S-Type Asteroids, Ordinary Chondrites, and Space Weathering: The Evidence from *Galileo*'s Fly-bys of Gaspra and Ida

Clark R. Chapman
Southwest Research Institute
1050 Walnut St., Suite 429
Boulder CO 80302

Invited Review Article for *Meteoritics & Planetary Science* (**31**, 699-726)
9 May 1996, Revised 20 August 1996

Abstract.

New observations of the S-type asteroids Gaspra and, especially, Ida by the Galileo spacecraft demonstrate that a "space weathering" process operates, which modifies the reflectance spectra of fresh material to be redder, straighter, and have shallower absorption bands. The weathering process appears similar to, but less potent than, that observed on the Moon. It operates in the sense that would tend to convert spectra of ordinary chondrites to have the spectral traits of S-type asteroids. These results appear to resolve the major obstacles of the long standing "S-type conundrum" about the provenance of ordinary chondrite meteorites. A wide body of recent research, reviewed here, builds on previous meteoritical evidence to support a new, developing consensus that the larger S-type asteroids are a diverse assortment of silicaceous assemblages, which *includes* the OC parent bodies. Recent fairly realistic laboratory simulations of space weathering processes have changed OC spectra to resemble S-type spectra. J. F. Bell's highly regarded earlier paradigm that OC parent bodies would be found only among sub-10 km main-belt asteroids has been tested by an extensive observational survey by R. Binzel and his proteges; the result is that no small, main-belt analog for the OC's has been found, not even the somewhat OC-like object Božněmcová.

This article reviews the history of the S-type conundrum, which set the stage for Galileo's historic fly-bys. I then review the findings about Gaspra and Ida, including results about their geology, their geophysical structure and probable origins, and about Ida's small moonlet, Dactyl. Density constraints on Ida set by Dactyl's orbit rule out (for Ida, at least) the classic view of S-types as metallic, stripped cores of differentiated precursor asteroids. New analysis of the Galileo spectral images of Ida is presented that provides strong evidence that space weathering occurs on Ida and that Ida, and the Koronis family asteroids in general, are plausibly OC-like in composition. After reviewing 1990's developments on the S-type conundrum, I advocate a new perspective that the ordinary chondrite parent bodies are among the S-type asteroids, a diverse grouping that also contains other silicaceous and silicate/metal assemblages, presumably including various stony-irons and primitive achondrites represented in meteorite collections; Gaspra may be such a metal-rich assemblage.

Introduction

A long-standing key question in meteoritics and planetary science is whether the ordinary chondritic (OC) meteorites are derived from the so-called S-type asteroids. It is pivotal to the larger issue of how to relate meteoritic samples in general to their parent bodies in the heavens, observed from afar. Most researchers presume that the parent bodies for all meteorites (except lunar meteorites and presumably Martian SNC's) are main-belt asteroids, or fragments of them. Since visible and near-infrared reflection spectra of asteroids have characteristic signatures (e.g. absorption bands) of many major meteoritic minerals, the hope has been to correlate meteorite classes with asteroid spectral types (cf. Chapman, 1976; Gaffey & McCord, 1978). Then we would have a spatial and geological context for interpreting meteorites -- we would know better at what distance from the sun they formed (since predominant asteroid spectral type varies with solar distance [Gradie & Tedesco, 1982]) and we might learn specific traits (like size) of their parent bodies. Once meteorite classes are linked to spectral types, other evidence (e.g. proximity to a resonance) might narrow the linkages to particular asteroids.

A quarter century ago, Anders (1971) was optimistic that it would soon be possible "to trace each group of meteorites to its parent body in the sky;" he argued against mounting spacecraft missions to asteroids since such questions would soon be resolved by meteoriticists and groundbased astronomers. Kuiper (1971) responded,

> "As a groundbased observer most of my life, I would naturally sympathize with the point of view of Anders. I think all of us who are working in the laboratory or as astronomers feel that we can do ten times better or we would not be in the business in the first place. We see many possibilities ahead. I think at the same time it is not right for us to say that the rest must wait until we have made progress."

Anders' opposition to an early asteroid mission is widely thought to have delayed such endeavors. However, the passage of two decades has shown Kuiper to be correct. Connecting meteorites with their parent bodies has been a much more intractable problem than Anders, and most asteroid researchers, supposed. A spacecraft (Galileo), finally, has encountered two asteroids, and fresh progress has been made on this vexing and important issue.

The S-type conundrum, stated very simply, has two elements: (1) Straightforward interpretation of the spectra of S-type asteroids, which is the most common spectral type in the inner part of the main asteroid belt (from where most meteorites are thought to be derived), is that S-types are metal-rich, olivine-rich objects with variable amounts of pyroxene. Classically, they have been thought to be most analogous to very rare stony-iron meteorites like pallasites. (2) The most common meteorites, however, to reach the Earth's surface are OC's (perhaps second to carbonaceous chondrites in near-Earth space before preferential atmospheric ablation of the latter), whose spectral analogs are rare or absent among the >1000 main-belt asteroids that have been surveyed spectrally to date.

These elements can be reconciled if either (1) the processes that deliver meteorites to Earth are extraordinarily selective or (2) the straightforward method of interpreting asteroid spectra (by comparing with spectra of pulverized meteorites in the laboratory) is misleading us, for some reason. The implications of either solution could be quite profound. For example, extreme selectivity in meteorite delivery processes would undermine a whole body of experimental and theoretical work on the physics of asteroid fragmentation and chaotic orbital mechanics. It would also undermine a paradigm among cosmochemists that OC's are representative of common (rather than exceptional) inner solar system materials. On the other hand, the failure of remote-sensing techniques to provide reliable mineralogical assays of asteroid surfaces could point to unexpected surficial processes on asteroids (e.g. "space weathering") that somehow disguise or cover up the underlying material. It could also undermine confidence in a major remote-sensing technique (reflection spectroscopy of solid-surfaced planetary bodies) that still plays a major role in both telescopic and spacecraft-based studies of planets, satellites, and small bodies in the solar system.

Potentially important insights about asteroids and meteorites are confounded until a solution to the conundrum is obtained. For instance, if OC's are common materials derived from the 3:1 Jupiter resonance at 2.5 A.U., then the physical and chemical conditions (e.g. temperature, oxygen fugacity) inferred from analyses of OC's can calibrate solar nebula models at 2.5 A.U. Indeed, so much cosmochemical thinking has been shaped by the systematics of the OC's that many underlying assumptions in meteoritics would have to be revised if, instead, OC's represent only one millionth of the mass of the asteroids or if they come from somewhere else entirely (e.g. from comet nuclei).

One of the most significant questions about the early solar system concerns heating processes. Evidently, some primitive materials reaching the Earth's surface have never been substantially heated. Other materials (e.g. the basaltic achondrites and the irons) represent the crust-to-core end-members of bodies which were melted to the point that metals sank to their cores and lighter silicates floated to the top of intervening mantles. At one end of the range of possibilities is that S-type asteroids are all metallic cores of such differentiated bodies, with silicate mantles and crusts subsequently stripped away by collisions. If this is the case, then the inner asteroid belt was heated extensively followed by pervasive, thorough collisional fragmentation and dispersal of asteroid materials. On the other hand, if all S-type asteroids are undifferentiated, OC-like bodies, then the heating was modest, and the few obviously differentiated objects, like basaltic Vesta and metallic Psyche, could perhaps be explained by special, atypical circumstances or events. And far less robust collisional evolution would then be inferred.

