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SPACE WEATHERING OF ASTEROID SURFACES

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■ **Abstract** Visible and near-infrared spectra of reflected sunlight from asteroid surfaces exhibit features that hold the promise for identifying surface mineralogy. However, the very surfaces that are observed by remote-sensing are also subject to impingement by micrometeoroids and solar wind particles, which are believed to play the dominant role in space weathering, which is the time-dependent modification of an asteroid's reflectance spectrum. Such space weathering has confused the interpretations of telescopic spectra of asteroids, especially concerning the possible association of common ordinary chondritic meteorites with so-called S-type asteroids. Recent spacecraft studies of asteroids (especially of Eros by NEAR-Shoemaker) have documented aspects of space weathering processes, but we still do not understand the physics of space weathering well enough to confidently assay mineralogy of diverse asteroids by remote-sensing. A review of the intellectual history of this topic reveals the complexity of interdisciplinary research on far-away astronomical bodies.

INTRODUCTION

Remote sensing is an essential approach to learning about the nature of asteroids. Asteroids are very numerous (orbits of more than 220,000 have been determined as of 2003) and they are distributed throughout an enormous volume of space, mainly between the orbits of Mars and Jupiter. Spacecraft can visit only a very few of them. Missions to date have relied on remote-sensing observations, whether during flyby, orbit, or even resting on the surface of the asteroid Eros (in the case of NEAR-Shoemaker). A few missions involving in situ analysis or sample return are in progress or being proposed. Yet the intensive studies of a few asteroids can be extrapolated to the whole population only through reliance on Earth-based telescopic remote-sensing observations.

Meteorites have been a prime resource for addressing early epochs of Solar System formation and history. However, the specific provenance of most meteorites remains unknown. A very small percentage of meteorites come from the Moon and Mars, demonstrated by comparisons with returned lunar samples or in situ measurements on Mars, although the locations of origin on those bodies are unknown. The basaltic achondritic meteorites (HEDs = howardites, eucrites, diogenites) are generally believed to have originated on Vesta (Keil 2002), but even this plausible association (based on interpretations of remote sensing) remains not proved in full. For all other meteorites, individual parent bodies remain unknown. It is possible, however, that remote sensing can help associate classes of meteorites with certain classes or groups of asteroids; for instance, analysis of reflected visible and infrared (IR) sunlight from asteroid surfaces can provide clues about the mineralogical composition of asteroid surfaces and permit comparisons with meteorites. In the decades since fledgling attempts to do this in the 1940s, final success of such endeavors remains elusive.

Processes generically called space weathering impede our ability to remotely assess the mineralogy and other attributes of the surfaces of asteroids and other airless bodies. There is the unfortunate conjunction between the immediate surface of a body that is remotely sensed and the surface that is exposed to space and hence is potentially subject to contamination or modification over long periods of time. Such changes might involve accretion or erosion of particular materials, or modification of materials in situ by energetic impacts or irradiation. I define space weathering as the observed phenomena caused by those processes (known or unknown) operating at or near the surface of an airless Solar System body that modify the remotely sensed properties of the body's surface from those of the unmodified, intrinsic, subsurface bulk of the body. Two primary questions concerning asteroids have been (*a*) is space weathering happening, and (*b*) if so, what are the physical processes responsible and exactly how are they manifested?

Space weathering processes were first recognized to be operating on the Moon in the early 1970s from comparisons of returned lunar samples with telescopic reflectance spectra (visible and near-IR) of the relevant Apollo landing sites; however, a consensus about the specific physical processes responsible for lunar space weathering has been reached only during the past decade (Hapke 2001). It is expected that similar processes must be operating on Mercury. A variety of space weathering processes affect the surfaces of Jupiter's satellites, augmented by that planet's strong magnetic field (Johnson et al. 2003). What has been less clear, and much more controversial, is the degree to which space weathering processes may be operating on asteroid surfaces, and whether they have therefore confused our interpretations of asteroid compositions.

The most salient issue associated with space weathering of asteroids concerns the relationship between the so-called S-type asteroids and the ordinary chondrites. S-type asteroids (which I define below) are the most common type of asteroid in the inner half of the asteroid belt, the zone from which we now expect most meteorites are derived. Ordinary chondrites (OCs) are the most common meteorites in our collections. (Biases of various sorts affect the relative proportions of these kinds of asteroids and meteorites, but both are very common.) It was thus surprising that straightforward application of remote-sensing techniques in the 1970s found that essentially no OCs had been measured to have the spectral reflectance characteristics of S-type asteroids (or almost any other type of asteroid), and essentially no asteroids had spectra resembling typical OCs. Thus it seemed that (*a*) there were no visible parent bodies among the asteroids for the common OC meteorites and (*b*) the common S-type asteroids were unrepresented among common meteorites in our collections. I return to this "S-type conundrum" below. The conundrum could be resolved if, in fact, space weathering is modifying the surfaces of many OC asteroids to look like S-types.

The importance of space weathering in affecting asteroid surfaces is still being debated, although there now is no doubt that it is happening to a degree. The precise nature of the process(es) responsible for it is still not agreed upon, although the broad outlines of a solution may be coming into focus. Clark et al. (2002) have written a recent review of asteroid space weathering. My goal in this review is not to dryly summarize the literature on space weathering of asteroids. Rather it is to provide a case study of remote sensing and of its role relative to other forms of inquiry in reliably indicating the true nature of distant astronomical objects for which ground truth is not readily available. I first describe some of the history of the topic before analyzing the current state of the field.

DISCOVERY OF LUNAR SPACE WEATHERING

Early in applying quantitative remote sensing observations to asteroids, astronomers realized that their colors were varied (Bobrovnikoff 1929), and it was hoped that color observations (or more detailed reflectance spectra) of asteroids could relate them to meteorites by comparison with laboratory reflectance spectra of meteorites. These efforts, in the 1940s through 1960s, were impeded by (*a*) the imprecision of the early asteroid and meteorite measurements (because the color differences are rather subtle) and (*b*) the rather undiagnostic filters that became standardized in post–World War II astronomical photoelectric photometry (the UBV system). (The pre-1970 work is reviewed by Chapman et al. 1971.) Both situations improved in the 1970s when extensive libraries of visible and near-IR spectra were obtained for crushed/powdered samples of meteorites (cf. Chapman & Salisbury 1973, Gaffey 1976) and 24-color spectral reflectance data were obtained for 277 asteroids (Chapman et al. 1973, Chapman & Gaffey 1979).

Spurred by the impending Apollo landings on the Moon, the first serious application of remote sensing techniques to infer planetary mineralogy was to the lunar surface. Just before Surveyor landers returned in situ analyses of lunar composition and the subsequent return of Apollo lunar samples to laboratories on Earth, Hapke (1968) interpreted telescopic data on the optical properties of the Moon in terms of equivalent laboratory measurements of powders of terrestrial rocks and meteorites. Presciently anticipating that the solar wind might space-weather the lunar surface, his lab compared measurements of the powders irradiated with a beam of 2 keV hydrogen ions (to simulate the solar wind) with measurements of unirradiated powders; Hapke found that the irradiation greatly modified the optical properties. He concluded that the lunar surface might consist of basalts and not ordinary chondrites, a hypothesis then under debate. His conclusion turned out to be correct, but his experimental results (and those of others at the time) were clouded

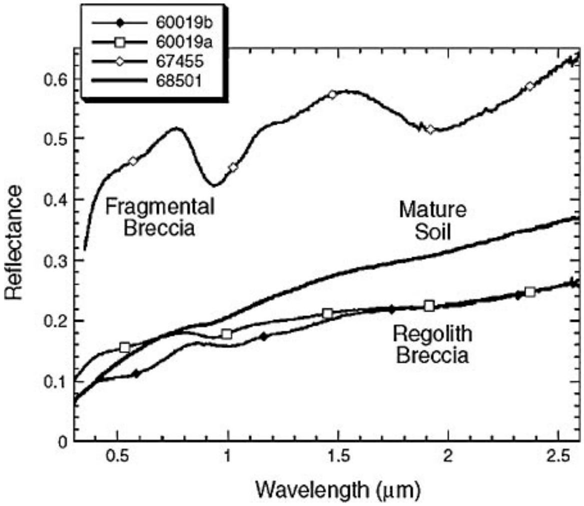

Figure 1 Spectral reflectance of lunar soil and regolith breccia versus lunar lithic fragments (fragmental breccia). The mature soil shows only the weakest hints of the deep absorption features in the spectrum of the fragmental breccia. (Courtesy Carlé Pieters.)

by issues such as contamination, which continued to plague laboratory simulations of solar wind bombardment through the 1970s. With hindsight, it is clear that nature is more complex than Hapke modeled in the 1960s, and that his pre-Apollo laboratory simulations and interpretations cannot now be considered definitive.

