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ASTEROIDS: RELATIONSHIPS WITH OTHER SMALL BODIES

Clark R. Chapman

Southwest Research Institute, 1050 Walnut St. (Suite 426), Boulder, CO 80302, USA

ABSTRACT

Asteroids may be considered to be remnants of the populations of planetesimals that formed in the inner solar system (including the Trojans). Although there are physical and observational reasons why it has been convenient to distinguish asteroids from comets, they may actually be much more similar to each other than is generally thought. This review addresses the generic physical interrelationships among the small bodies (including small bodies like IDP's and meteorites and hypothetical bodies like vulcanoids and meteorite parent body models), emphasizing the large gaps and biases in our inventories of these populations and knowledge about their real physical characteristics. The history of planetary science, for example the study of Saturn's rings, reminds us that we should remain cognizant of how much we still have to learn about objects that are so difficult to observe and study and avoid being fooled by false extrapolations into the unknown.

INTRODUCTION

The asteroids are one portion of a diverse population of objects, including comets and meteoroids, which have given the name to the Asteroids/Comets/Meteors (ACM) meetings. Elsewhere in these proceedings there are accounts from other perspectives concerning the relationships among these small bodies. I was invited to consider the interrelationships from the perspective of *asteroids*.

My first task, inevitably, is to define just what an "asteroid" is (and what the other classes of small bodies are) and to separate out the matters of definition and taxonomy from the more substantive issues involving physical characteristics and processes. I then devote some space to how the processes of orbital, physical, and chemical evolution of small-body populations (including origin and destruction) yield interesting interrelationships among the types. For example, what are the ways in which (some) comets evolve into asteroid-like objects (of some type) and how have we been confused by our failures to appreciate some of the relevant processes?

I then briefly consider the interrelationships of asteroids with three major populations of small bodies: comets, interplanetary dust particles (IDP's), and meteorites. Throughout these discussions, I will repeatedly emphasize the importance of observational biases (including complete invisibilities) in affecting how we view these populations. For instance, an analysis involving only those small bodies that we *observe and know* yields a very different view from one that considers all the possible bodies that could exist *as allowed by observational limits*. In the latter case, we not only need to understand the errors on the observational limits but we must also apply judgements about the physical processes that are likely to be relevant so that we aren't bogged down in a solar system full of hypothetical but non-existent particles. As I will show, the history of planetary astronomy is replete with examples of how our perceptions have been changed when once-invisible populations finally became accessible to new-technology observations. With my emphasis on scientific methodology and history, I have chiefly referenced older research papers that may be unfamiliar to modern readers; I have chosen not to fill the paper with references to most very recent work, much of it reported at this ACM meeting, although I provide a general perspective on where I think the research stands in 1996.

In keeping with trends in the field, I believe that the distinctions between asteroids and other types of small bodies have become blurred in recent years and that the distinctions that have been made in the past will have less utility in the future. A proper understanding of the solar system, and indeed of planetary systems around other stars, requires that we "see" all of the small-body populations for what they are, correcting as best we can for the extreme observational selectivities imposed upon us by our location on Earth.

TYPES OF SMALL BODIES

"Asteroids" were originally defined by their appearance -- different from stars in that they moved and different from comets in that they lacked comae or tails. Of course, all of the first asteroids found had orbits with semi-major axes in what we now call the *main belt* of asteroids. Over succeeding decades, similar bodies were found in more distant orbits (including the Hildas and the Trojans). During the early half of this century, small objects with small semi-major axes and/or large eccentricities were discovered that actually crossed the Earth's orbit. Still more recently, Atens have been found with semi-major axes interior to the Earth's orbit. All of these "asteroids" could be readily separated from almost all "comets" because the latter (by definition) show at least sporadic cometary activity and have orbits that are more eccentric, and usually have larger semi-major axes, than asteroid orbits. In recent decades, physical observations have shown that asteroids are typically made of rocky minerals and metals while comets have appreciable volatiles (dominantly water ice) at or near their surfaces. Thus we came to understand that asteroids are small, devolatilized remnant planetesimals formed in the inner solar system and comets are a sample of small, volatile-rich planetesimals stored in the colder, more distant parts of the solar system; the examples of comets that we observe in the inner solar system are recently derived by chance dynamical perturbations from the invisible populations stored in outer solar system reservoirs.