For two decades, the S-type conundrum has stubbornly resisted solution. Until recently, most asteroid spectroscopists have regarded S-types as being made of diverse metal-rich assemblages, not including the OC's, while most meteoriticists have continued to assume that OC objects are common in the inner asteroid belt and are (or include, or are among) the S-types.

Now there is a new, unprecedented body of data about S-types obtained when the Galileo spacecraft (Johnson *et al.* , 1992), enroute to Jupiter, flew past two S-type asteroids -- the first asteroid encounters in the history of spacecraft exploration of the solar system. On 29 October 1991, Galileo encountered the small, S-type, inner main-belt asteroid 951 Gaspra (Belton *et al.*, 1992b). On 28 August 1993, the same spacecraft investigated the larger S-type asteroid 243 Ida (Belton *et al.*, 1994). Ida is a member of a group of asteroids, called the Koronis family, which all have similar orbits; Hirayama (1918), who first recognized the Koronis family, proposed that it might be the remnant of a disrupted precursor body. Galileo carried two instruments that happened to be well suited for investigating the mineralogy and geology of S-type asteroids: the Solid State Imaging system (SSI, a camera with seven filters, not including the "clear" filter, in the range 0.38 to 1.1μm [Belton *et al.*, 1992a]) and the Near Infrared Mapping Spectrometer (NIMS, a device with much coarser spatial resolution but higher spectral resolution, extending to >2.5μm [Carlson *et al.*, 1992]). As of this writing, there remain some unresolved issues concerning the calibration of NIMS, in particular for point sources, so I rely more heavily on the SSI data from Gaspra and Ida.

As I will demonstrate, Galileo images of Ida in different colors convincingly show that some kind of "space-weathering" process modifies the spectral character of Ida's surface with time. It is my contention that the observed spectral changes operate in the sense that would convert OC-like material to have the spectral character of S-type asteroids. In addition, SSI spectra of Ida's small satellite Dactyl (discovered by Galileo [Belton and Carlson, 1994; Chapman *et al.*, 1995]), as well as constraints on the bulk density of Ida determined from Dactyl's orbit (Belton *et al.*, 1995; 1996), indicate that Ida, Dactyl, and -- by extension -- all Koronis family asteroids may be of OC-like composition. They are probably *not* of metal-rich, thoroughly differentiated composition. My contention cannot be proven in the absence of returned samples from these bodies. But it is the most reasonable inference to draw from the Galileo observations.

In this article, I also review the current state of other research (groundbased observational, experimental, theoretical) bearing on the S-type/OC conundrum. I argue that the most reasonable interpretation is that the OC's are derived from a collisional size distribution of S-type asteroids -- which includes main-belt S-types of the sizes already well surveyed -- and that OC's comprise at least an appreciable fraction (e.g. >~20%) of the S-types. Although the S-types undoubtedly contain a wider diversity of mineralogies than are represented by the OC's alone, it is not yet clear how large a fraction (if any at all) of S-types must be taken to be thermally differentiated bodies, as in the traditional stripped-core model.

Thus, I claim that a fundamental feature of the Bell *et al.* (1989) "big picture" paradigm, namely that most inner main-belt asteroids are differentiated (or at least metamorphosed), could be wrong. Moreover, we can now comfortably reject Bell's view that OC's come from an as-yet-largely-undiscovered population of small asteroids, which are accidentally and grossly over-represented in meteorite collections; Bell (1995b) concluded on the basis of that view that meteorites are "in many cases useless" for understanding asteroids. Instead, the prevailing expectation of meteoriticists that meteorites, and OC's in particular, are representative of main-belt asteroids is now being supported by reflection spectroscopic techniques, which previously appeared to give only contrary evidence.

In my view, the S-type issues debated during the past two decades are not simple, and it *required* the close-up investigation of two S-type asteroids by a spacecraft to point toward the probable solution. It will take further research, however, including enhanced groundbased radar studies (which can clarify the metal content of numerous S-types) and the intensive year-long orbital investigation of the S-type asteroid Eros during 1999 by the Near Earth Asteroid Rendezvous (NEAR) spacecraft (perhaps augmented by prospective sample return missions) before the issues are substantially resolved (for a popular summary of the S-type conundrum and the potential role of NEAR, see Chapman [1996]). Complementary telescopic spectral studies of asteroids (both near-Earth and main-belt) remain important.

In order to discuss the lessons for meteoritics raised by Gaspra and the Ida-Dactyl system, I must review much of the other knowledge gleaned by Galileo, including asteroid geology, cratering history, inferences about regolith, and the origin of Ida and Dactyl from the break-up of the Koronis parent body. Therefore, beyond reviewing the S-type conundrum, this article also provides a general review of the implications for meteoritics of Galileo's data on Gaspra and Ida. I begin with a review of the intellectual history of the S-type/OC conundrum.

History of the S-Type Conundrum

Because of the interdisciplinary nature of the S-type debate, and the philosophical framework in which arguments have sometimes been couched, I believe it will be illuminating to review, in some detail, the development of the debate. The potential association of meteorites and asteroids has been recognized for nearly two centuries, from the time the first asteroids were discovered and meteorites were first widely accepted as rocks from interplanetary space. Bobrovnikoff (1929) obtained the first spectra of asteroids. During the next four decades, there were astronomical programs in several countries designed to obtain colorimetric data on asteroids (see review by Chapman *et al.*, 1971). Many of these were done with the conscious goal of correlating asteroid colors with laboratory measurements of meteorite colors.

Recognition of (and Definition of) S-Types

The early programs were inconclusive, partly because color differences among asteroids and meteorites are fairly subtle and because standard astronomical spectrophotometry (e.g. UBV photometry) was done in just a few filters in the relatively undiagnostic visible part of the spectrum. Nevertheless, a cluster of asteroids in UBV colorimetric coordinates was recognized by Chapman *et al.* (1971) and Hapke (1971), including such asteroids as 3 Juno, 6 Hebe, 7 Iris, 8 Flora, and 433 Eros; these are what we now call S-types. Hapke (1971) found that *powdered* (but not solid) samples of some materials, including the OC meteorite Bruderheim, roughly matched the colors of this group of asteroids, but he claimed no diagnostic association. (Egan *et al.* [1973] later found, from more refined measurements, that Bruderheim does *not* conform to asteroid spectra.)

Major progress was made in the 1970's when more sensitive, well-calibrated spectrophotometry, with higher spectral resolution extending into the infrared to 1.1μm, was obtained in a program of 24-filter spectrophotometry (0.3 to 1.1μm) (Chapman *et al.*, 1971, and subsequent papers reviewed and summarized by Chapman and Gaffey, 1979). The first classic S-type spectrum published from this program was of 192 Nausikaa. Chapman (1972) subsequently gave the designation R (for "reddish") to the growing number of Nausikaa-like spectra; they were soon called S-type (see Bowell *et al.*, 1978, for a demonstration of the one-to-one correspondence between Chapman's original R-type and S-type).

