fragments, and are small enough (<4 km in diameter) to be fragments of the crust of a

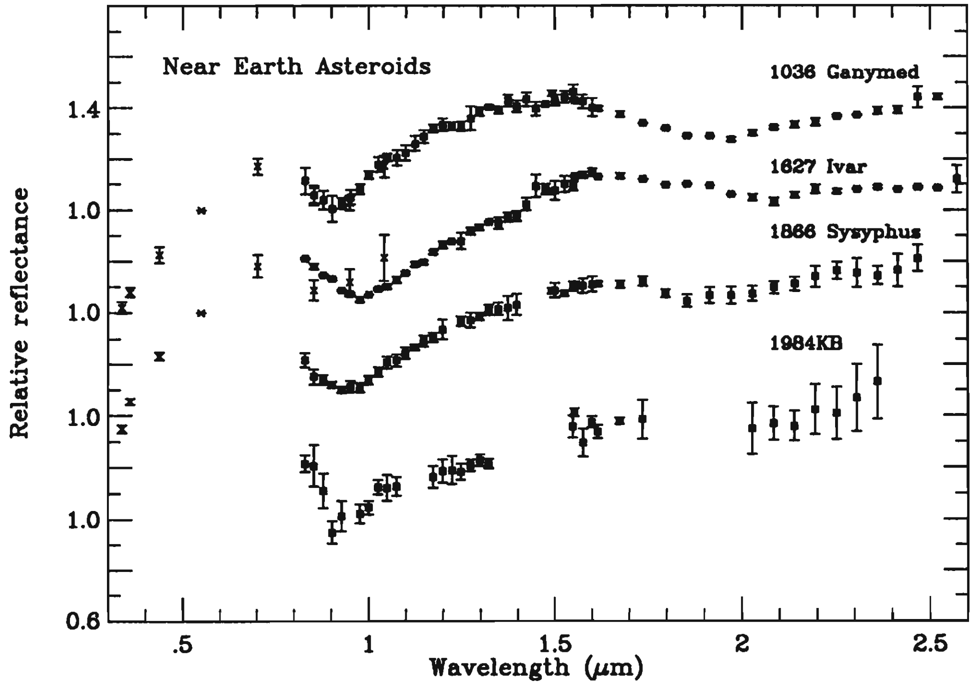

Figure 16. Reflectance spectra of four near-Earth S-class asteroids, scaled to 1.0 at 0.55 μm. The x's are data from the ECAS survey (Zellner et al. 1985) and the squares are data from the 52-color asteroid survey (Bell et al. 1992, in preparation).

disrupted differentiated asteroid (Cruikshank et al. 1991). Interestingly, their orbits are very similar, suggesting that they were all part of a larger fragment that was collisionally disrupted while in an Earth-crossing orbit. In addition, the orbits of these near-Earth asteroids may be related to the peak fall times for HED meteorites. This may be a case where the study of meteorite chemistry, spectra, and fall statistics has come together with remote sensing and orbital dynamics to describe the origin, evolution, and current location of a major meteorite parent body.

The A-types are thought to represent the next lower zone of a differentiated asteroid (Fig. 7). These asteroids are interpreted to be nearly pure olivine and may be derived from the mantle of extensively differentiated parent bodies (Bell et al. 1989; Cruikshank and Hartmann 1984). The best meteorite analog for this interesting asteroid type are the extremely rare brachinites. The 200-gram meteorite Brachina is the only non-Antarctic member of this type. This points up what some workers (see, e.g., Bell et al. 1989) have termed "the great dunite shortage." If some asteroids are really differentiated then there should be, along with the identified fragments of crust (V-types) and core (M-types) material, a substantial amount of mantle material, that is olivine-rich, dunite-like rocks, in the asteroidal and meteorite populations. However, A-type asteroids are relatively rare and dunite-like meteorites are very rare. Another suggested meteorite analog for the A-type asteroids are the