Returned lunar soils (which have reflectance spectra resembling telescopic spectra of lunar maria) were revealed to have optical properties that differ dramatically from those of pristine lunar rocks (Figure 1). The differences were attributed to regolith processes, such as vitrification (conversion of rocky minerals to glass within the agglutinates in the upper layers of the regolith by melting owing to hypervelocity micrometeoroid impact), a type of space weathering (Conel & Nash 1970, Adams & McCord 1971). A prominent hypothesis (Housley et al. 1973) was that the upper layers of the soil were saturated with hydrogen implanted by the solar wind, and then melted by micrometeorite impacts that reduced the iron in ferrous-containing minerals. The result was magnetized metallic iron particles of order 1 to 30 nm in size (nanophase) being created within mineral grains and modifying their optical properties. Hapke and his associates conducted experiments in the 1970s (history reviewed by Hapke 2001) that cast doubt that these specific processes, while they occurred, were responsible for the remotely-sensed spectral changes; Hapke et al. (1975) offered an alternative (and now deemed essentially correct) model of vapor deposition of nanophase metallic particles on surfaces of grains within the powdery uppermost layer of the particulate surficial regolith.

Unfortunately, for many years lunar researchers never really grappled with the Hapke et al. proposal. During a 15-year period from the late-1970s through the early-1990s, lunar research was at low ebb, and agglutinization and vitrification remained the paradigm for lunar space weathering. Because the Moon was the baseline against which asteroid space weathering issues were argued during the same period, the lunar paradigm that ignored the surficial glaze impeded resolution of the asteroid debate. Finally, Keller & McKay (1993) demonstrated that the nanophase-iron was located within vapor-deposited grain coatings (the vapor being produced by solar wind sputtering and/or micrometeorite impact); this was consistent with other newly learned attributes of lunar space weathering (reviewed by Pieters et al. 2000), such as the dominance of space weathering effects by the finest fraction of the lunar soil, indicating a surficial rather than volume-related process (Pieters et al. 1993). Vapor deposition of coatings, rich in submicroscopic metallic iron particles, onto semitransparent grains within a powdery layer of such grains—not melting and vitrification—is the key element of lunar space weathering, from a remote-sensing perspective. Opaque or packed grains inhibit the multiple scattering and reflection that otherwise augments spectral contrast and also inhibits modifications by space weathering, which is why carbonaceous materials and bare rock surfaces are expected to be less readily space weathered than powders of semitransparent grains.

The first asteroid to be well observed in 24 colors was Vesta, and its reflectance spectrum proved to be compellingly similar to laboratory spectra of certain HED meteorites, causing McCord et al. (1970) to assert that these meteorites come from Vesta. It remains widely agreed (Keil 2002), although not without dissent, that the HED meteorites come from Vesta (or from other asteroids in Vesta's dynamical family; such Vestoids are believed to be fragments ejected from Vesta by a large impact, perhaps the one that formed its giant polar crater). This promising success in associating a type of meteorite with a particular asteroid inspired hopes that meteorite/asteroid connections would be rapidly understood through further remote-sensing studies (cf. Anders 1971a), but the success has not been replicated in the subsequent three decades. Space weathering may be largely to blame. [Anders was so confident that Earth-based studies of asteroid/meteorite connections would be successful that he opposed the idea of an early spacecraft mission to Eros or other asteroids, which had a potent effect in delaying the first dedicated mission to an asteroid (when the NEAR-Shoemaker mission was finally approved a quarter-century later, its destination turned out to be to Eros); the ensuing debate about Anders' conclusions at the seminal 1970 conference "Physical Studies of Minor Planets," by G. Kuiper, H. Alfvén, H. Urey, F. Whipple, and others (published at the end of Anders 1971a) is remarkable to read.]

ASTEROID SPACE WEATHERING DEBATES

Introduction

As I recount the history of the space weathering debates below, remember that they did not occur in an intellectual vacuum confined to remote-sensing specialists alone. There was similar progress, and occasional stasis, in understanding other issues—especially small-body orbital dynamics and collisional processes—which also affect how meteorites (particularly OCs) might be derived from main-belt asteroids (particularly S-types). The question to keep in mind is, How much should specialists in one field rely on the current paradigms of another field? As Alfvén remarked in his reply to Anders (1971a), "It is obviously unreasonable to write one evolutionary history [of the solar system] for physicists and another, completely different, for chemists." But accepted hypotheses in one specialty are, of course, incompletely developed, and may turn out to be actually wrong. As we examine the history of the space weathering debates, we can learn about the dangers of either blindly accepting, or blindly rejecting, the insights from different research specialties that bear on our problem. And we must turn a self-critical eye to the uncertainties in our own specialty because our assertions can similarly affect researchers in other disciplines who wish to take into account our scientific results.

Anders (1971a,b) not only looked hopefully to remote sensing to resolve the meteorite-asteroid relationship but also to classical physics. The then-recently determined orbits for a couple of meteorites (recovered from the ground as falls, but whose incoming trajectories had been photographed) stretched into the asteroid belt, and Anders hoped that improved understanding of meteorite orbits might eventually associate meteorites with particular asteroids. Anders reflected the perspective, which was and remains common among cosmochemists, that meteorites must have originated on main-belt asteroids, and he imagined ("optimistically" in his own words) that asteroidal cratering and collisional fragmentation, followed by then-not-yet-understood dynamical processes, might well bring them to Earth.

Anders' hopes were bluntly dismissed by Alfvén (see Anders 1971a): "His hypothesis is not demonstrably supported by the laws of celestial mechanics." Alfvén suggested that cosmochemists were "neglecting the laws of physics." Wetherill (1971; at the same conference) developed the then-conventional, physics-based analysis—which may seem strange today—that OC meteorites are derived from large, dead Jupiter-family comets in Earth-crossing orbits and not from the asteroid belt at all. Wetherill appealed to the laws of physics to claim that meteorites could not possibly be derived from the Moon, Mars, or main-belt asteroids. His statements about the laws of impact-cratering physics and orbital dynamics seemed to be correct at the time. We now know, however, that physics actually does permit ejection of lunar and Martian meteorites by cratering impacts. Moreover, the first dynamically plausible "escape hatches" from the asteroid belt (Jupiter commensurabilities in the Kirkwood gaps and secular resonances affecting inner-belt asteroids) were in the process of being discovered by two of Wetherill's own graduate students, P. Zimmerman and J. Williams, just in time to make it into "notes in proofs" in both Anders (1971b) and Wetherill (1971); see also Zimmerman & Wetherill (1973).

What nobody in 1971 could have foreseen, however, was that a decade later the then-new physics of chaos would be demonstrated (Wisdom 1985) to control the dynamics of small bodies in the Solar System, especially near resonances like those studied by Williams and Zimmerman; such chaotic dynamics explains the amazingly effective way that asteroidal fragments ejected into resonances can rapidly become Earth-crossing. The "laws of celestial mechanics" had changed and Anders' optimism was justified. For another decade, those debating the origin of OCs would adopt that result and argue that OCs indeed arrived from the main asteroid belt, but only from asteroids very near narrow, selective escape hatches, so that the vast majority of asteroids still could not contribute meteorites to Earth. But the "laws of celestial mechanics" have changed yet again during the past few years as it has become understood that still another process (formally in the literature in 1971 but not in the consciousness of researchers until recently) moves far-away asteroids into the chaotic resonance zones so that small asteroids (Morbidelli & Vokrouhlický 2003), and meteorites (Vokrouhlický & Farinella 2000) throughout most of the main belt (out to ∼2.9 AU) can reach the Earth. This process is the Yarkovsky effect (cf. Peterson 1976) in which warming by sunlight of a spinning body's surface, and subsequent asymmetric thermal emission, causes the body among other things to drift in semimajor axis.

As I recount the evolution of remote-sensing studies of asteroids below, bear in mind that most meteoriticists who explicitly considered the parent-body context of their samples continued to believe throughout that abundant, large parent bodies for common meteorite types existed in the asteroid belt, regardless of the changing opinions of astronomers. Their views were buttressed by research in their own specialties, even as many asteroid astronomers relegated the OC parent bodies to very small hypothetical bodies constituting a small minority of the mass of the asteroid belt. For example, Wilkening (1977), Pellas (1988), and Lipschutz et al. (1989) were among those who pointed out that more than a third of xenolithic clasts in meteorites (meteorite fragments embedded in other types of meteorites) are OCs, which constitutes robust proof—given that any particular asteroid is in a collisional regime representing much of the asteroid belt—that OC material is very abundant among main-belt asteroids.