The early idea of a dichotomy between asteroids and comets was reinforced by the wide separation of the storage locations due to the presence of the giant planets. So far, we know of no major stable zone of remnant planetesimals between the Trojan zones, at 5 AU, and the Edgeworth-Kuiper Belt beyond 34 AU. Until the present decade, observational difficulties (due to low illumination by the faraway sun and great distance from Earth) prevented observation of *any* objects (other than Pluto-Charon) within the outer storage locations. We only see those objects that *come from* those reservoirs; even if an object's semi-major axis is still located well beyond Neptune's orbit, it must have an exceptional eccentricity for us to see it in the inner solar system, and we see it only while it is very briefly in an exceptional inner-solar-system environment. Such rare examples of outer solar system planetesimals that we can see -- comets -- are on very different kinds of orbits from those of asteroids, even though some of the comets may have been originally formed, prior to ejection into the Oort Cloud, not far beyond the Trojans. That led to an orbital criterion (the Tisserand invariant with respect to Jupiter; Kresák, 1979) that almost cleanly separates comets from asteroids. Comets, as outer solar system objects, get into the inner solar system by crossing Jupiter's orbit whereas any main-belt asteroid unlucky enough to do so (e.g. by resonant enhancement of its eccentricity and aphelion) is no longer with us.

A physical process that further serves to accentuate the apparent differences between asteroids and comets is the rate of sublimation of water ice as a function of distance from the sun (Watson *et al.*, 1963). The dynamically depleted zone between the main asteroid belt and Jupiter's orbit corresponds to the distance from the sun where surficial water ice sublimes rapidly to where it is essentially stable on geological timescales. Thus, whatever their internal constitutions, the surfaces of asteroids -- which have spent their entire history only a few AU from the sun -- have been depleted of volatiles and thus show no cometary activity whereas comets obviously do.

In summary, we are led to a general distinction between comets and asteroids: asteroids are relatively volatile-free remnants of planetesimals formed in the inner solar system and comets are volatile-rich remnants of planetesimals formed in and beyond the outer zone of giant planets. As we shall see, however, these distinctions are partly superficial. Some outer solar system planetesimals could be volatile-poor, due to early processing, and all comets that reach the inner solar system soon become dormant or dead (i.e. more asteroid-like). Conversely, many main-belt asteroids could well be volatile-rich in their interiors. Furthermore, in physical and compositional properties, the Trojans (generally called "asteroids") might be similar to the fraction of Oort cloud comets that originated in the adjacent vicinity of Jupiter out to Saturn. Even dynamically, the distinctions are not pure: a few comets could evolve into asteroidal orbits and the Oort cloud could contain a tiny fraction of objects originating from the asteroid belt. Moreover, escaped Trojans have very similar orbits to Jupiter-family comets (H. Levison, pers. comm., 1996).

There are other types of bodies besides comets whose relationships with asteroids I will discuss. There are *smaller* bodies derived from the larger asteroids and comets. These include meteoroids and interplanetary dust particles (IDP's), which are manifest in a variety of ways (e.g. zodiacal light, dust bands and trails detected in the infrared [e.g. by IRAS] or radar, visible and radar-detected meteors, IDP's collected in the stratosphere and ocean depths, impacts onto spacecraft particle detectors). Of particular interest, because of the extent to which they can be studied by a diversity of sophisticated laboratory techniques, are meteorites -- those pieces of small bodies that survive atmospheric entry and are collected on the surface of the Earth. Many meteorites contain constituent particles (e.g. chondrules and other inclusions) which were once populations of small particles in space but are now incorporated into the meteorites.

Then there are bodies that are not really different (in origin or physical nature) from those already discussed but which are given different nomenclature for one reason or another. For example, the Centaurs are essentially comets, but their dynamical evolution has not (yet) brought any of them into the inner solar system; thus they generally do not manifest cometary behavior and, because our observational limitations permit us to see only the largest examples in the population, the known ones are quite large objects compared with typical comets and asteroids observed in the inner solar system. There are, of course, numerous orbital classifications of comets (long-period, Jupiter-family, etc.) and asteroids (Apollos, Amors, Cybeles, etc.) that serve various uses, but which will not concern us here.