TABLE I

Inner Belt Asteroids

Type	Interpreted Surface Mineralogy	Meteorite Analogs
V	Pyroxene, feldspar	HED association
A	Olivine or olivine-metal	Brachinites
S	Metal, olivine, pyroxene	Pallasites, mesosiderites CV/CO chondritex (K-type), ordinary chondrites
M	Metal, trace silicates (enstatite?)	Irons (enstatite chondrites?)
R	Pyroxene, olivine	none
B,C, F,G	Hydrated silicates, carbon, organics, opaques, shock-darkened silicates?	CI, CM chondrites, black/gas-rich ordinary chondrites?
Q	Olivine, pyroxene, metal	Ordinary chondrites
E	Enstatite	Enstatite achondrites
T	Organic-rich silicates, carbon	none

Outer Belt Asteroids

Type	Interpreted Surface Mineralogy	Meteorite Analogs
D	Organic-rich silicates, carbon	none
P	Organic-rich silicates, carbon	none

somewhat more abundant pallasite meteorites (M. J. Gaffey et al. 1989), but they are also a suggested analog for some S-type asteroids. Another possible mantle-derived asteroid is the R-type which is a single-member class made up of the asteroid 349 Dembowska. Analysis of its reflectance spectra suggests a mineralogy that contains both olivine and pyroxene and may be a partial melt residue of incomplete differentiation (M. J. Gaffey et al. 1989). Unfortunately the meteorite collection contains no potential analogs for this mineralogy.

A more common asteroid type are the M-types (Fig. 13) which have the spectral characteristics of almost pure metal assemblages and are direct analogs to the metallic meteorites (M. J. Gaffey et al. 1989; Ostro 1989). This material may represent the cores of differentiated asteroids. However, there is a great deal of geochemical variety in the iron meteorite population. The 13 different classes of iron meteorites suggest origins from a number of different parent bodies and/or a variety of geochemical conditions. Several M-type asteroids have been identified in Earth-crossing orbits and their metallic composition has been strongly confirmed by radar (Ostro 1989). However, water bands have been observed on two main-belt M-type asteroids (Jones et al. 1990). This strongly indicates that at least some M asteroids are not metal rich and that there may be significant mineralogical variation within the M class.

Perhaps the most complex class of asteroids is the S-type (Fig. 15). Their spectra, on average, indicate subequal amounts of olivine and pyroxene with a substantial metallic component (M. J. Gaffey et al. 1989). The standard analog for S-types are the pallasites which show an interesting assemblage of large olivine grains set in a matrix of iron-nickel metal. This indicates that some S-types may represent the core-mantle boundary of a differentiated asteroid where the silicates (principally olivine) of the mantle are in direct contact with the metallic core (M. J. Gaffey 1984,1986). However, the S-type group is very large and includes a number of objects that may not conform to this standard interpretation (M. J. Gaffey et al. 1992). A number of S-types are rich in pyroxene and may represent a larger cross section of the mantle and lower crust of an asteroid. Some S-types have lower metal contents and may be the parent bodies of ordinary chondrite meteorites. Other S-types (principally the Eos family) have already been split-out to form the K class (Bell et al. 1989). The K-type asteroids have lower albedos and flatter spectral features than most S-types and are interpreted as analogs for the CV and CO carbonaceous chondrites (Fig. 18). Because of their number, inner belt origins, and moderate albedo, the S-types are well represented in the planet-crossing asteroid population. About half of the identified near-Earth asteroids are S-types and examples of the spectra of four planet crossing S-types are shown in Fig. 16 .