The S-Type Conundrum (1970s and 1980s)

Early photometry of asteroids based on photoelectric sensors (Chapman et al. 1971, Hapke 1971) revealed two predominant colorimetric groups: (*a*) those with slightly reddish sloping reflectance spectra throughout the visible out to ∼1 μm (such asteroids often display a weak absorption band near 0.95 μm and are commonly in the inner half of the belt) and (*b*) those with flat reflectance spectra (often with drop-offs into the UV, commonly located in the outer half of the main belt). Matson (1971) concurrently measured the albedos of many of the same asteroids with IR radiometry, finding that they also fell into two broad groups. It was soon realized that Matson's moderate-albedo asteroids were the same as the colorimetric group (*a*) and the very dark asteroids were those in group (*b*). Chapman et al. (1975) corrected the ever-growing sample of asteroid observations for systematic biases against darker, more distant bodies and made the first estimates of the true distributions, with both diameter and semimajor axis, for the two major classes of asteroids. They introduced the taxonomy that called the reddish, moderate-albedo (*a*) group the S-type (mnemonic for silicaceous because the 0.95 μm band had been interpreted as being due to silicate minerals) and the neutral-colored, low-albedo (*b*) group the C-type (mnemonic for carbonaceous because, by analogy with carbonaceous meteorites, the blackening agent was believed to be due to some form of the cosmically abundant element carbon). Thus began the C-S-M. . . asteroid taxonomy that has now been expanded to include most letters of the alphabet and has been further refined by many researchers (the latest taxonomy is due to Bus & Binzel 2002).

Most asteroids can still be regarded as being Ss or Cs [or at least S-like or C-like (here I include the dark but reddish Ds and Ps as C-like; they predominate beyond the main belt, e.g., among the Jupiter Trojans)]; I also discuss Ms (mnemonic for metal), Vs (chiefly Vesta and many smaller members of its dynamical family), Qs (originally thought to represent OC parent bodies), and several rare high-albedo types (Es, Rs, and As); see Figure 2. It must be emphasized that the S and C groups each display a broad range in observational parameters; certainly, a great diversity of mineralogical compositions may reside within a single group, justifying the extensions and subdivisions of the later taxonomies.

I now discuss the space weathering debates over the S-type conundrum as they have unfolded since the early 1970s (a history for 1971–1996 is in Chapman 1996). Chapman & Salisbury (1973) tried to match asteroid spectra with laboratory spectra of meteorite powders. They noticed both the similarities between S-types and OCs (e.g., absorption band near 0.95 μm) and differences (the straightened, reddish slope of S-type spectra through the visible and the diminished depth of the absorption band) and evaluated what processes might convert OCs to look like S-types. The most likely, in their view, was impact vitrification and production of dark-red glasses, which was then the leading explanation for lunar space weathering (see above discussion). But they noted difficulties, including (*a*) uncertainty whether vitrification of OC material would behave like lunar vitrification, (*b*) impact velocities in the asteroid belt that might be too low for efficient vitrification, (*c*) expected immaturity of asteroidal regoliths owing to low gravity and hence loss of most ejecta to space rather than reincorporation into the regolith, and (*d*) the apparent lack of space weathering on Vesta (otherwise a body of lunar-like, basaltic composition). Similar issues were later raised by Matson et al. (1976, 1977), again in the context of the then-accepted paradigm for lunar space weathering.

Because it thus seemed doubtful that lunar-like space weathering could rationalize the mismatches between asteroids and meteorites, Chapman & Salisbury (1973) and later researchers were nearly unanimous, for a time, that asteroid spectra had to be taken at face value and that meteorites must be derived from comparatively few asteroids, of which the OC parent bodies or their fragmentary remains were as yet not found. McCord & Gaffey (1974) emphasized quasi-quantitative methods for interpreting reflection spectra in terms of mineralogy, disdaining simple matching of spectra. They concluded that many S-types might be akin to stony-iron meteorites, noting that both the gently reddish sloping character of

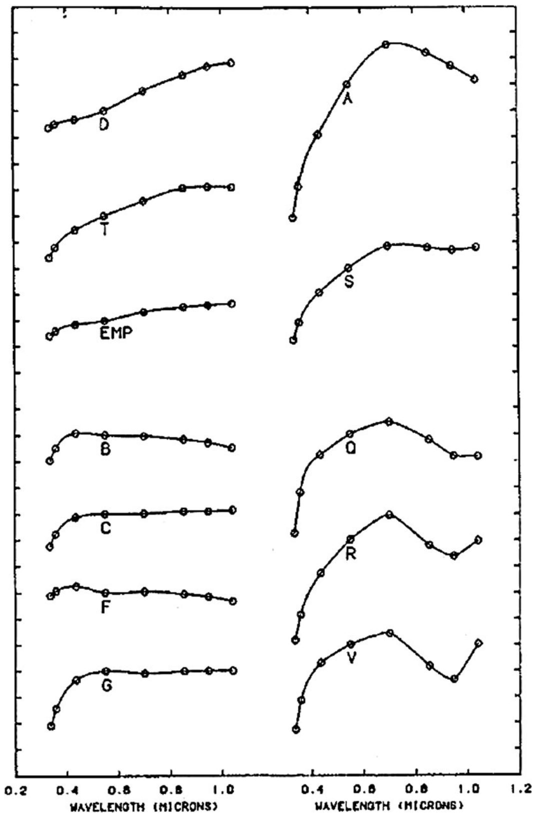

Figure 2 Spectral reflectance curves (0.35–1.1 μm) for the more common taxonomic types of asteroids. Types A, Q, R, V, and E have high albedos, types S, M, and T have moderate albedos, and the remainder have low to very low albedos. Types S, Q, R, and V have a second absorption band near 2 μm, as in the fragmental breccia in Figure 1. (Courtesy D. Tholen.)

nickel-iron [as measured in the laboratory, like that of M-type asteroids (some of which are independently known to have very high metal content from their high radar reflectance)] combined with the opacity of iron particles might, when augmented by the spectral contribution of the silicates in a stony-iron, result in a combination reflectance spectrum that is generally like that of olivine and/or pyroxene but linearized, reddened, and reduced in spectral contrast (i.e., the depth of the absorption band is reduced). Cosmochemists were not generally satisfied with ascribing the abundant S-type asteroids to stony-iron meteorites; the latter constitute only approximately 1% of meteorite falls, despite their inherent strength—a property that might even cause them to be over-represented among terrestrial meteorites compared with the abundance of the parent bodies in the asteroid belt.

Throughout the 1980s and early 1990s, Gaffey, Jeff Bell, and others developed various arguments against an association between OCs and S-types. Some S-types were interpreted as definitely being nonchondritic, some akin to carbonaceous chondrites, and others to differentiated bodies of one or another sort. Attempts to find physical processes (e.g., physical sifting and segregation of metal and silicate particles within OC regoliths) that might reconcile OCs with S-types failed; one problem is that the metal grains in OCs are neutral-colored, not reddish (Gaffey 1986). There was little dissent from the view that S-types are not OCs (a rare example is Feierberg et al. 1982) beyond some skepticism (Wetherill & Chapman 1988). In the meantime, McFadden et al. (1984) identified 1862 Apollo (a near-Earth asteroid, or NEA) as the first of what would be called Q-types, with a reflection spectrum similar to OCs. The problem is that Q-types have been identified only among the smaller NEAs (about 20% of NEAs are Q's; Binzel et al. 2002). Despite a false alarm (Binzel et al. 1993), they remain elusive among main-belt asteroids, although some spectra verging toward Q's have recently been measured among smaller asteroids near the inner edge of the belt (Burbine & Binzel 2002). In any case, a paradigm was proposed by Bell et al. (1989) that OCs are derived from yet-to-be-found, very rare, and/or very small Q-type asteroids in the main belt by what Bell [and especially Gaffey (1995)] imagined to be highly selective dynamical processes for delivery of materials to the Earth. Indeed, the influence of the Yarkovsky effect in sampling most of the asteroid belt was not yet appreciated even by dynamicists, so it was reasonable at the time to expect at least some degree of selectivity—if not as much as Gaffey and Bell demanded—in the representation of the variety of asteroid types among the meteorites.