Chapman, Morrison, and Zellner (1975) first defined the C and S types, based on the individual correspondences, within a sample of ~100 asteroids, of the bimodality in their albedos (measured both radiometrically [Morrison, 1974] and polarimetrically [Zellner *et al.*, 1974]) and the bimodality in reflectance spectra (McCord and Chapman, 1975a). That is, individual asteroids in one of the albedo modes (e.g. higher albedo) all fell within the same spectral mode (e.g. reddish). The letter "S" was adopted as a mnemonic for "silicaceous" (note: *not* "siliceous") to reflect the fact that a major aspect of S-type spectra is the dominance by the signature/s of the *silicate* minerals pyroxene and olivine. ("S" was also taken by some to stand for "stony-iron," the favored meteorite analog for S-types, proposed by McCord and Gaffey [1974] for 3 Juno and 6 Hebe. Several authors have criticized us for basing classes on debatable interpretations, rather than on simple descriptions, of the asteroid spectra.) S-types were defined by Chapman, Morrison, and Zellner as having albedos >9% (calculated using the calibration then in effect), having moderate 1μm absorption bands, and having reddish colors in the visible. The definition was subsequently refined by Bowell *et al.* (1978) who also added, as a component of the definition, limits on the important BEND parameter defined by McCord and Chapman (1975a).

Since Tholen's (1984) principal components cluster analysis of the 8-color "ECAS" survey (Zellner *et al.*, 1985), the somewhat ill-defined working definition of S-type has been those asteroids that are grouped together with classic S-types in a Tholen-type cluster analysis; Tholen's cluster of S's has since been found to be robust by other workers using other clustering algorithms and including infrared reflectance data out to 2.5μm (see Gaffey *et al.*, 1993a; Howell *et al.*, 1994). However, the S cluster is very large, encompassing roughly half of the variability among all asteroids in many parameters. Thus recent papers on asteroid taxonomy have emphasized the definition of consistent and useful sub-classes *within* the S-type population.

Early Interpretations of S-Type Spectra and Meteoritic Analogs

In my first analysis of 24-filter spectrophotometry of 31 asteroids (Chapman, 1972), in the virtual absence of comparable laboratory measurements of meteorites, I made a tentative suggestion: "The red [S-type] asteroids...would be the ordinary chondrites in this model."

Soon laboratory spectra were measured for ~40 meteorites (the majority were OC's), which led to a comparative analysis by Chapman and Salisbury (1973). While they noted spectral similarities between what are now called the S-types and OC's (e.g. absorption bands near 1μm), they also called attention to one of the most significant differences: the asteroids have a "reddish" slope from the ultraviolet (UV) into the near-IR that is too *linear* compared with the more curving spectra of the OC's. (McCord and Chapman's [1975a] BEND parameter quantifies the relative linearity or curvature, measured at 0.4μm, 0.56μm, and 0.73μm.) While Chapman and Salisbury noted Chapman *et al.*'s (1973) earlier match between some OC spectra and that of the small Earth-approaching asteroid 1685 Toro, in general they found few matches between any of the meteorite types and asteroid spectral classes.

Chapman and Salisbury sought explanations for the mismatch between OC's and the S-types: "Of particular interest is any process that might convert the spectra of OC's into those of the most common reddish asteroids." They noted that unequilibrated OC's (e.g. petrologic types 3 and 4) had shallower absorption bands and lower albedos than equilibrated OC's and, thus, more closely resembled the reddish asteroids. They also considered degree of shock as well as differences between the physical state of a crushed meteorite in the laboratory and a true asteroidal regolith.

Chapman and Salisbury gave most consideration to micrometeoritic impact vitrification (conversion into glass), which was at the time the leading explanation for analogous -- but more extreme -- spectral differences between lunar rocks and lunar soils. (This is one of several processes in the general category of *space weathering* -- any process that causes surface [or near-surface] materials on an asteroid exposed to interplanetary space to change color and/or albedo with time.) As they noted, "[i]f dark red glasses are produced by impact-vitrification of chondrites, then the R3 class asteroids [including the S-type asteroids 3 Juno, 6 Hebe, and 192 Nausikaa] could be of OC composition."

However, Chapman and Salisbury then argued *against* their own suggestion of vitrification as a way to reconcile OC and S-type asteroid spectra for several reasons, including:
(1) the lack of demonstration that meteoritic materials would respond to vitrification to the same degree as the iron- and titanium-rich lunar maria basalts;
(2) the lower impact velocities in the asteroid belt, lower than required for efficient glass-production;
(3) the less mature regoliths expected due to less effective retention of ejecta on low-gravity asteroids; and
(4) the existence of a few asteroids, notably 4 Vesta (McCord *et al.*, 1970), that exhibit pure, unmodified spectra, which argues against a ubiquitous space-weathering process.
(Many of these same arguments were later made by Matson *et al.* [1977], and most of them remain pertinent today.)

Chapman and Salisbury, therefore, adopted the working hypothesis "that the meteorite/asteroid [spectral] comparisons can be taken at face value." They concluded that "it appears that most types of meteorites, including the most common OC's, are not typical of main belt asteroids." (Egan *et al.*, [1973] reached a similar conclusion.) Chapman & Salisbury went on to say that their "comparisons are consistent with deriving most meteorites from a very few unusual asteroids...." This was the first statement of what has remained (as further developed by Bell *et al.*, 1989) the canonical interpretation of S-types.

So what are S-types made of? It was immediately evident (Chapman, 1972) that the 1μm absorption feature in S-types was due to a combination of pyroxene and olivine. Gaffey (1974, 1976) measured numerous meteorites in the laboratory, including irons and one stony-iron. Interpreting that data base, McCord and Gaffey (1974) were the first to propose what became, for at least a decade, the accepted interpretation of S-types as stony-irons. They argued briefly (see amplification by Gaffey & McCord, 1978) that several spectral attributes of metallic iron contributed to the S-type signature: the reddish, linear spectrum of metal yielded the reddish, linear continuum on which the signatures of admixed silicates were superimposed. Moreover, the opacity of the metal would diminish the multiple scattering of light within silicate grains, generally weakening the silicate absorption bands (including the 1μm band and the UV band whose "edge" provides curvature to silicate spectra in the visible).

Developments from the Reflection Spectroscopy Perspective

For two decades, most asteroid reflection spectroscopists have operated under the assumption that "what you see is what you get" and have continued to discount any space weathering explanation. The most thorough and influential paper of the 1980's was that of Gaffey (1984) who made two important contributions: (a) he demonstrated that the metallic particles in OC's cannot plausibly produce the linear red component of S-type spectra, in part because (for reasons still not understood) OC metal has a neutral, not a reddish, color (this evidence was expanded upon by Gaffey, 1986); (b) he claimed to show[1] that minor spectral differences on opposite sides of 8 Flora are not consistent with differences that would be expected on a non-differentiated OC body (the olivine/pyroxene ratio and pyroxene composition do not vary in the sense that the H, L, and LL chondrites differ from each other due to oxidation state) but rather imply that Flora is differentiated. In these, and other, papers and abstracts published in the mid-1980's, Gaffey developed his earlier model that S-type asteroids exhibit the core-mantle regions of differentiated bodies that had been collisionally stripped of their mantles and crusts.

Some researchers (e.g. Gaffey, 1984, 1985a), continued to advocate the Chapman & Salisbury view that OC's are derived from "a very few unusual asteroids." But other possibilities were suggested, including (a) OC's are *not* derived from the main asteroid belt but rather from comets (cf. Wilkening, 1979; Gaffey *et al.*, 1989); (b) OC's are derived from various larger asteroids, whose spectral signatures are masked because they are *covered up* by other material (e.g. dark, carbonaceous dust derived from elsewhere in the asteroid belt -- this view has been espoused by J. Wasson); and (c) OC's are derived from some common C types, whose original OC-like spectra have been blackened by shock (Britt, 1996). As we will see later, these options are difficult to defend.