Also worth mentioning are rare small bodies that are *not* comets or asteroids, *per se*. SNC meteorites, believed to be derived from Mars, are an example. Also interstellar dust and dust derived from the Jupiter system (perhaps ultimately from Io), as recently detected by Ulysses and Galileo, has connections with neither asteroids nor comets.

So far in a class by itself is Dactyl, the small satellite of the asteroid Ida, discovered by the Galileo spacecraft. Such satellites of asteroids may be found to be common, and similar circum-cometary objects may be discovered in the future. Although they are fundamentally asteroidal or cometary in their physical make-up, the fact that they are orbiting another body holds important clues concerning the physical characteristics of the parent and the origin of the bodies.

There are also various important *hypothetical* small bodies. They fall in three general categories: (a) populations of small bodies not yet detected but which might exist ("vulcanoids," interior to the orbit of Mercury, are a prime example [Leake *et al.*, 1987]); (b) populations of primordial bodies that once existed, and may be represented indirectly such as by ancient crater populations on planetary surfaces, but which have been depleted so that they no longer remain today (the Late Heavy Bombardment projectiles are an example); and (c) entirely hypothetical bodies, whose reality and relationship to other primordial or existing small bodies remain to be proved (protoplanetary or planetesimal populations are an example; meteorite parent body models, inferred from cosmochemical evidence, are another).

Beyond small bodies themselves, there are tracers of previously existing small bodies left when they encounter a planet or other object. Each crater, whether microcrater on a lunar rock or multi-ringed basin on a planetary surface, is the signature of a once-existing small body. Additionally, there are fossilized and chemical remnants and signatures. The Earth's atmosphere and oceans may represent cometary or asteroidal material from early epochs of accretion and bombardment.

PROCESSES AFFECTING SMALL BODIES

Whatever solar nebular material was *not* incorporated into the major planets and satellites remains today as small bodies -- comets and asteroids and their smaller siblings. Because there is a correlation between an object's mass and its degree of subsequent alteration and evolution, it is crudely correct to say that small bodies are generally less altered and more pristine than larger ones, and thus provide a potentially clearer look at the kinds of materials that existed during early epochs of solar system history. This is a primary reason for scientific interest in these bodies.

But no small body is entirely primitive. All of them have evolved in various ways. Evolutionary processes were particularly powerful during early epochs, although many continue even now. The earliest processing affected the nebular dust and condensates and the early generations of planetesimals -- accretion, break-up, erosion, thermal and chemical processing, dynamical evolution and orbit change, and so on.

After the planetesimals, meteorite parent bodies, protoplanets, and -- eventually -- final planets had formed, the remaining bodies were nonetheless subject to relatively intense processes of differentiation, devolatilization, catastrophic disruption and reassembly, fragmentation, and orbital evolution (e.g. resonance sweeping and capture). Nearly all of these processes are believed to have been considerably more active during the first ½ b.y. or so than since then, especially closer to the sun. There is clear evidence (in meteorites, for example) for early spike/s of heating in the early solar system, although the relative importance of the early evolution of the sun, decay of shortlived radionuclides, accretionary heating, etc. is a matter of continuing research. The sheer abundance of small bodies not yet accreted during early epochs guaranteed a higher rate of collisions and impacts, and also the probability of particularly energetic collisions, which have by now lessened considerably.

Yet the continuing evolution remains important. Even the largest asteroids are subjected to continuing bombardment, chiefly by other asteroids, at a high enough rate to produce deep megaregoliths (or even reassembled rubble piles or dispersed asteroid families). While asteroidal materials are not generally believed to have been subject to large-scale heating or endogenic processes in recent aeons, they have certainly been physically fragmented and altered by a suite of collisional, cratering, and regolithic processes, which must be understood if we are to read back through the modifications to primordial times. Collisions fragment, and often disrupt asteroids, destroying larger ones and creating smaller ones. (Since such collisions are stochastic, otherwise identical bodies may evolve quite differently and individual objects have a chance of avoiding destructive collisions altogether.) The resulting collisional cascade generates ever smaller objects, ranging down to meteoroids and dust, some of which retain (for a while) dynamical memory of their origins (as in the IRAS dust belts apparently associated with major asteroid families). But eventually small asteroidal particles become decoupled dynamically from their point of origin and join the interplanetary complex of debris, potentially indistinguishable from debris of cometary and other origins.