This general picture was not really changed when Gaffey et al. (1993) began focusing on differences among the diverse S-types and identified a fraction of S-types, called S(IV)s, as having the correct silicate mineralogy to be OCs. In essence, it was expected that the properties of the two pyroxene absorption bands (near 0.95 μm and 2 μm)—their band center wavelengths and their relative strengths, defined as the ratio of band areas under an inferred continuum—should be unaffected by any space weathering process (see Figure 3). Only for S(IV)s (perhaps a quarter of all S-types) were the implications of these band properties compatible with the range of mineralogies of known OCs (LL, L, and H). Gaffey originally called the S(IV)s "least unlikely" to be OCs; his hesitancy to be more positive about a linkage was because most of the spectral differences between OCs and S-types still apply to S(IV)s: weak bands, linearized-and-reddened spectrum. Then events happened in the early 1990s that caused many researchers to look afresh at space weathering and its possible role in elucidating the S-type conundrum.

The S-Type Conundrum: The 1990s and Afterward

I have already described the reinvigorated examination of lunar space weathering processes that was underway in the early 1990s (cf. Pieters et al. 1993, Keller & McKay 1993), which provided a backdrop to new developments in asteroid

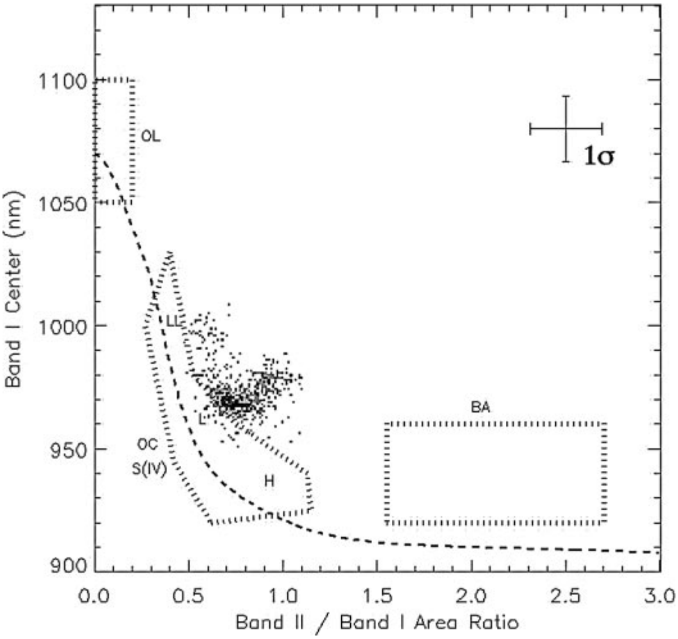

Figure 3 Band center versus band area ratio diagram for S-type asteroids (defined by Gaffey et al. 1993). BII = 2 μm band, BI = 0.95 μm band (ranging from 0.92–1.1 μm in this figure). The S(I) box, labeled as the olivine field (*OL*), is at the upper left; the S(IV) zone in the middle (with typical positions for LL, L, and H OC meteorites labeled); and the basaltic achondrite (*BA*) field is in the lower right, where S(VII) types also fall. The unresolved spread of data points are for Eros, based on NEAR-Shoemaker NIS data (Bell et al. 2002).

research. Then, in October 1991, the Galileo spacecraft obtained the first close-up pictures (including color images) of an asteroid, in this case the S-type asteroid 951 Gaspra. It had been realized before encounter (Chapman 1991), from analysis of Gaspra's absorption band position, that Gaspra [which is not an S(IV)] is too olivine-rich to be even an LL OC (the most olivine-rich type of OC). But Gaspra nonetheless provided the first spatially resolved information hinting that space weathering processes occur on asteroids. Belton et al. (1992) noted modest color differences on Gaspra, which were correlated with topography; the least reddish colors tended to be on ridges, so it was inferred that a loose regolith on Gaspra was moving downhill, leaving fresher material exposed on the ridges. Several small, fresh craters were also less red than the typical surface of Gaspra, so Belton et al. hypothesized that reddening by a space weathering process was operating on Gaspra so that only the freshest surfaces remained less reddened. Even more dramatic color differences were found on Ida (Belton et al. 1994), obviously associated with fresh impacts and their ejecta (Geissler et al. 1996,

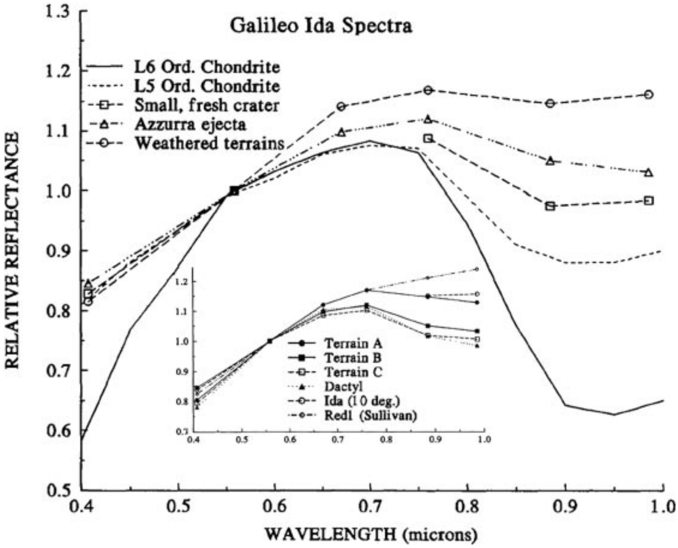

Figure 4 Spectral space weathering trends observed for different terrains on Ida. The main figure shows (from *top* to *bottom* on the *right*) weathered terrains on Ida, ejecta from Azzurra, the small fresh crater discussed in the text, an L5 OC, and an L6 OC. The inset shows data for regions discussed by Sullivan et al. (1996) plus Dactyl. The general trend of space weathering goes from starting conditions like the OC meteorites to Terrain A or even Red1.

Sullivan et al. 1996). As demonstrated by Chapman (1996), the spectral trends on Ida (Figure 4) are such that the geomorphologically freshest units (as well as Ida's small moon, Dactyl, which has likely been collisionally broken up and reaccreted in comparatively recent times) have reflectance spectra intermediate between OC meteorites and the S(IV) spectrum that characterizes most of Ida, implying that there is a process that over time modifies Ida's spectrum from something like an OC to the spectral traits of S-types. In particular, the freshest places on Ida exhibit a less red, less linear spectrum than most of Ida, and show especially deep 0.95 μm absorption bands (roughly half the depth for OC meteorite powders).

Further evidence of space weathering of asteroids, especially in the context of S-types, was reported by Binzel et al. (1996, 2002), who measured reflectance spectra of numerous NEAs, many of them smaller than the smallest main-belt asteroids for which spectra have been measured. They found, among the non-Cs, a variety of spectra ranging from OC-like (i.e., Q-types), through intermediate types, all the way to S-types (Figure 5). There is a rough correlation with size, in the sense that smaller NEAs have deeper absorption bands and hence are more OC-like; given that expected collisional lifetimes are younger for smaller objects,

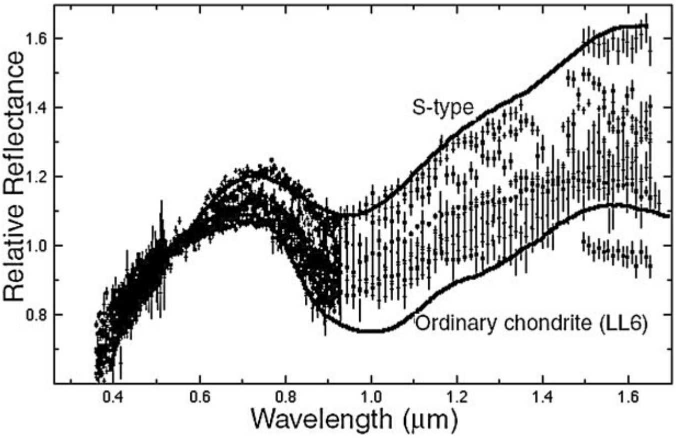

Figure 5 A continuum of reflectance spectra range from S-types to Q-types. More asteroids were observed out to 0.9 μm, and only a few to longer wavelengths. (Courtesy R. Binzel.)

it is reasonable to infer that, as a result of stochastic catastrophic collisions, some NEAs are younger than others and reflect more pristine reflectance spectra, whereas others have had time since they were created in such collisions to space weather and now look more nearly like traditional S-types. A variant on this inference is that regoliths are thinner and more short-lived on smaller bodies with minimal gravity, and that such rapid erosion of regoliths freshens smaller bodies more rapidly than bigger bodies. Very rapidly rotating, monolithic NEAs $<$150 m in size should either have no regolith or, if a powdery surface is maintained against negative-g by some other force (e.g., electrostatic), then such a powder (necessary for the Hapke space weathering mechanism to operate) should at least be eroded rapidly by small impacts; either way, one would expect such small, super-rotators to look like Qs rather than Ss (definitive reflectance spectra are difficult to measure for such nonspherical rapid rotators and have not yet been obtained). If space weathering operates similarly on NEAs and on main-belt asteroids, then a spread of Q- to S-types like that documented by Binzel et al. (1996) should be seen among small main-belt asteroids once techniques permit such small, distant objects to be measured. (It may eventually be possible to distinguish between micrometeoroid impacts and solar wind sputtering as the dominant space weathering process by comparing the mean transition diameter from S-types to Q-types for main-belt asteroids versus that for NEAs because of different impact rates and solar wind fluxes at the different semimajor axes.)