Morrison (1978), McFadden (1983), Gaffey (1984, 1985b), and Bell (1986) proposed that OC's may be derived solely from common smaller asteroids, which are too small and faint to have been surveyed spectrally and for which there are no larger associated objects. This view, elaborated on and proposed as part of a new paradigm by Bell *et al.* (1989), challenged what had been the widely accepted view that most meteorites come from larger asteroids and their fragments. For a few years, Bell's "big picture" became orthodoxy among most asteroid spectroscopists. I evaluate Bell's perspective later in this review.

Non-Spectroscopist Perspectives on S-Type/OC Relationship

Contrasting with the view of asteroid observers that S-types are stony-iron cores and that large OC parent bodies are absent in the main belt, meteoriticists concerned with the issue almost unanimously continued to believe that OC's do come from the main belt (cf. Anders, 1975) and that large S-types are the most likely parent bodies for them. Arguments were based on evidence from cosmic-ray exposure ages, solar-wind gas implantation, frequency of foreign clasts (xenoliths) in various meteorites, inferences about parent body dimensions from cooling rates measured by several methods (including metallography and Pu fission tracks), plus more indirect arguments. I will not review them now, for they are familiar to readers of *Meteoritics and Planetary Science*; however, I will return to several of them later. Anders' summary of the situation in the late 1970's was:

> "Thus we are left with two possibilities. Either the S asteroids are stony irons... Or they are OC's, in which case we must explain why the spectral reflectivity data tell us otherwise... I, at least, find it easier to believe that the spectral reflectivity data mislead us than to accept the alternative: that the most abundant meteorite class [OC] has no asteroidal equivalent, and the second most abundant asteroid class [stony-iron] has no xenolithic and only rare meteoritic equivalents." (Anders, 1978)

---

[1]The theoretical basis of Gaffey's work on Flora's rotational variation is strong (see also McSween, 1992), but the observational work is weaker; the data must be reanalyzed or, preferably, new observations should be made. There is the general problem that Gaffey interprets parameter differences that are roughly at the level of error bars, which are apparently based on counting statistics alone but do not include errors in such effects as atmospheric corrections. (Visual examination of his Fig. 8 does not support the adopted error bars, ~±0.003μm, for Band I center shown in his Fig. 10.) A potentially more serious problem of the analysis is that Gaffey used what is now known to be an incorrect rotation period for Flora (the discrepancy is large, about 0.8h: at the end of his 4-night observing run, Gaffey was observing roughly the *opposite* side of Flora from what he imagined). Therefore, instead of sampling Flora at all rotational aspects, his data pertain to only about half of the rotational aspects and exclude one face of Flora. Some of the night-to-night spectral variations, which Gaffey believes are real, are difficult to understand since the hemisphere being observed was changing in central longitude much less than he supposed (Flora presents roughly the same side to Earth on successive nights). Gaffey (personal comm., 1996) has reanalyzed the data with the correct period and believes his fundamental conclusions can be sustained, but I believe that Gaffey's results on Flora are so important that they should be confirmed by a new observing project.

Later perspectives on the conundrum, emphasizing the meteoritical point-of-view, may be found in Wasson and Wetherill (1979), Lipschutz *et al.* (1989), and McSween (1992).

In the mid-1980's, strong support for deriving OC's from S-types came from Wisdom's (1985) work demonstrating the virtual certainty that some meteorites are derived from the inner part of the belt by chaotic dynamics associated with the 3:1 Jupiter resonance. Further work on dynamical delivery mechanisms (Wetherill, 1985; Wetherill, 1988) provided a robust argument that some Earth-crossing fragments (and probably the majority of them) must come from asteroids adjacent to the 3:1 Kirkwood gap and the $\dot{\nu}_6$ secular resonance. Although efficiency parameters in the delivery process (e.g. quantity of impact ejecta of appropriate sizes reaching a resonance from a nearby asteroid) are poorly known, it seems inevitable that Earth must receive many meteorites from the S-type asteroids (like 6 Hebe [see Farinella *et al.*, 1993] and members of the Maria family [Cellino *et al.*, 1996]), which constitute at least half of the asteroids near the 3:1 resonance. If meteorites from the 3:1 resonance aren't the OC's, which types are they? And then where would the OC's come from?

Chapman's Position on S-Type Conundrum

I have tried to keep the door open during the past two decades[2] to the *possibility* that a "space weathering" explanation would ultimately resolve the S-type/OC conundrum, even as I (and my various co-authors of reviews of the topic) generally adopted the stony-iron interpretation of S-types:

* Chapman (1974) first proposed that S-type asteroids are the stony-metallic cores of geochemically differentiated precursors, collisionally stripped of their mantles and crusts. (This argument was based on the size distribution of S-types, which has since been superseded by better data [Gradie *et al.*, 1989] that no longer support this idea.)
* "Silicaceous or Stony-Iron Asteroids...generally cannot be matched with OC meteorites because their spectra bend insufficiently in the visible." Chapman, Morrison, and Zellner (1975)
* "Gaffey and McCord (197[8]) have argued persuasively that the overall reddish color of these [stony-iron (S)] asteroids is due to an admixture of nickel-iron, in abundances exceeding those found in OC's.... Suggestions that OC assemblages might be modified to S-type in impact regolith environments (e.g. by impact shock and vitrification or compositional sorting) are deemed unlikely." Also: "OC's are quite rare among the asteroids." (Chapman, 1976)
* "No definitely confirmed asteroid analog for OC has been found in the main belt so far...The asteroid belt might yet be salvaged as a location for parent bodies of OC's...if the common S type asteroids are actually OC's rather than the preferred stony-irons." (Chapman *et al.*, 1978)

At times I have favored the interpretation of particular, unusual asteroids as having OC-like compositions. The idea of McCord and Chapman (1975b) that 349 Dembowska might be an LL chondrite, based on its unusual spectrum, was thought to be invalidated by later infrared data (Larson & Veeder, 1979); subsequent analyses of Dembowska (Feierberg *et al.*, 1980; Chapman, 1979; Gaffey *et al.*, 1993b [suggesting H-type silicate compositions]) reflect the difficulties of spectral analyses. I have suggested that several Earth-approaching asteroids (1685 Toro, Chapman *et al.*, 1973; 433 Eros, Pieters *et al.*, 1976) may be OC-like, since these smaller objects tend to have more curving spectra in the visible (larger BEND parameter) and deeper absorption bands than typical large, main-belt S-types. It has been unclear if deeper absorption bands and larger BEND parameters reflect a trend correlating with semi-major axis or with size; as early as 1973, Johnson and Matson (1973) pointed out that the comparatively small, inner-main-belt asteroid 43 Ariadne is spectrally similar to Toro and thus might be an OC, and several other Flora region S-types (including Flora itself) have been offered as being S-types that are least unlike OC's. An extreme example of the trend for small asteroids with small semi-major axes to look more like OC's is 1862 Apollo, which is indistinguishable from laboratory spectra of OC's and was defined as the first member of a distinct Q-type (McFadden *et al.*, 1985; Tholen, 1984); several other small, unusual S-type Earth-approachers verge in the direction of Q's (whether they are Q's or S's is often uncertain due to poor observing conditions and hence noisy data). Very recent work by Binzel *et al.* (1996) clarifies what these earlier data were trying to tell us; see later discussion. Earth-approachers, of course, are in transient, planet-crossing orbits and -- like the meteorites -- must be derived from longer-lived storage locations, in the main belt or conceivably elsewhere.