In addition to the physical evolution due to collisions, there is continuing orbital evolution due to resonances associated chiefly with the larger planets. Even within the seemingly stable zones of the asteroid belt, where there is a high volume density of asteroids, the action of minor gravitational perturbations and the continuing collisional evolution causes a gradual random-walk dispersal of orbits of uncertain magnitude. Near resonances, the evolution becomes much more rapid and pronounced; assisted by the large jumps possible in chaotic zones, asteroidal fragments can evolve into planet-crossing orbits and then suffer such fates as colliding with a planet, diving into the sun, or being ejected from the solar system by Jupiter.

Our goal is to try to understand the interconnections of all of these bodies which, through their orbital and physical changes, can be difficult to disentangle from cometary bodies of very different origins.

Even for bodies in the far outer solar system, which are relatively protected from energetic collisions (e.g. because relative velocities are low) and from heat sources (like the sun), the modest evolution that does proceed preferentially affects their *surfaces*; and it is characteristics of, and phenomena on or near, a body's surface that is what we *observe*. Also, as demonstrated by the ease of Comet Shoemaker-Levy 9's tidal break-up (Asphaug and Benz, 1996), comets may be very much weaker than asteroids so that even the minimal collisional environment in the Edgeworth-Kuiper

Belt may be sufficient so that comets, like asteroids, have become a population of collisional fragments rather than preserved planetesimals (Farinella and Davis, 1996).

OBSERVATIONAL BIASES

Scientists like to study what is known to exist and often become uncomfortable when dealing with hypothetical possibilities defined only by upper and lower limits. Unfortunately, in assessing populations of small bodies from our vantage point on (and near) Earth, we are fraught with major gaps in our knowledge. Since the bodies are inherently small, and generally far away, they are individually faint. Even in ensemble (i.e. as diffuse background or bands) they are difficult or impossible to observe, given current technology. The information we do have is often of an extremely diverse nature, involving very different observational techniques that are difficult to cross-calibrate.

Assessing the small particle end of the size distribution of the interplanetary dust complex has been particularly troublesome. Widely divergent measurements and interpretations of data from satellite and spacecraft dust detectors in the 1960's and early 1970's put that whole approach into disrepute from which it has only recently recovered. Another approach rests on observations of meteors and bolides, but in order to obtain such a fundamental quantity as mass, uncertain luminous efficiencies must be invoked. Wilhelms (1993, p. 210) has noted that influential scientists were "misled" just before analysis of the Apollo 11 lunar rocks about the absolute age of the Moon's surface by relying on poorly calibrated (and secret!) measurements of atmospheric shock waves due to large bolides.

Given the relatively steep (high numerical value of the index) power-law size distribution characterizing small meteoroids and dust, they present sufficient cross-section to reflected sunlight to yield a detectable zodiacal light, which constrains estimates of the population. The situation is far worse for objects ranging from meters to hundreds of meters in size (in the inner solar system) and up to hundreds of kilometers in size in the outer solar system where, until recently, observational technology precluded *any* possibility of detecting individual bodies. Assessments of the numbers of these objects have had to rely chiefly on interpreting the lunar cratering record, which has important ambiguities. The lunar surface (and more recently observed surfaces of asteroids) is literally saturated with craters made by objects of these sizes. Moreover, serious suggestions by Shoemaker (1965) that many are secondary, not primary, craters and by myself (Chapman *et al.*, 1970) that many may be endogenic have yet to be disproved. And to the degree that the craters are primary impact craters, it is virtually impossible to distinguish those made by asteroids from those due to comets.