Perhaps the most significant evidence for space weathering of S-types comes from an analysis of Sloan Digital Sky Survey (SDSS) five-color asteroid colors by D. Nesvorný, R. Jedicke, R.J. Whiteley, and Ž. Ivezić (manuscript entitled "Evidence for asteroid space weathering from the Sloan Digital Sky Survey" submitted to *Astron. J.*). In an important earlier dynamical study, Nesvorný et al. (2002) showed that an asteroid within the large, old, S-type Koronis family (of which Ida is a member) broke up in a catastrophic collision very recently, exactly 5.8 million years ago, forming a family within a family called the Karin cluster. SDSS data show that Karin cluster members' reflectance spectra almost exactly mimic the spectra of Ida's fresh "Terrain C" and Dactyl (as shown in Figure 4), thus differing from typical Koronis family members (including Ida) in the direction of OC spectra. This is a particularly powerful result because the bulk material of Karin cluster members must be the same as that of Koronis family members because it was a Koronis family member that broke up to form the Karin cluster; moreover, we now have a measurement of the rate of space weathering phenomena because of the well-defined age when the fresh surfaces of the cluster members were created. Evidently, space weathering processes go at least halfway toward S-type maturity (we don't know exactly how far because we don't know the exact traits of the starting material) in several million years. Nesvorný et al. (manuscript submitted) also find a correlation between S-type colors and less robustly inferred ages of other asteroid families, consistent with asteroids maturing asymptotically to common S-type colors in several hundred million years.

The meaning of these space-weathering rates is not obvious, however. Hapke's (2001) theoretical estimate of a 50,000-year timescale for space weathering in the asteroid belt by solar wind (not even including micrometeoroids) must in reality be augmented by various relevant processes, which must differ for (*a*) Karin cluster members; (*b*) the apparently similar, partly space weathered, fresher terrains on Ida; and (*c*) Ida's moon Dactyl (similar in diameter to the Karin cluster members but in a special orbital environment around Ida). For instance, if the surfaces of Karin cluster members were originally bare rock 5.8 million years ago, rapid space weathering would first require the development of a surficial layer of dust on those objects. Indeed, the timescale to reach space weathering maturity may depend more on the timescale for developing an equilibrium regolith than for just changing colors of inert materials.

In summary, a variety of strong circumstantial evidence now exists that reflectance spectra of some OC-like asteroidal materials are being modified with time to resemble S-type asteroids. This does not mean, however, that all (or even a large fraction) of S-types are really inherently OCs. But it is plausible that other, non-C/non-OC asteroids made of different proportions of silicate minerals similar to those in OCs may also be space weathered in analogous ways, yielding (for example) linear, reddened S-type spectra with weak absorption bands, but whose absorption band centers fall outside the range of S(IV)s; the non S(IV)s are not likely to be OCs, unless space weathering processes are capable of changing band centers as well, which is not thought to be the case (see below). Less well studied are possibilities that very different mineralogical assemblages (e.g., C-like asteroids) may be space weathered to a degree. I address these issues after reviewing recent work that attempts to simulate space weathering processes.

LABORATORY MODELING OF ASTEROIDAL SPACE WEATHERING

It had long been realized that laboratory experiments might be useful in order to simulate potential space weathering processes on asteroidal materials, such as OC meteorites. But a post-Apollo decline in funding for extraterrestrial materials laboratory research, combined with the general disrepute of asteroidal space weathering, prevented continued support for such simulations. The first direct attempt to simulate space weathering of OCs was made in poorly documented experiments in Russia in the mid-1990s (Moroz et al. 1996). It appears that the experiments greatly exceeded natural irradiation, with energies, pulse durations, and pulse frequencies so great as to produce abundant melted glass (Yamada et al. 1999). Nevertheless, the Moroz et al. experiments were a wake-up call. The pulsed laser irradiation modified the reflectance spectrum of an OC meteorite to much more closely resemble an S-type spectrum, in terms of a linearized, reddened continuum, decreased spectral contrast, and slightly lowered albedo, although the resulting spectrum of the sample was not a perfect match for any S-type asteroid.

A more extraordinary result of the Moroz et al. experiments was that an attribute of reflectance spectra heretofore deemed immune from modification by space weathering, the central wavelength of the 0.9–1.0 μm absorption band, also was changed by the irradiation. Indeed, it is plausible that space weathering processes may, in general, change the apparent wavelength of that band, as it is a combined band due to a mixture of bands at different wavelengths owing to olivine and pyroxene; the central position of the combined band shifts depending on the olivine-to-pyroxene ratio (as well as the Fe/Mg ratios of the silicates). Because the optical properties of olivine are very different from those of pyroxene (e.g., olivine is more transparent than pyroxene), any alteration process is unlikely to manifest itself on the two minerals to yield a combination band with precisely the same center wavelength. This is just another of several processes (variation in band shapes and centers with temperature is another; cf. Hinrichs et al. 1999) that undercut previous assumptions that central wavelengths of bands are intrinsic (this is a central assumption of Gaffey's analysis of S-type compositions based on band-area ratios and central wavelengths).

More realistic simulations of space weathering have been done in a series of laser experiments by Yamada et al. (1999) and Sasaki et al. (2001), designed so that the pulse duration was equivalent to the effect of micrometeoroid impacts. Not only do these experiments transform the reflectance spectra of olivine (especially) and pyroxene in ways that would change OCs to look like S-types, but the tell-tale signs of the process predicted by Hapke et al. (1975) and discovered to produce lunar space weathering effects (Keller & McKay 1993) are found in the simulations: The mineral grains have become coated with vapor-deposited nanophase iron (Figure 6). If micrometeoroid impacts of the sort simulated in these experiments dominate asteroidal space weathering, then the relevant timescale for significant space weathering is calculated by Sasaki et al. (2001) to be of order 10^8 years.

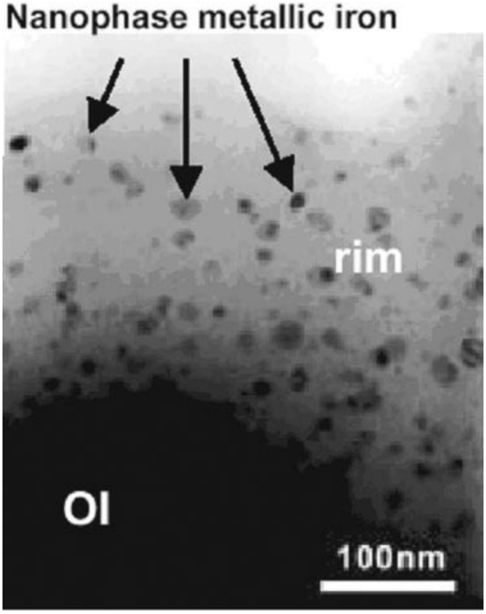

Figure 6 Nanophase iron deposits on olivine grains from a laser simulation of micrometeoroid impact. (Courtesy E. Kurahashi.)

It is very plausible that processes other than micrometeoroid impact contribute to space weathering, including all varieties of solar and cosmic irradiation. For example, Lemelle et al. (2003) have considered the damage caused to the surfaces of olivines by irradiation by 30-keV solar wind electrons, perhaps effected by electrostatic discharges breaking down the dielectric lattice. Several researchers (e.g., Kareev et al. 2003) regard micrometeorite bombardment as a minor process compared with sputtering caused by irradiation by the solar wind (perhaps especially by heavy ions; Kracher et al. 2003) or even galactic cosmic rays. Hapke (2001) calculates that solar wind bombardment would produce sufficient nanophase iron coatings to account for asteroid space weathering in only 50,000 years; but he notes that regolith churning could lengthen the real timescale appreciably.