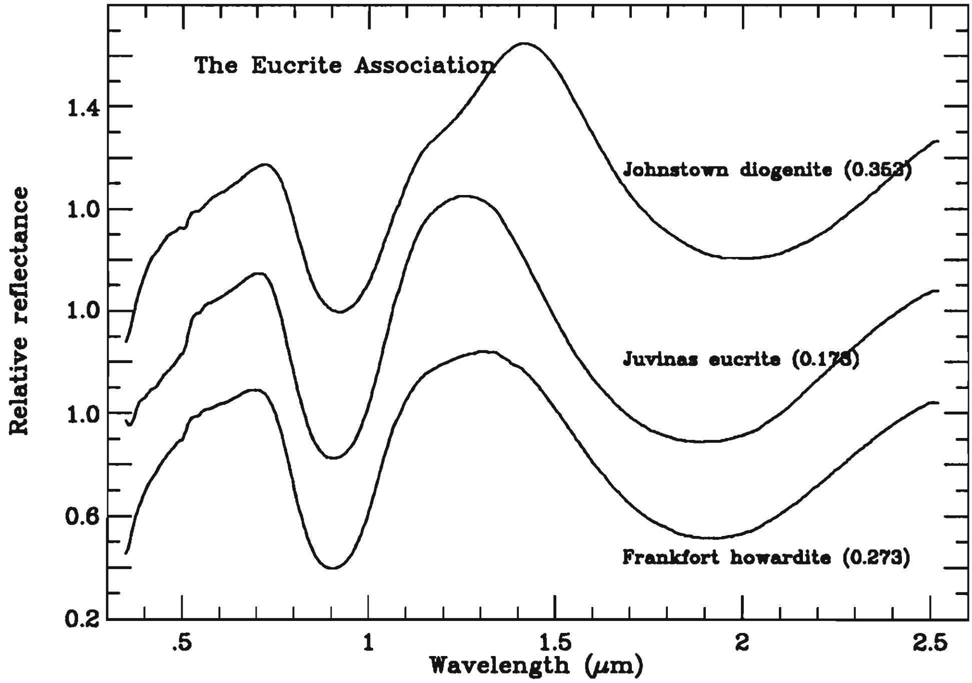

Figure 17. Reflectance spectra three eucrite meteorites from M. J .Gaffey (1976).

A long running controversy in asteroid science has been the identification of the asteroidal source of the ordinary chondrite meteorites. Ordinary

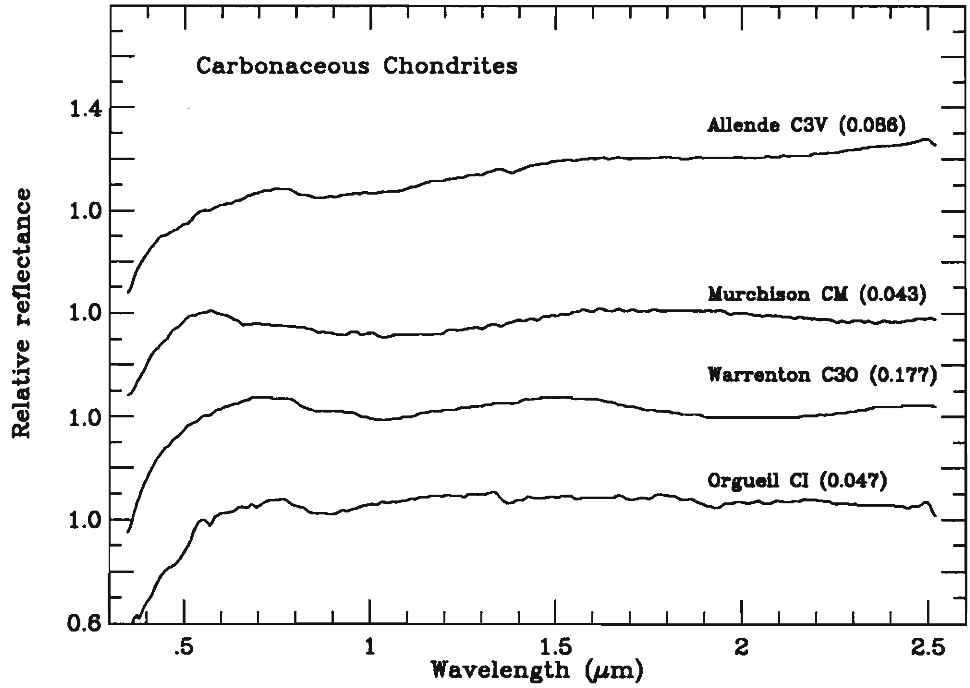

Figure 18. Reflectance spectra of four carbonaceous chondrite meteorites from M. J. Gaffey (1976).

chondrites are by far the largest meteorite type, accounting for approximately 80% of observed meteorite falls, but so far only one asteroid, the small Earth-crosser 1864 Apollo has been identified as an ordinary chondrite analog. A number of S-type asteroids have spectral absorption bands roughly similar to those of ordinary chondrites, but S-types typically have a strong red continuum slope that is not seen in ordinary chondrites (M. J. Gaffey 1986). A number of explanations for the lack of ordinary chondrite parent bodies have been put forward:

1. At least some S-types are ordinary chondrites, but regolith processes enrich the metal content of the regolith and increase their apparent spectral red slope (Bell et al. 1989).
2. Ordinary chondrite parent bodies are in the asteroid belt, but 4.6 Gyr of collisions have ground them down to sizes that are too small to see with current telescopes (Bell et al. 1989).
3. Regolith processes can darken ordinary chondrites, so their parent asteroids actually have the spectra of the dark C-type asteroids (Britt and Pieters 1991).
4. Ordinary chondrites do not even come from asteroids, but are actually cometary material (M. J. Gaffey et al. 1989).

Whatever the final answer, this subject promises to be a source of lively debate for some time in the future.

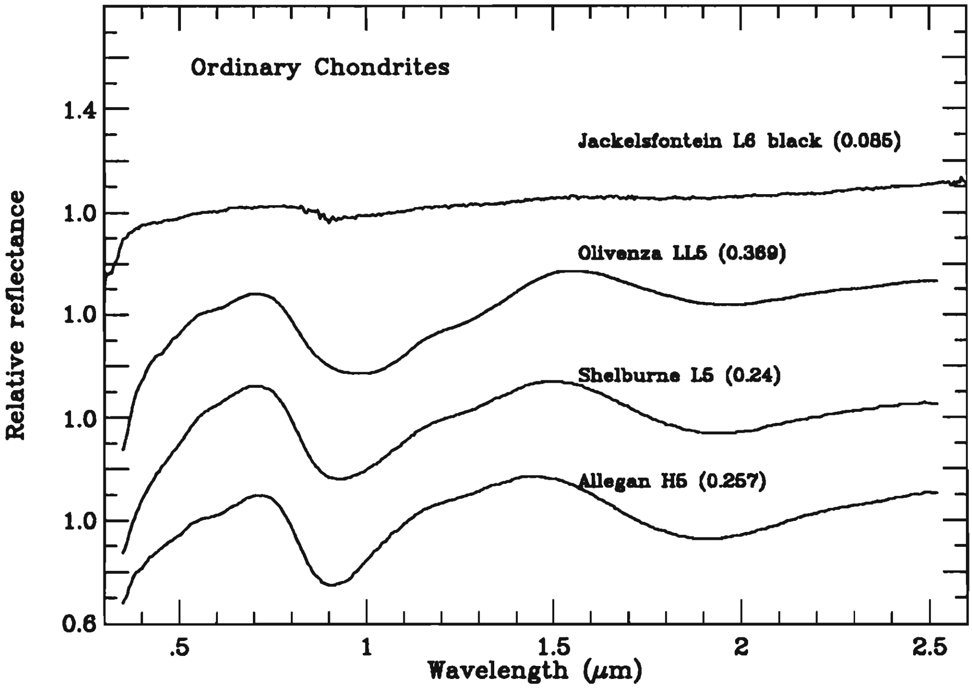

Figure 19. Reflectance spectra of four ordinary chondrite meteorites from M. J. Gaffey (1976) and Britt (1991).

In general, the differentiated asteroids of the V, A, R, S, and M types probably

represent a transect from the crust to the core of differentiated asteroids and as such they can tell us a great deal about the geochemical evolution of a differentiating body. The V-type asteroids would be the surface and crustal material. The A-types would be from a completely differentiated mantle while the R-type would represent a mantle that experienced only partial differentiation. S-types would be the core-mantle boundary with large silicate crystals directly in contact with the metallic core or more mantle material. And finally, M-types represent samples of the metallic cores of these asteroids. Metallic meteorites are shown in Fig. 20.