[2]I wish to thank Laurel Wilkening for insisting that I join the Meteoritical Society more than two decades ago, giving me longer exposure than most of my other asteroid spectroscopist colleagues have had to the meteoritical evidence on this topic.

Occasionally, I have taken a neutral position on whether it is more likely that S-types are akin to stony-irons or OC's (Chapman, 1979; Wetherill & Chapman, 1988). Also, Greenberg & Chapman (1983) developed an inductive model, with numerous *ad hoc* assumptions (some now known to be wrong), which seemed to explain the delivery of meteoritic samples from the asteroid belt on the *assumption* that S-types were OC's.

On one occasion (Feierberg, Larson, and Chapman, 1982), I co-authored a paper that strongly leaned toward the conclusion that "some [S-types] may be OC parent bodies." In reaching this judgement, Feierberg *et al.* gave heavy weight to meteoritical arguments for expecting large OC parent bodies in the part of the asteroid belt where S-types predominate. They also argued, on the basis of some preliminary experiments with finely divided metal powders, that the spectra of S-types were not incompatible with OC metal abundances. In effect, they explained the apparent spectral differences between OC's and S-types as due to regolith processes, in particular the possibility that metallic iron is preferentially comminuted so that its spectral signature is enhanced -- an idea due to Anders (1978). I return later to the possible role of silicate/metal fractionation in asteroid regoliths.

In summary, I have steadfastly agreed that (a) straightforward interpretation of S-type spectra seems to imply stony-iron compositions and that (b) speculations about space weathering or regolith processes that might resolve the conflict have usually not been successful when subjected to laboratory tests. On the other hand, I (and sometimes my co-authors) *have* occasionally been willing to evaluate hypotheses that were motivated by the weight of meteoritical evidence, which compels us to keep looking to the S-types as OC parent bodies and, therefore, to downplay the spectral mismatch. I have always felt that it is important to take seriously the meritorious arguments of *both* of the mutually irreconcilable sides of this debate. In virtually all of the articles I authored or co-authored on this topic during the past quarter century, I cautioned that the S-type/OC issues were unresolved. Only now, with Galileo data on Ida in hand, have I moved to a position of believing it to be very likely that the OC parent bodies are among the larger S-type asteroids. That is the view I advocate in this article.

Pre-Galileo State of the Debate

By the time Galileo approached Gaspra, several developments had further expanded the alternatives and somewhat narrowed the gaps among some of the opponents in the debate. I will leave to historians of science to determine whether the imminent arrival of Galileo to an S-type asteroid helped to focus some of the pre-encounter convergence-of-thinking that occurred, but I suspect that it did.

On the meteoritical side, the widely expanded collections from the Antarctic, combined with refined analyses, were beginning to uncover a broader range of "unusual" meteorite types, including anomalous stony-irons, lodranites, primitive achondrites, and other metal-rich silicate assemblages, beyond the classic stony-irons (mesosiderites, pallasites, and IAB irons). While ~15 types of anomalous meteorites are represented typically by just a couple of examples, compared with the dozens of examples of the classic stony-irons (already regarded as rare meteorite types), Bell and others promoted the idea that the observable S-types were parents for these rare meteorites, not for OC's (cf. Hiroi *et al.*, 1993). Although the dividing line has become less sharply defined between the extreme alternatives of S-types as either OC's, on the one hand, or classic stony-iron cores on the other, the different perspectives on meteoritic diversity and abundances remain profound.

On the astronomical side, the 52-color infrared survey (unpublished; see Bell *et al.*, 1988) shifted interest from the 0.3 - 1.1μm spectral range to the 0.8 - 2.5μm range, encompassing both of the pyroxene absorption bands. The reddened continuum of S-types continues (to some extent) in this spectral range, and the new data engendered several attempts to explain it: enhanced metal signature, various space weathering processes, etc. I will return to these later, but a fair summary would be that no explanation for the reddish continuum of S-types has proven to be entirely satisfactory.

A significant step toward the middle ground was taken by Gaffey (1992) and Gaffey *et al.* (1993b) in research done roughly contemporaneously with return of Galileo's Gaspra color data in November 1991. The important paper by Gaffey *et al.* defines seven sub-classes of S-types, separated on a plot defined by two spectral parameters: (1) center wavelength of Band I (the 1μm pyroxene/olivine band) and (2) the ratio of areas of Band II (the 2μm pyroxene band) and Band I (this ratio parameter was defined by Cloutis *et al.* [1986]). These parameters cleanly specify the olivine/pyroxene ratio of the silicates, and the first one also helps to distinguish orthopyroxenes from the more calcic clinopyroxenes. The significant result is that the S(IV)'s (S with Roman numeral IV), constituting nearly 30% of the 39 large S-type asteroids studied (including the classic S-types 3 Juno and 6 Hebe), have silicate compositions compatible with those of OC's. Moreover, Gaffey *et al.* noted that S(IV)'s may have other spectral traits slightly less incompatible with OC's than the traits of other S-types, and also that S(IV)'s constitute more than half of the S-type asteroids near the 3:1 resonance escape hatch. For these reasons, Gaffey *et al.* concluded:

> "...the present results do not preclude the presence of an OC component among the large S-asteroids.... The most likely candidates for main-belt OC parent bodies among the large S-asteroids are those members of the S(IV)-subtype which have the lowest spectral slope.... However...it appears improbable that OC parent bodies could constitute more than about 10% of the larger members of the S-asteroid population."

Thus, for the first time, Gaffey gave less weight to the continuing spectral discrepancies involving absorption band depths and linear reddish slopes, gave greater weight to such evidence as proximity to the 3:1 resonance, and adopted a more-or-less neutral stance toward the possibility that some S(IV)'s (especially Juno and Hebe) might be OC parent bodies. In essence, Gaffey *et al.* emphasized that the S class constitutes a very broad grab-bag of diverse silicaceous objects, and that it is not implausible that undifferentiated silicate bodies (the OC's) might be among them. (Although J. F. Bell was co-author of this work, later abstracts published by Bell [1994, 1995a, 1995b] show that he has continued to favor finding OC parent bodies among very small asteroids rather than considering large S-types like Hebe to be possible OC's. Gaffey [1996a,b], on the other hand, has evolved to the point of proposing that Hebe *is* the H chondrite parent body.)

My own pre-Gaspra-encounter view is summarized in a short abstract (Chapman, 1991) written before the encounter. I pointed out the very wide range of observable and inferred parameters among the S-types, noting that inferred silicate compositions "span the ranges of both OC's, known stony-irons, and more." I went on to note that Gaspra was among the majority of S-types that seem "too olivine-rich to be considered as parent bodies for even the most olivine-rich OC's."

> "Therefore, it is plausible that Gaspra is a differentiated object. As a member of the 'Flora families,' it is quite plausible that Gaspra will be found to have heterogeneous units reflecting the differentiated mineralogy that Gaffey inferred from rotational spectral variations on Flora."

I further noted that Ida "is a pyroxene-rich S-type having traits that render it a much more likely candidate for being an OC," and I concluded that Galileo's observations of Gaspra alone were not likely to resolve the S-type controversy.