Clearly, the detailed submicroscopic processes that can affect the optical properties of grain surfaces exposed to space are only beginning to be characterized. Inevitably, various physical, chemical, and electromagnetic properties of the grains, as well as the physical arrangement of the grains (e.g., packed, monolayer, loose fairy-castle structure) must affect their specific responses to sudden impact of electrons, ions, and micrometeoroids, as well as the ways in which sputtered atoms and vapors recondense on grain surfaces. Moreover, the optical characteristics of the grains and their physical arrangements (e.g., in very low-gravity regoliths) necessarily affect the degree to which reflected light is modified by the surficial coatings. Of course, some theoretically conceivable effects may have negligible practical manifestations. It will be the goal of future laboratory experiments and theoretical analyses to determine which effects dominate in order to figure out how to see through space weathering alteration and reveal robust remote sensing information about the intrinsic nature of the material.

Some may continue to argue that until the physics and chemistry of space weathering is fully understood, it is not proven that space weathering has occurred in any given instance of an asteroid spectrum and that the simplest assumption is to take it at face value. I think such an approach is fallacious. It is now clear that both impact and irradiation of meteorites and meteoritic minerals at energies and doses similar to those known to exist in space are very effective at modifying the optical and other characteristics of surficial grains. Not only must it be assumed that some degree of space weathering has taken place on an asteroid, until proven otherwise, but certain other verities of remote sensing (e.g., the constancy of band center positions) must also be viewed with some skepticism. Gaffey (2001) may be right that, in many cases, asteroidal space weathering is not so severe as to invalidate his band-area-ratio versus band-center approach to assay of asteroidal mineralogy, but I think this assumption must be critically reevaluated.

SPACE WEATHERING OF NONORDINARY CHONDRITIC ASSEMBLAGES

Because of the significance of the S-type/OC conundrum, most discussions of asteroid space weathering have been in that context. However, the processes of impact and irradiation that affect S-types are ubiquitous and necessarily impinge on asteroids of all types. During previous decades, there was little reason to be concerned about possible space weathering of low-albedo C-type asteroids and other dark asteroids in and beyond the main belt. The inherent opacity of carbonaceous material, which results in relatively flat, featureless reflectance spectra, prevents transmission, multiple scattering, and reflections within powders, suppressing both spectral features and any process that might modify them. More recently, however, high-quality data are being obtained of the deep absorption features near 3 μm, and high signal-to-noise data in the visible are revealing slight but important features. Some features are related to the cosmochemically important issue of whether the minerals are dry or hydrated—there appears to be a mixture of both dry and wet objects among the low-albedo asteroids. Indeed, hydrated minerals may be unusually sensitive to modification by processes like shock and space weathering (Rivkin et al. 2002). Although there has been some experimentation on space weathering of carbonaceous materials (e.g., Shingareva et al. 2003), much more needs to be done. Nesvorný et al. (manuscript submitted) suggest that there is a correlation between the colors of C-type asteroid families and inferred ages of families, implying that a space weathering process may be active.

Another space weathering issue involves the original asteroid identified as a meteorite parent body, Vesta. Given that its basaltic surface is roughly similar to the lunar surface, which is intensely space weathered, why is Vesta not? Can its environment (e.g., less solar wind flux, more rapid impact churning of its regolith) be responsible? That olivine is much more readily space weathered than pyroxene (cf. Hiroi & Sasaki 2001) helps explain why OC asteroids in the same part of the asteroid belt as Vesta would be space weathered, whereas Vesta remains comparatively pristine. Several researchers have considered that a major impact, perhaps the one that produced the giant crater at one of Vesta's poles and perhaps also its family of smaller Vestoids, might have redistributed fresh ejecta around Vesta, freshening its appearance. Such a large impact is unlikely to have happened very recently, however; moreover, most Vestoids actually look somewhat more reddened and space weathered than does Vesta itself. (Indeed Vesta's reflectance spectrum could have been modified slightly by space weathering and still be consistent with reflectance spectra of unweathered HED meteorites.) There are potential ways to address questions about Vesta, Vestoids, and their relationships to HED meteorites (e.g., a weak 0.5065 μm absorption feature of V-types may be affected by space weathering; Hiroi et al. 2001). In the meantime, despite uncertainties, there remains a consensus (Keil 2002) that Vesta, Vestoids, and HED meteorites are related. Several other relatively high-albedo asteroids with deep absorption bands (the R-type 349 Dembowska and the A-type 446 Aeternitas) must have major components of space weathered olivine, according to analysis by Hiroi & Sasaki (2001).

Many other meteorite types have major fractions of the semitransparent minerals olivine and/or pyroxene, and thus the surficial regoliths on their parent bodies would be expected to be as susceptible to space weathering as the S-, V-, A-, and R-types discussed above. Such meteorites include the stony-irons and primitive achondrites. Probably, such parent bodies are among the S-type asteroids (Burbine et al. 2002), especially those that deviate greatly from S(IV) characteristics in the band-area-ratio/band-center relationship of Gaffey et al. (1993). One must remember, however, that these band characteristics could be modified by severe space weathering in some cases, so OCs could exist among some non-S(IV)s and non-OCs among the S(IV)s.

THE PUZZLING CASE OF EROS

The NEAR-Shoemaker Mission

Although there were skeptics, there was widespread expectation in the asteroid community that the first dedicated spacecraft mission to an asteroid would finally resolve the S-type conundrum and determine the composition of an asteroid. Eros, a very large NEA, was one of the best-observed asteroids, having been the target of a telescopic observing campaign during a close approach in 1975 as well as the target of later radar observations. It was known to be an S(IV) (Chapman 1995), so there was every expectation that it would be revealed (or not!) to be a space-weathered OC by the well-instrumented spacecraft. Also of great interest were hints in spectral reflectance data summarized by Murchie & Pieters (1996) that Eros was compositionally different on opposite sides, one side being perhaps S(II) or S(III) while the other S(V).

Not only did the NEAR-Shoemaker spacecraft have a near-IR spectrometer (NIS) and a multispectral imager (MSI), like the Galileo spacecraft that studied Ida, but it also had X-ray and gamma-ray spectrometers (XRS, GRS) sensitive to chemical composition. The high spatial resolution but modest compositional capabilities of the first two instruments were neatly complemented by the poor spatial resolution but potentially excellent compositional diagnosticity of the XRS and GRS instruments. NEAR-Shoemaker orbited Eros for a full year; although NIS ceased functioning part-way through the mission and the GRS instrument had inadequate signal-to-noise during the orbital mission, the latter problem was overcome when GRS was able to collect good data after the spacecraft was unexpectedly landed on the surface of Eros at the end of the mission. Overall, the mission was very successful in obtaining the planned observations. See McCoy et al. (2002) for a succinct scientific summary of the mission, emphasizing compositional issues.

Eros is Probably an Ordinary Chondrite

The interpretation of the Eros data has been less straightforward than expected. First, the compositional differences discussed by Murchie & Pieters (1996) were evidently overinterpretations of noisy data because they are not confirmed by either the NIS or the MSI. Indeed, Eros has surprisingly uniform colors. There are essentially no detectable color variations around Eros at visible wavelengths and even the ~10% 0.95 μm/0.76 μm reflectance variations detected by the MSI are two to four times smaller than those observed on Gaspra and Ida (Murchie et al. 2002). Similarly, Bell et al. (2002) conclude that color differences on Eros are “inherently weak and difficult to detect” from analysis of over 200,000 spatially resolved NIS spectra, covering mainly the northern hemisphere of Eros; McFadden et al. (2001) find NIS spectra to be uniform to 1%–2%. (Improved NIS data reductions are discussed by Izenberg et al. 2003.) The general spectral reflectance characteristics of Eros are consistent with the S(IV) [edging toward S(III)] type that had been inferred from ground-based data, having band parameters consistent with an L or perhaps LL OC composition. In sharp contrast with Eros’ spectral homogeneity, it exhibits large albedo variations (typically on steep slopes), perhaps twice that observed on Gaspra or Ida (Murchie et al. 2002). Thus, in having small color variations but large albedo differences, Eros differs greatly from the other similarly sized S(IV) asteroid studied by spacecraft, Ida. I return to this issue below.

The XRS and GRS instruments provided compositional information never previously obtained for an asteroid. Calibration difficulties still cloud some of the results and the generality of the GRS data (essentially all from within a meter of the instrument's location on the surface of Eros) is open to question. Also, unlike the other instruments that sense the uppermost surface of Eros, the GRS integrates over depths of tens of centimeters. Nevertheless, the conclusion is clear from these two instruments—independent of any other evidence—that Eros is a cosmochemically primitive object. That is, it has roughly chondritic proportions of the elements measured, exhibiting none of the wild departures characteristic of planetary differentiation processes (e.g., the Moon, Vesta, or the various differentiated achondritic meteorites). McCoy et al. (2001) summarize and attempt to synthesize these data, including the NIS and MSI results, with the goal of obtaining a robust, unique specification of the chemical and mineralogical composition of Eros.