In the absence of direct information that objects exist, observational astronomers are prone to assume that they do not exist. Since the presence or absence of objects of a particular size is so strongly dependent on the method of observation (e.g. the wavelength), great errors of omission have been made by observers assuming that what they see is all there is. This is particularly relevant to comets where traditional observational techniques were sensitive to dust (and gas) and to kilometer-and-larger scale cometary nuclei but insensitive to objects of intermediate sizes. Only recently have advances in longer-wavelength observing techniques, especially radar, finally revealed the presence of large particles near comets and along their orbits. In addition, much of the literature on comets refers to comets "of typical size" and fails to consider the potential significance of (a) very large comets (which may well completely dominate the integrated mass of comets but which are not seen inside Jupiter's orbit due to their rarity -- Comet Hale-Bopp maybe a partial exception) and (b) very small comets or comet fragments (which, if their size distribution is steeper than I think is probable, could dominate the integrated mass of comets instead of large ones). I believe there will be much more evolution in the understanding of the size distribution of comets and of the relative amounts of icy and rocky material of which comets are made. The usual apparently precise estimates of "dust-to-ice ratio" completely ignore the possibility of very different compositions of invisible, macroscopic cometary constituents remaining within the nucleus and shed from the nucleus in splitting events.

The history of estimates of Saturn ring particles is a case in point, where deductions of "mean particle size" (rather than the more likely power-law-like size distribution) were always just one or two orders of magnitude larger than the wavelength of the radiation being used to probe the rings. In the 1960's, the ring particles were believed (from visible-light photometry and Mie scattering theory) to be ~100μm in size. Following radar detection of the rings, particles were estimated (Pollack *et al.*, 1973), to be a couple of centimeters across. However, the Voyager radio occultation experiment finally revealed that most of the mass of the rings is contained in particles approaching 10 meters in diameter! When the evolution in understanding comets reaches a similar state, I have a hunch that comets could well be found to be hiding large quantities of non-volatile dirt and rocks. (Volatile chunks of the same sizes would be nearly as invisible, but if they existed they would reveal their presence by showing activity just as comets themselves do.) As icy mudballs rather than dirty snowballs, many comets may be revealed to be more "asteroidal" than is currently believed.

Some final comments on population size distributions, observational biases, and detection limits are in order. It is exceptionally important to identify the largest member of any thus-far-unrevealed population. Even statistics of one -- a single object -- can be very important (for example, see Shoemaker and Wolfe's [1982] evaluation of what was then the sole "Jupiter-crossing asteroid" (Hidalgo), taken to be the largest in a population of Jupiter-crossing extinct comets). We have all been witness to the profound impact on planetary science of the discovery of 1992 QB_1. It will be equally vital to detect the largest members of populations at 100 AU and beyond, as well as in potentially stable zones among the outer planets (e.g. Neptune Trojans) or interior to the orbit of Mercury ("vulcanoids").

When we find new populations, however, we must be cognizant of the influence of other biases. For a long time, it was believed that what we now call S-type asteroids dominated the main-belt asteroid population whereas, in fact, low-albedo asteroids dominate. Indeed, because of the same albedo bias, we are only beginning to realize that the Trojans are nearly as populous a collection of asteroids as the main belt (at any particular size, there are less than twice as many main-belt asteroids as Trojans). When we find the "top ends" of new populations, however, we must be extremely cautious in extrapolating to smaller sizes. For a long time it had been thought that a collisionally fragmenting population should reach an equilibrium size distribution with a differential power-law index of -3.5 (Dohnanyi, 1971). Since then, bias-corrected estimates of asteroids as well as observations of populations of smaller (~100 m scale) craters on Gaspra, Ida, and now even Ganymede fail to verify the expectation. If equilibrium power-laws do not apply to asteroids, they are even less likely to apply to the less-evolved populations farther out in the solar system.

COMETS AND ASTEROIDS

Accepting my working definition that comets are outer solar system remnant planetesimals and that asteroids are remnants of planetesimals formed in the inner solar system, many of the questions about relationships between the two types of bodies deal with straightforward observational issues: for example, is a particular asteroidal object really a dormant comet (like 4015 Wilson-Harrington)? The usual formulation of the problem (cf. Jewitt, 1996) assumes that a comet is icy (at least at depth) and an asteroid is not, and the observational question is whether a detectable atmosphere (coma) exists, which may or may not be true for a comet and will never be true for an asteroid. Several observational programs are exploring these possibilities.