As Galileo closed in on Gaspra, no one expected it to be an OC, but there were some limited hopes held open that Ida -- as a probable S(IV) -- *might* prove to be an OC. Even this was doubted by most, if not all, asteroid researchers. A late pre-Ida-encounter contribution to the debate was publication (Binzel *et al.*, 1993a) of visible and near-IR reflectance spectra of many of the members of the Koronis family, of which Ida is a member. Original UBV and 8-color spectrophotometry of Koronis family members (Gradie, 1978; Gradie *et al.*, 1979) emphasized the similarity of colors and thus the compositional homogeneity of the Koronis parent-body (which would be consistent with undifferentiated OC composition, but not necessarily so with a differentiated body). Binzel *et al.* (1993a) instead chose to emphasize the minor variations among spectra of Koronis members and speculated that some degree of differentiation within the parent body might be implied. (I will address these data again later.) Neither Ida, nor Koronis members generally, could be regarded as *specific* candidate source bodies for OC's, because their position in the outer belt is far from the 3:1 resonance. But the potential for examining one large fragment from a family of S-types, apparently of the S(IV) subtype, held promise for elucidating the relationship between S-types and OC's.

Thus Galileo had the serendipitous opportunity to investigate the S-type conundrum. Its reconnaissance would be of two very different S-types: a presumably differentiated, exceptionally olivine-rich object (Gaspra), and an example of the S(IV) class (Ida), which might well be an OC despite having the classical spectral differences that distinguish S-types from OC's. Although Galileo would have a slightly better opportunity to measure reflectance spectra (being unimpeded by terrestrial atmospheric features near 1.9μm, for example), the chief advantage would be Galileo's spatial resolution: the NIMS instrument would obtain spectra of units small compared with the sizes of the asteroids, and Galileo's camera would produce color maps at spatial resolutions down to ~100 m. By correlating SSI spectral signatures with the more well-defined NIMS spectra, Galileo investigators hoped to study how the mineralogy varied at very small spatial scales, which might shed light on the nature of differentiation processes, if any. Thus Gaffey's Flora experiment -- looking for spatial variations in reflectance spectra indicating differentiation -- could, in principle, be carried out at dramatically better spatial resolution than the hemispheric resolution possible from the Earth.

It was realized (Chapman and Davis, 1991) that the tests might not be conclusive. There would be proof of differentiation if observations showed large mineralogical differences on different parts of the object (e.g. different olivine/pyroxene ratios or -- more spectacularly -- obviously metallic units interspersed with silicate portions). Given the several tens of kilometers scale of these bodies, there was the prospect that such heterogeneities might show up. But there were three ways in which a differentiated body would not necessarily reveal itself:

* If the scale of differentiation were large, and the parent body had not been subsequently "rubblized" (fragmented and reassembled [Davis and Chapman, 1977; Chapman 1978]), an asteroid might be a homogeneous fragment of *one* of the differentiated units (e.g. the mantle), and would not exhibit portions with complementary compositions (e.g. reflecting the core or crustal components).
* If the scale of differentiation were very small (e.g. less than a few resolution elements, <100 m), either because the inherent scale of phase separation was small or as the result of extensive rubblization in which all of the previously differentiated large-scale elements had been extensively fragmented and remixed, then evidence for differentiation would be subtle, at best.
* If the underlying body had diverse, differentiated units, but was covered with a homogeneous layer by the ejecta from the last, major impact ("painted gray"), then apparent homogeneity would mask any proof of differentiation.

On the other hand, it was plausible (from research on catastrophic fragmentation and reassembly, and from research on ejecta emplacement and regolith processes) that differentiation might well be recognizable on the spatial scales that would be observed -- ~100 m to ~10 km. Thus the stage was set to *prove* if one or both bodies were differentiated. It would be harder to prove that an object was undifferentiated. Nevertheless, as with any first spacecraft reconnaissance of a planetary object, there was an opportunity for a major leap in understanding. It was accidental that the investigation of the S-type conundrum should be addressed by a long-delayed Jupiter-bound mission, but -- thanks to a mid-1980's policy change by NASA (see NASA Solar System Exploration Division, 1984), which mandated asteroid encounters during outer-solar-system missions -- that was what the fates had decreed.

As it has turned out, Galileo's contribution to the S-type problem has been rather different from what anyone imagined. The evidence is dramatic. But it involves such unexpected elements as an unforeseen moonlet (Dactyl) orbiting around Ida, which is another (and very small) member of the Koronis family, with its own spectral traits; Dactyl's orbit also yielded important (if not definitive) estimates of the bulk density of Ida itself -- very low, indeed, for any body hypothesized to be iron-rich. Another important discovery is the large fresh crater Azzurra, and its ejecta blanket, deposited discontinuously around the grotesquely shaped Ida. That the spectral reflectance of Azzurra's ejecta and other fresh features differs from most of Ida proves that there is space weathering on Ida. But, first, let us consider the less definitive results from Gaspra.

Galileo Observations of Gaspra

Gaspra was observed less well than Ida for at least two reasons. First, with an average diameter of 12 km, it is less than half the size of Ida. Second, conservatism regarding uncertainties in Gaspra's position with respect to the spacecraft necessitated a sequencing strategy that would *guarantee* acquisition of some Gaspra imagery at the expense of the highest possible resolution. (Galileo Project engineers were bolder in planning the Ida encounter.) Therefore, the best one-color resolution achieved on Gaspra is 54 m/pixel (~330 resolution elements along Gaspra's 18 km length, compared with ~1600 elements for Ida). The best 4-color sequence for Gaspra has a resolution of 160 m/pixel (~110 elements along Gaspra) compared with the final Ida color sequence (~108 m/pixel, ~470 elements along Ida). An enhanced color image of Gaspra, superimposed on the higher resolution best image, is shown in Fig. 1.

Galileo's preliminary Gaspra results are presented by Belton *et al.* (1992b). Detailed analyses are in a special issue of *Icarus* (Vol. 107, #1, January 1994), summarized by Veverka *et al.* (1994a). Gaspra has a very irregular shape (Thomas *et al.*, 1994), 18.2 x 10.5 x 8.9 km, characterized by planar regions separated by ridges; although Thomas *et al.* interpret Gaspra as a single, coherent object, the possibility that it is a compacted binary object is not ruled out (Chapman *et al.*, 1996a). There are some presumably extensional grooves on Gaspra (Veverka *et al.*, 1994b) as well as evidence for localized compression.

Gaspra's rather smooth surface records a population of moderate-sized but nearly erased craters and a superimposed sparse population of fresh small craters (Carr *et al.*, 1994; Chapman *et al.*, 1996a). Gaspra's fresh crater population in the 100 m - 2 km size range, deemed to represent the production population of projectiles, shows a very high ratio of small-to-large craters, characterized by a differential power-law population index of about -4.3. Gaspra has no craters with diameters even half of the body's radius, unlike most crater-saturated bodies in the solar system, including Ida. Yet Gaspra is nearly saturated by small craters with diameters (100 m) near the resolution of the best images. The expressed population of fresh craters does *not* reflect a collisional equilibrium population of impactors (with an index of -3.5), as postulated by Dohnanyi (1971), although it *is* consistent with populations of small lunar and Martian craters of similar sizes, and with inferences from the Spacewatch program (Rabinowitz, 1993) about the population of near-Earth asteroids.