McCoy et al. (2001) could not obtain a fully consistent result, taking each data set and its errors at face value. For example, the Fe/Si ratios obtained by the XRS and GRS instruments are mutually inconsistent; the differences are consistent with mechanical removal of metallic Fe from OC material, possibly caused by processes responsible for forming the "pond" in which NEAR-Shoemaker landed and where the GRS measurements were made. A second inconsistency is that the XRS data tend to favor an H OC composition, whereas the NIS data favor more olivine-rich L or LL compositions. Nevertheless, with one major exception (sulfur), the analyses all favor OC compositions among known meteorite types (Figure 7) and can be reconciled with each other if the calibrations of the instruments and analysis techniques are not quite as secure as each of the investigators expects. Certain hypothetical primitive achondrites (however, not among known types of primitive achondrites), such as OC-like parent material altered by limited partial melting, is another potential solution, according to McCoy et al. (2001), and could account for some of the inconsistencies in Fe and S abundances. However, that type of processing would be unlikely to yield a compositionally homogeneous body; moreover, it is dynamically and physically unreasonable to suppose that we have no meteorites on Earth from either Eros or its parent body (cf. Bottke et al. 2002). Thus McCoy et al. (2001), while eschewing the term space weathering, "...question the basic assumption that the regolith of Eros is indicative of the composition of the underlying bedrock." They go on to conclude that the most likely analogs for Eros are OCs.

The robust measurement of minimal S on Eros (at least a factor of 2 depletion and perhaps an order of magnitude or more) suggests that something special has happened to the S, which is much more volatile than other rock-forming elements. Nittler et al. (2001), attempting to interpret their XRS data, calculate that from known rates and efficiencies for photo- and ion-sputtering and micrometeoroid impact, a centimeter-thick layer of Eros' surface should be depleted in S in only 10 million years, less than the likely time Eros has spent in its present Earth-approaching orbit (see also the calculations by Killen 2003). These authors rule out the likelihood of any other, non–space weathering explanations for the low sulfur abundance on Eros and concur with McCoy et al. (2001) that Eros is probably of OC composition.

Why is Space Weathering Different Between Eros and Ida?

Given the probability—even if not as definitive and precise as we hoped—that NEAR-Shoemaker has found Eros to be an OC, I turn again to the perplexing issue of why its color and albedo variations are so different from those of Ida, another S(IV) body for which plausible space weathering trends were identified (e.g., by Chapman 1996). These issues have been most thoroughly addressed by Clark et al. (2001), who concentrated on the prominent albedo contrasts within the large crater Psyche (Figure 8); they find albedo contrasts of order a factor of 2, but only very modest (few percent) color variations. The color variations are in the direction expected for space weathering, in that the brightest, presumably freshest, areas are slightly less red. This is confirmed by Izenberg et al. (2003) who note that the bright walls of the large crater Himeros as well as of Psyche are not only fresher in having considerably higher albedo than the crater floors or general terrain on Eros, but also in having very slightly deeper bands and less red slope. But the color differences are extremely subtle compared with those on Ida. Thus, as Clark et al. conclude, the process that space weathers Psyche's interior walls "must be a strange two-step mechanism whereby materials are reddened before darkened. . .and darkened [much] more than reddened." Indeed, the albedos of the bright areas in Psyche are similar to pristine OCs, yet their colors are nearly as maturely space weathered as Eros and S-asteroids. Most of Eros, although not as much as Ida, is globally considerably darker than OCs (or any noncarbon-bearing stony meteorite), so a darkening process is necessarily involved. For Ida, it appears that the darkening precedes the reddening [because the relatively unweathered

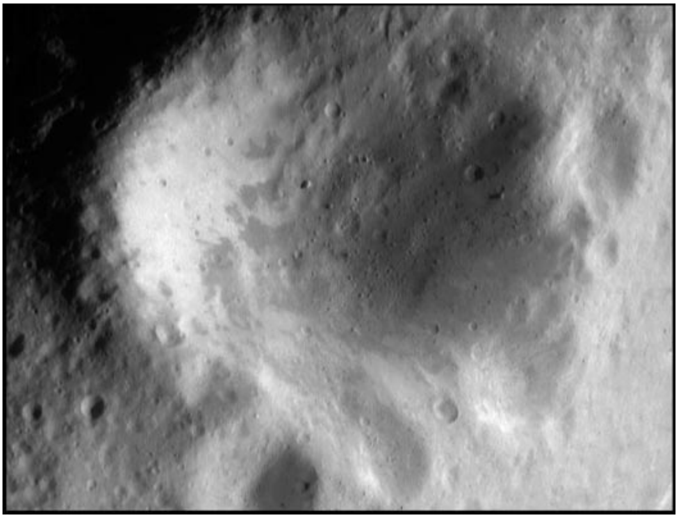

Figure 8 NEAR-Shoemaker image of the crater Psyche, showing the prominent bright features on its steep interior slopes.

units are only marginally brighter than the rest of Ida (Helfenstein et al. 1996)], but for Eros the darkening happens after the reddening. The behavior of Eros is at least qualitatively similar to the behavior of increasing amounts of nanophase Fe, as shown in figure 26 of Hapke (2001); perhaps it is the darkening of Ida that is anomalous [Ida's geometric albedo is 0.21 compared with Eros' 0.29, and its single-scattering albedo is half that of Eros (Domingue et al. 2002)].

Clark et al. (2001) and Bell et al. (2002) both attempt to model a suite of factors that might cause the effects observed on Eros. Following Hapke (2001), they model four processes or factors: (*a*) amount of submicroscopic vapor-deposited iron, (*b*) a neutral, opaque component (perhaps admixed carbonaceous material or darkening by shock), (*c*) particle size, and (*d*) composition (I've noted above that olivine is especially susceptible to space weathering; Fe composition may also be relevant because that is what is vaporized, reduced, and redeposited in submicroscopic coatings). Bell et al. find a nonunique parameter mix that reproduces the reflectance spectrum of a particular OC meteorite. Clark et al. find that the most significant parameters required to convert the bright regions in Psyche crater to common Eros reflectance properties are nanophase iron and a neutral, opaque component; but that fails to explain why the bright regions are already unexpectedly space weathered in colorimetric properties before darkening has occurred. (One idea of Clark et al., namely that shock darkening might be a factor, is implausible: Impact shock, at least by the larger impacts that are believed responsible for shock darkening of some meteorites, is a localized phenomenon and would not be expected to yield broad, global homogeneity in albedo and colors that dominantly characterize Eros.)

Assuming that Eros and Ida have the same intrinsic composition, only the space environment is different: We need not consider how processes affect diverse mineralogical assemblages differently, which is a problem when using the Moon or even Vesta for comparison. There are three major factors affecting space weathering on Ida and Eros: (*a*) solar wind flux, which is reduced roughly an order of magnitude in the asteroid belt compared with Eros' present position [in which it probably has resided for many tens of millions of years (Michel et al. 1998)]; (*b*) micrometeoroid impact rates, which are roughly similar near Earth and in the asteroid belt (but velocities are higher closer to the Sun); and (*c*) large impacts that churn and cover over the regolith, which are at least two orders of magnitude more frequent in the asteroid belt (but this ratio in impact flux may vary considerably with impactor size). If the size distribution (but not flux) of impactors, ranging from cratering impacts down to micrometeoroids that space weather the surface, was invariant with semimajor axis and was the only factor affecting both space weathering and geological evolution of an asteroid's surface, then Ida and Eros should appear the same, within normal stochastic limits. But they don't.

One of the more puzzling differences is that downslope movement appears to freshen the interior surfaces of Eros' large craters during a period in which few, if any, small fresh craters form. One might expect that mass-wasting is episodic, triggered by seismic shaking by large and/or nearby impact cratering events. But there is no analog on Eros of even the small, less-weathered craters that dig through the regolith and produce bluish spots on Ida. Perhaps something other than shaking by impact is responsible for downslope movement on Eros (e.g., diurnal thermal changes, but Ida also spins like Eros). D. Nesvorný (personal communication, 2003) suggests that tidal forces caused by Eros' frequent approaches to terrestrial planets may induce downslope mass-wasting following each such encounter. [Cheng et al. (2002) have considered how shaking of Eros can induce mass-wasting and formation of "ponds".]