Of course, there are objects like extinct comets and Trojans that plausibly contain ices at depth, even if their near-surfaces are devolatilized. In addition, a true asteroid (i.e. from or still in the main belt) could well show minor, or even major "cometary" activity. If primitive main-belt asteroids still retain volatiles below their surfaces (and evidence of pervasive hydrothermal activity in carbonaceous chondritic meteorites suggests that many asteroids once had such volatiles), then impacts could, at least rarely, cause venting that might make such an asteroid look like a comet. In fact, detection sensitivities are approaching limits where even iceless, differentiated asteroids may be found to have tenuous atmospheres (like the Moon's).

Conversely, some outer solar system planetesimals were conceivably subjected to sufficient early heat (perhaps from decay of ^{26}Al or other short-lived radioactive isotope or resulting from involvement in an energetic collision) to deplete them of volatiles. Wilkening (1979) suggested that comets might have ordinary chondritic (metamorphosed) or even differentiated nuclear cores, covered with icy mantles; the idea is not widely accepted, but it violates beliefs more than it violates hard evidence.

Numerous researchers, in the last decade, have searched for correlations between physical and orbital properties of NEO's (Near Earth Objects) in the hopes of discriminating dead comets from asteroid fragments derived from the main belt. While there are suites of properties that are more likely to indicate asteroidal nature than cometary nature, and vice versa, unique classifications are usually not possible for individual NEO's.

Most observations of asteroids and comets pertain to their surfaces. Evidence is now slowly mounting concerning the geophysical, bulk structure of these objects, and it seems that distinctions are beginning to blur even on this front. The historical view of comets was often as wisps in the ether, and the general insubstantial nature of comets continued to be represented in the twentieth century by Lyttleton's sandbank model. In sharp contrast, asteroids were regarded as monolithic chips of solid rock, differing from pebbles only in being much bigger. Since the original proposal of Davis and Chapman (see Chapman, 1978) that many of the larger asteroids would have a "rubble pile" structure, the evidence continues to mount that not only large asteroids but even small ones may be gravitationally bound aggregates of smaller fragments. Evidence discussed at this ACM meeting includes radar observations, modelling the formation of doublet craters, the lack of rapidly spinning asteroids, and new hydrocode modelling of asteroid break-up. Although the icy conglomerate model portrayed comet nuclei as coherent objects, Weissman's (1986) extension of the rubble pile concept to comets and later developments (most notably the break-up of Shoemaker-Levy 9) have highlighted the inherent weakness of many comets. Although the bulk properties of both classes of bodies remain poorly understood, comets and asteroids increasingly look like similar kinds of objects.

INTERPLANETARY DUST PARTICLES AND ASTEROIDS

In my view, our understanding of the complex of interplanetary dust is less mature than of comets and asteroids. This is not surprising, given the very tiny sizes of the dust, the additional forces that can move them around and modify them, and the extreme observational biases to which their study is subject. I have already mentioned above the disparate data sets and collection regions from which we have learned about IDP's (from spacecraft detectors to polar ices and seafloors).

The nominal story, presented at this ACM meeting, is that the zodiacal light can be understood as being 1/3rd asteroidal and 2/3rds cometary in origin. There are strong velocity biases, however, that favor the stratospheric collection of asteroidal particles. Some models suggest that more than half of all collected IDP's come from the Themis and Koronis families alone (primarily the Themis family). Nevertheless, researchers have yet to find any significant subgroup of IDP's that, despite some similarities, is clearly associated with any major meteorite type (D. Brownlee, pers. comm., 1996).

While the processes that deliver meteorites to the Earth select from certain portions of the asteroid belt, IDP's can be derived from the whole asteroid belt, and from other existing and hypothetical populations farther out in the solar system (Trojans, Edgeworth-Kuiper Belt objects, etc.). In the absence of any clear understanding of the physical processes that liberate small grains and dust from comets, comet trails, asteroids, asteroid families, etc., I think it is difficult to know how many of the IDP's come from what sources. As analytical techniques improve and are applicable to ever smaller samples, IDP's can begin to be considered as actual meteorites, and it thus becomes ever more important to try to link IDP's with their sources.