The lack of saturation by larger craters reflects either (a) comparative youthfulness of Gaspra (it hasn't been around long enough, in its present configuration, to be fully cratered -- perhaps only a couple hundred m.y. or less) or (b) it is made of metal or something very strong so that the cumulative projectile flux, even over billions of years, has formed only an undersaturated population of comparatively small craters (Chapman *et al.*, 1996b). Either way, the cumulative volume of crater ejecta from Gaspra's craters would spread only a thin layer of ejecta around Gaspra, <10 m deep (even if all of the ejecta were retained); since Gaspra's size is near the transition between escape and retention of most ejecta (Housen, 1992), that is an upper limit to the thickness of Gaspra's modern regolith. Of course, if Gaspra retained a rubble-pile structure from its previous history (or the previous history of its parent body), then its modern regolith would be only a surficial layer of soil on top of a much deeper megaregolith. Gaspra's older population of degraded, larger craters is presumably a remnant from at least one previous epoch of cratering. Photogeological inferences for the depth of Gaspra's regolith range from meters to tens of meters (Carr *et al.*, 1994).

The spatial resolution of the color images of Gaspra limit their utility. However, correlation with higher-resolution one-color images permits some extrapolation to smaller spatial scales. The NIMS data on Gaspra have much better *spectral* coverage and resolution than SSI data, but have marginal *spatial* resolution (only several NIMSels -- NIMS resolution elements -- across Gaspra) with attendant ambiguities associated with proximity of many of the NIMSels to Gaspra's limb or terminator.

The color images show undoubtedly real but modest (typically 5%) color differences across Gaspra (Carr *et al.*, 1994; Helfenstein *et al.*, 1994a). Locally, spectral differences approach 30%. The sense of the differences is that there are two "extreme" units: (a) slightly higher albedo, relatively blue units with a deeper 1μm absorption band and (b) slightly lower albedo, redder units with a shallower absorption band. Average Gaspra is closer to unit (b). There is a clear correlation between color and elevation, in the sense that the bluer unit is located preferentially on ridges. It also appears to be correlated with several small, fresh craters, chiefly located on the ridges. The redder unit is preferentially located on the lower, flatter facets.

These correlations led the Galileo imaging team (Belton *et al.*, 1992b; Helfenstein *et al.*, 1994a; Carr *et al.*, 1994) to conclude that (1) there is a space weathering process that changes Gaspra's color with time, converting unit (a) into the more typical unit (b); and (2) that there is a tendency for the older material to migrate downhill from the ridges and fill in the lower planar regions. The latter seems to require the presence of a particulate regolith. The observed space weathering was discussed in terms of the previous literature on S-types: vitrification, shock, solar wind bombardment, enhanced metal content, etc. It is noteworthy, however, that the space weathering observed on Gaspra, however subtle (hence potentially controversial as to its reality), operates in the same sense as the vastly more potent space weathering process on the Moon and -- as we shall see -- as the process operating on Ida.

The Galileo color images are good at mapping units of different mineralogy but are comparatively poor at characterizing what the different mineralogical assemblages are (the filters centered at 0.76, 0.89, and 0.99 μm define only one side of the 1μm band, making it virtually impossible to study how the band center might vary across the surface of Gaspra, and the 2μm band cannot be observed at all). NIMS overcomes these obstacles, but suffers because the spatial resolution of NIMS only marginally resolves the ridge and facet units between which SSI detected color changes. Preliminary analyses of NIMS data by Granahan *et al.* (1994a) seem to confirm that the color variations observed by SSI extend out to 2.5 μm (i.e. reddish units in the visible also have a reddish slope in the infrared); the NIMS analyses also confirm the groundbased reflectance spectra (summarized by Helfenstein *et al.*), which show Gaspra to be an exceptionally olivine-rich S-type asteroid. Granahan *et al.* also tentatively conclude that the bluer unit is more olivine rich (longer wavelength Band I center, shallower Band II). The latter conclusions would strongly indicate that Gaspra is a differentiated body; however, unless a space weathering process can modify the apparent olivine/pyroxene ratio (not previously thought to be possible, but see later discussion), this conclusion would be inconsistent with the interpretations of Carr *et al.*, in particular. I prefer to regard Granahan *et al.*'s conclusions as premature; a possibility is that Gaspra's small size produced photometric gradients that altered observed band depths and positions so as to mimic mineralogical changes (R. Carlson, pers. comm., 1996).

Since SSI's spatial resolution on Gaspra is limited and color variations on Gaspra are so modest, even the SSI conclusions based on the observed color differences must be regarded as suggestive rather than definitive. Certainly, Galileo revealed no prominent evidence of great compositional heterogeneities across Gaspra that would have proved its differentiated composition. Another piece of evidence -- Gaspra's apparent modulation of the interplanetary magnetic field in its vicinity -- originally interpreted (Kivelson *et al.*, 1993) as potentially implying that Gaspra is metal-rich is now understood (Hood and Sonett, 1994) as not being diagnostic of its composition. Instead of Galileo providing definitive evidence, our picture of Gaspra as a fragment of a differentiated precursor body must rely on some evidence previously in hand (its extremely olivine-rich composition) combined with possible explanations for its differences from Ida (e.g. that its undersaturated crater population might reflect a metallic composition instead of an unusually young age; also that it might be a coherent fragment [of predominantly metal?] rather than a rubble pile [of stone?]). Independent of whether or not it is differentiated, Gaspra provided an important foretaste of the dramatic evidence to come from Ida concerning space weathering.

Galileo Observations of Ida

The first images of Ida to be returned from Galileo, in September 1993, were 5 frames in a single filter (clear) that were mosaicked to produce a lovely portrait of Ida (Fig. 2), which was analyzed by Belton *et al.* (1994). The rest of the Ida data were transmitted back to Earth the following spring. These included the images through spectral filters as well as the images showing Ida's satellite Dactyl. The ensemble of data has been thoroughly analyzed in a series of papers in *Icarus* (Vol. 120, #1, March 1996).

<u>Geology of Ida</u>

Ida's shape proved to be even more irregular than that of Gaspra or any other solar system object yet encountered by spacecraft. The best fit ellipsoid is 59.8 x 25.4 x 18.6 km; it can be described crudely as croissant-shaped and has actual maximum and minimum dimensions of 55.8 and 14.8 km (Thomas *et al.*, 1996). In addition to a 40 km long ridge, there is a "waist" around much of the middle of the body that appears to separate the object into two chunks. The reality of this two-component appearance is enhanced by significant differences in the geology expressed on the two parts. The heavily cratered portion to the top of Fig. 2 is in what Thomas *et al.* call Region 2. Not only does it contain all, or nearly all, of the craters larger than 6 km diameter (Chapman *et al.*, 1996b), but virtually all of the grooves seen on Ida are also in this region. Region 1 shows no large craters, but contains the prominent ridge (which does not extend into Region 2) as well as the unusual, large indentation known as Vienna Regio.