Chapman et al. (2002) have suggested that part of the difference between Ida and Eros could be explained simply by the relocation of Eros, during the past several tens of millions of years, into an environment where large impacts occur at least 100 times less frequently, whereas space weathering by solar wind impingement is augmented. Major impacts (like the one that formed the crater Azzurra), which originally distributed the not-yet-maturely space weathered ejecta on Ida, would have occurred on Eros, as well, when it was in the main asteroid belt; but Eros is unlikely to have had any craters form larger than a few hundred meters in size since it entered its current environment. So Azzurra-like ejecta from before 50 or 100 million years ago may well have rapidly matured on Eros in its new environment; and even the much more frequent, recent, smaller impact craters like the 1 km bluish crater on Ida studied by Sullivan et al. (1996) may all have matured on Eros. Except for rare, very small (all $<$200 m), recent impact craters, virtually all of Eros' surface would be maturely space weathered, provided—as seems likely—that space weathering reaches maturity on timescales less than several tens of millions of years in Eros' current orbital environment. Indeed, for some reason, smaller impacts (those that form craters $<$100 m in diameter) are much rarer and less frequent on Eros than had been expected (Chapman et al. 2002), so it may be that there is essentially no surface on Eros (even at small scales) that isn't rather old, dating from when the asteroid was in the main belt. Only the anomalously bright steep slopes are an exception. [Beware of a caveat in considering Eros' present orbit as representative of its orbital environment since leaving the main asteroid belt; Michel et al. (1998) present a minority of scenarios in which Eros' aphelion remains in the asteroid belt, even while its perihelion approaches Earth. In this case, its impact and solar wind environments would not be nearly so dissimilar from its earlier, main-belt environment.]

Although such a first-order explanation for Eros' space weathered uniformity may apply, namely ascribing the differences between Eros and Ida to the different current semimajor axes of the two bodies, two serious difficulties remain: (*a*) Even the highest-resolution color images show no fresh features (tiny impact craters are anomalously rare, but the numerous bare rocks also show space weathered colors in MSI images); and (*b*) the downslope freshening of interior walls fails to exhibit Ida-like behavior. It is especially difficult to understand why the countless blocks and boulders on Eros should appear space weathered. After all, an inherent aspect of space weathering, as understood on the Moon, is that it requires a powdery surface (Hapke 2001). Moreover, one might expect boulders to be relatively youthful geologically (they haven't been comminuted by impacts or covered over by regolith). Thomas et al. (2001) show that most of the ejecta blocks on Eros were excavated by the impact that formed Shoemaker crater, one of the largest on Eros, which must be at least hundreds of millions of years old. If, in addition, the blocks have become coated with a fine particulate dust, perhaps by the kind of electrostatic levitation that has been proposed to explain the level ponds on Eros (Robinson et al. 2001), then we can begin to understand why the highest-resolution images show homogeneous, space weathered colors on Eros.

Most problematic are the issues with Psyche crater. The downslope processes freshen its surface rapidly relative to the cratering rate and relative to space weathering darkening rates (but infrequently relative to space weathering reddening rates). This dilemma would be resolved if two things were true: (*a*) Space weathering processes that are much more important on Eros than Ida (i.e., solar wind sputtering) rapidly reddens Eros, whereas those more important on Ida (especially more rapid regolith evolution, and perhaps contamination by the C-type materials that predominate near Ida) darken it before reddening it; and (*b*) some process more frequent than jostling by cratering impacts is causing downslope movement on Eros. As yet, there is no compelling reason for expecting a darkening process to predominate on Ida. Nor is there understanding of how the steep slopes on Eros are so efficiently freshened, although Nesvorný's suggestion that mass-wasting would be induced by tidal deformation of Eros during close approaches to planets may be the answer. In conclusion, NEAR-Shoemaker's close-up examination of Eros has revealed a space weathering process at work, but its attributes remain imperfectly understood.

CONCLUSIONS

Space weathering of asteroids is a concept that has evolved over the decades in ways that may say more about the sociology of science than about physics. As I have shown, the study of asteroid compositions has taken place within the context of many other relevant developments in fields as distinct as lunar sample studies and Solar System orbital dynamics. Sometimes the conclusions of investigators in different specialties have been inappropriately ignored; occasionally, their results should have been ignored, in retrospect, because they turned out to be wrong. Relevant aspects of the physics of impacts (by micrometeoroids and solar wind) into mineral grains were surely being studied in the 1960s and 1970s and, together with laboratory studies of then-recently-returned lunar samples, should have been recognized as potentially relevant to the rather modest spectral differences between OC meteorites and S-type asteroids (modest at least compared with the huge differences between Moon rocks and lunar regolith soils). But several iconic facts (e.g., vitrification/agglutinization as the cause of lunar space weathering or the apparent spectral purity of Vesta) stood in the way, and even as late as the mid-1990s, strongly negative attitudes toward asteroidal space weathering inhibited the funding (at least in the United States) of laboratory simulations and other research concerning plausible space weathering processes.

When such studies were finally undertaken, primarily in Russia and Japan, they demonstrated that the optical properties of asteroidal minerals are necessarily changed by the space environment impinging on asteroid surfaces. Indeed it was not until the 1990s when much improved telescopic techniques plus close-up studies of two asteroids by the Galileo spacecraft demonstrated that space weathering was occurring on some asteroids. Recent studies of the colors of a very youthful subset of asteroids (Karin cluster) within the Koronis family (D. Nesvorný, R. Jedicke, R.J. Whiteley, Ž. Ivezić, manuscript submitted) reinforce these conclusions. Yet even after the dedicated, close-up investigation by NEAR-Shoemaker of Eros, an archetype of a potentially space weathered OC, serious questions remain about the suite of processes that comprise space weathering (and the processes against which space weathering competes, such as regolith turnover), so that we cannot fully explain important differences between Eros and Ida. Another chance is approaching to test predictions of the mineralogical composition of the NEA Itokawa based on telescopic data (Binzel et al. 2001) against measurements, and actual returned material, to be obtained by the Japanese Hayabusa (MUSES-C) spacecraft (launched May 2003, material returned to Earth in 2007).

Thus, we remain chastened in our expectations of the robustness of remote-sensing techniques applied to unreachable, or rarely reachable, objects in space. Remote sensing applied to terrestrial problems can frequently be checked against ground truth. But when we rely on theory, imperfectly relevant laboratory simulations, and indirect inference to determine the compositions of solid-surfaced Solar System bodies, we must be wary that we could well be led astray. For even though with hindsight we can see that some prescient hypotheses relevant to asteroidal space weathering were offered decades ago, the stop-and-start interdisciplinary research that has evolved since then has only very slowly directed us closer to the truth about these processes. And we have much more to learn about them.

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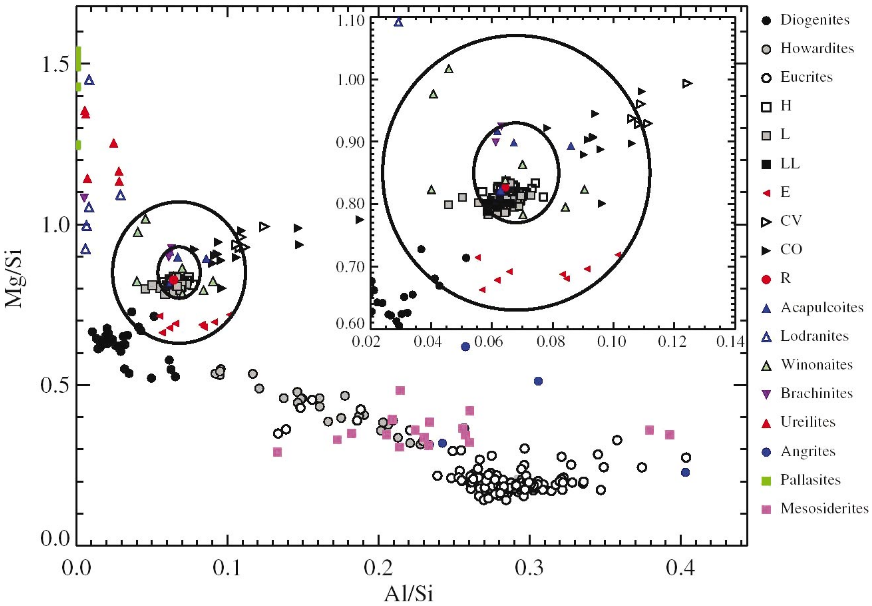

Figure 7 NEAR-Shoemaker XRS results for chemical composition of Eros. This is just one of many two-element plots, with associated tight and more liberal error ellipses. The inset focuses on the region of OCs. Most differentiated meteorites plot far from the data. (From Nittler et al. 2001.)

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