METEORITES AND ASTEROIDS

Since the roughly contemporaneous discovery of the first asteroids and the acceptance by the scientific community that meteorites are stones from space (cf. Marvin, 1996), it has been widely supposed that meteorites are derived from asteroids. Continuing research on meteorites has led to reasonably conclusive evidence that this is generally true (Anders, 1975, 1978). The important problem remains, however, about which of the diverse kinds of meteorites come from which asteroidal parent bodies. Since Watson's (1938) thesis, the major approach has been to try to match the spectral signature of asteroids (about the only compositionally relevant thing that *can* be measured through telescopes) with laboratory spectra of meteorites.

Apparent success by McCord *et al.* (1970) in identifying Vesta as the parent body for the eucrites and other related achondrites has not been followed up, until recently, by many other convincing cases. Indeed questions remain about Vesta, discussed at a Lunar and Planetary Institute meeting in October 1996, "Workshop on Evolution of Igneous Asteroids: Focus on Vesta and the HED Meteorites." I believe a major step forward has been taken in the last few years toward resolving a quarter-century-old problem about whether the ordinary chondrites come from (some) S-type asteroids (see review by Chapman, 1996). However, despite the general assumptions that most meteorites are derived from the 3:1 Kirkwood gap and that carbonaceous chondrites are related to C-type asteroids, few solid connections exist.

The nominal understanding is that meteorite parent bodies are roughly the size of large asteroids. Catastrophic collisions among asteroids create dispersed families of asteroids and smaller fragments, some of which can reach nearby resonances. Chaotic dynamics eventually delivers such fragments into Earth-crossing orbits. Meanwhile, collisional comminution continues, producing numerous meteoroids, which penetrate the atmosphere and are collected on the ground as meteorites. Detailed laboratory investigation of meteorites provides evidence about the body from which it was derived (size, degree of heating, solar wind exposure, presence of xenoliths [small pieces of neighboring bodies caught in the parent body's regolith], volatile content, isotopic signatures, etc.). In general, these data support formation at roughly the asteroid belt's distance from the Sun in bodies roughly like our perception of the archetypical large asteroid. A more detailed check can be made about whether the detailed mineralogy and chemical composition of the meteorite is compatible with proposed asteroidal source bodies. While groundbased spectral studies have failed to be sufficiently definitive, in most cases, there is hope that focussed spacecraft studies, for example by the Near Earth Asteroid Rendezvous (NEAR) spacecraft scheduled to orbit Eros in 1999, will provide definitive data. Perhaps it will be sufficient to bootstrap from the few spacecraft encounters with asteroids that are planned or proposed for the next decade to an understanding of other meteorite-asteroid connections based on less expensive Earth-based observations alone.

Asteroids are not the only sources of meteorites. A few meteorites have been fairly conclusively linked to the Moon (by comparison with Apollo samples) and to Mars (by comparison with Viking measurements of the Martian atmosphere, Becker & Pepin, 1984). So the question arises, why might we not have meteorites from comets? It would be extremely important to do laboratory studies of materials originally formed in the outer planet region or beyond in the Edgeworth-Kuiper Belt. Surely comets also disintegrate into fragments which presumably include non-volatile components (witness split comets and comet trails). Most comets on Earth-crossing orbits have higher intersection velocities than do most asteroids, but this is not true in all cases. So, while most cometary meteoroids would be destroyed by the high velocity entry, some cometary material would not, unless it is too fragile to survive. It is generally believed that cometary material is, in fact, very fragile; indeed, most asteroidal material may be too fragile to survive, as well, although some very weak material (which can be crushed between one's fingers) does make it through. But the fact is that we really do not know. We have prejudices about what asteroidal and cometary material might be like, but those opinions are based on data and observations subject to the enormous biases I have discussed above.

While the accepted viewpoints about the relationships between asteroids and other populations of small bodies are not obviously incorrect, the best stance to take toward small bodies is that we have much to learn and we may well be surprised many times as our Earthbased and spacebased powers of investigation progress.

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