The dark inner belt asteroids of the B, C, F, and G types (Figs. 8 and 9) are characterized by relatively featureless flat spectra. The proposed analogs for these asteroids are the dark CI and CM carbonaceous chondrite meteorites (Fig. 18) and the spectral differences between the asteroid types are thought to represent varying histories of aqueous alteration or thermal metamorphism (Bell et al. 1989). Many of these asteroids show hydration features indicating they may be valuable sources of mineralogically bound water (Lebofsky et al. 1990). However, the compositions of these asteroid types are probably more complex than this simple model suggests. The B, F, and G types all tend to show hydration features, but at least 40% of the C-types are anhydrous

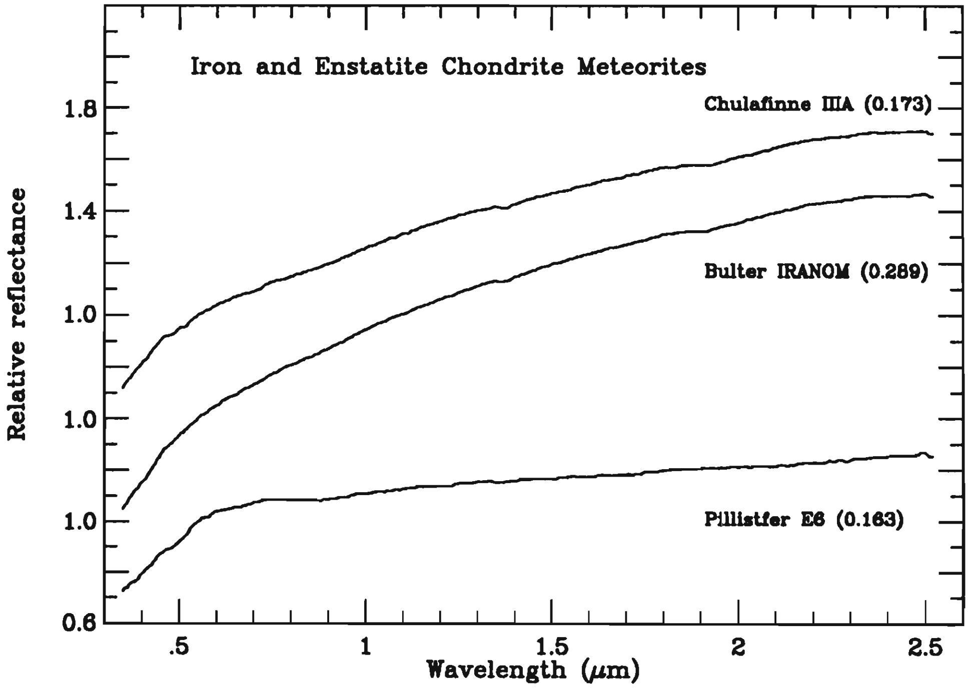

Figure 20. Reflectance spectra of two iron and one enstatite chondrite meteorites from M. J. Gaffey (1976).

(Lebofsky et al. 1990). The C-type may be, like the S-type asteroids, a collection of objects with roughly similar reflectance spectra but varying mineralogy. One suggestion is that regolith processes can darken and flatten the spectra of ordinary chondrite material, making an ordinary chondrite parent body with a mature regolith appear to be spectrally a C-type asteroid (Britt and Pieters 1991*a*, *b*). The E-type asteroids are excellent analogs for bright, red-sloped, but spectrally featureless enstatite achondrites. These asteroids are probably composed of the same differentiated enstatite assemblages as the enstatite achondrites (M. J. Gaffey et al. 1989). The T-type asteroids are something of an enigma. They are rare, probably anhydrous, inner-belt asteroids with dark, featureless, and moderately red spectra. These asteroids have no direct meteorite analogs and may be related to the P- and D-type asteroids of the outer belt (Lebofsky et al. 1990).

V. CONCLUSIONS

As we have seen in the previous discussions, there are many questions remaining about the detailed composition of the asteroids. Specifically, there are major types of meteorites for which we still do not know the asteroid parent bodies and there are major classes of asteroids for which we do not seem to have meteorite analogs. Also, because the taxonomic classes are determined solely from visual spectra, concerns have been raised as to the relationship of classes to mineralogy and the possibility that an individual class may contain asteroids of greatly differing mineralogy.

We must therefore caution any mineralogical interpretation of asteroids based solely on asteroid taxonomic classes. Until we can observe a range of classes close-up, there will remain doubts in the minds of asteroid scientists about the true compositional relationships between the various taxonomic classes and their meteorite analogs.

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