Ida's geology, first described by Belton *et al.* (1994), has been studied in more rigorous detail by Sullivan *et al.* (1996). They describe a suite of features that demonstrate the existence of a substantial regolith, 50 - 100 m thick, on Ida. The evidence for regolith on Ida is much more compelling than for Gaspra, due to the higher resolution images and because of the evidently much thicker regolith on Ida. Evidence includes ~20 large (up to 150 m across) ejecta blocks (Lee *et al.*, 1996), mass-wasting scars, the morphology of well-imaged grooves, and streaks oriented downslope. In addition, the full range of degradation states exhibited by Ida's craters, ranging from fresh to shallow and highly degraded, closely resembles lunar crater morphologies well understood to result from development of a regolith by saturated cratering impact. Chapman *et al.* (1996b) describe the size-frequency distribution of Ida's craters as following the saturation-equilibrium curve for diameters below about 1 km; given the typical depth/diameter ratio for fresh craters on Ida of 1:6.5 (Sullivan *et al.*), one expects an associated regolith depth ~150 m. Chapman *et al.* also note that the volume of ejecta from the largest craters on Ida would, if totally retained and spread around the body, make a layer ~150 m deep. Such rare, voluminous, interleaved ejecta blankets create coarse, poorly graded deposits better called megaregolith. Sullivan *et al.* see no evidence for a discontinuity between a regolith and underlying bedrock, as observed on the lunar maria; instead, the better-gardened upper layers probably grade into a much deeper megaregolith on Ida (indeed, as discussed below, the bulk of Ida's interior may be a coarse megaregolith or "rubble pile").

Chapman *et al.* (1996b) compare Ida's crater population with Gaspra's. Although Ida's craters saturate the surface at nearly all sizes, the population appears to be undersaturated -- hence in production -- for craters >1 km diameter on Thomas *et al.*'s Region 1. If Ida is being cratered by projectiles following the same steeply sloping production function inferred for Gaspra (differential index -4.3), then it has accumulated ~10 times as many craters as Gaspra. Everything else being equal, this might imply that Ida is ~2 b.y. old, using the same modelling parameters that yield a 200 m.y. age for Gaspra. However, there are some indications, although not definitive, that the Koronis family is considerably younger than that (Sykes *et al.*, 1989; Binzel, 1988). It has been suggested that the cratering rate in the immediate aftermath of the Koronis breakup may have been very high, although preliminary investigations do not seem to support the idea; possibly continued cratering by numerous small Koronis family projectiles could be causing Ida's surface to age more rapidly than other main belt asteroids (Binzel, 1995; Davis *et al.*, 1996). Other model parameters used in the Gaspra and Ida cratering age determinations are very uncertain (e.g. whether Gaspra has stony or metallic strength), so the age discrepancies are not serious ones. Ida's cratered surface could be as young as a few hundred m.y. or most of the craters could date back to the heavy bombardment period of early solar system history.

Internal Structure of Ida and Gaspra: Rubble Piles or Coherent Fragments?

Thomas *et al.* speculate on the nature of the structural dichotomy of Ida. Although studies of the surface alone cannot unambiguously define the interior structure, Thomas *et al.* infer a difference in mechanical properties between the two parts and poor coupling between them. (This conclusion is somewhat at odds with the work of Asphaug *et al.* [1996], who investigate the possibility that the grooves on Region 2 resulted from focussed seismic waves from the hypothetical impact that may have formed Vienna Regio in Region 1.) Thomas *et al.* decline to choose between the possibility that Ida inherited its structural dichotomy from its precursor body (the Koronis family object) or if the dichotomy instead indicates that Ida is dominated by two once-separate bodies that have come together in a contact binary configuration.

In either case, the low bulk density of Ida (see below) implies that the interior has appreciable porosity and voids. There is a strong inference, therefore, that Ida has an internal "rubble-pile" structure. The rubble pile concept was first proposed by Davis and Chapman (Davis and Chapman, 1977; Chapman, 1978; Davis *et al.*, 1979), who recognized that asteroids were likely to suffer collisions sufficiently energetic to fracture and fragment them, but not sufficient to launch the fragments into escape trajectories. The fragments would then reaccumulate into a multi-component object. The rubble pile concept has been widely adopted in the meteoritical community in attempts to reconcile meteoritical data with parent body models (cf. Taylor *et al.*, 1987).

It has never been clear what the size distribution of components of a rubble pile would be. If a solid, rocky object were fragmented and reaccumulated, the component pieces might have a size distribution like that of a typical Hirayama family, with most of the mass in the largest few pieces -- in some cases, such an object might look like a contact binary. However, subsequent collisions might also fail to disperse the object; it would be further pulverized by subsequent collisions and would evolve more nearly into a "gravel pile", with an internal structure resembling the lunar megaregolith. As originally formulated, the rubble-pile model was expected to apply chiefly to asteroids >100 km in diameter, whose gravity causes a large gap between the energy necessary to fracture and fragment them and the energy necessary to disrupt the body and disperse the fragments; such asteroids are calculated to undergo several generations of reaccumulation before final disruption (Davis *et al.*, 1985). Bodies originally the size of Ida and smaller were expected to be disrupted by the first collision sufficiently energetic to fragment them, thus not forming rubble piles. This expectation has been revised in recent years now that scaling considerations and hydrocode modelling (Ryan and Melosh, 1995) suggest that bodies ≥10 km diameter (or even smaller [Love and Ahrens, 1996]) are readily fractured but not easily disrupted.

Little attention has been given, however, to the probable internal structure of a fragment of a disrupted rubble pile, which is what Ida probably is as a member of the Koronis family (the Koronis precursor is expected to have been fragmented several times before it was disrupted). Recent studies of catastrophic disruption processes and asteroid families (cf. Davis *et al.*, 1996, and references therein), made in the context of understanding the formation of Ida and Dactyl, provide new insight concerning this matter and also may explain the numerous multi-component small asteroids that are being revealed by radar mapping (Ostro, 1993; Hudson and Ostro, 1995). Durda (1996) finds significant reaccumulation into contact binaries in his simulations. A smaller fraction of debris may even go into orbit around such an object, creating satellites like Dactyl; Durda finds it to be *likely* that an Ida-sized family member would have a satellite several hundred meters across or larger. Durda's modelling did not include asymmetric jets of ejecta (Martelli *et al.*, 1993), which would enhance the reaccumulation of multi-component bodies in the immediate aftermath of a disruptive collision. Therefore, it is quite plausible that a large family member of a precursor body 100-200 km in diameter (Gradie *et al.*, 1979; Marzari *et al.*, 1995) might have a rubble-pile/megaregolith structure, reflecting in part the fractured interior of the precursor body as well as the accumulation of smaller fragments in the immediate aftermath of the final disruption of that body.

Asteroid collisional modelling is not yet sufficiently secure to rule out the possibility that an Ida-sized, coherent object could have remained unfractured deep within the Koronis precursor body and have been ejected intact, without further reaccumulation, during the disruptive event. But it is reassuring to the modelers that the Galileo images suggest that Ida has a rubble-pile configuration. The contrasting interpretation of Thomas *et al.* (1994) that Gaspra *is* a coherent object suggests that it may be fundamentally different from Ida. While Gaspra is not a member of an identified family, that is probably because of difficulties in recognizing overlapping families in the "Flora region." Most Flora region asteroids, like Gaspra, are expected to be fragments of collisionally disrupted precursor bodies, just like Ida. I suggest that Gaspra's distinguishing trait may be that it is largely metallic, and thus it was strong enough to resist fragmentation prior to the final disruption of its precursor body. (Such an interpretation *cannot* apply to Ida, of course: its bulk density is much too low for a coherent metallic body, as discussed next.)

Ida's Satellite Dactyl and the Density of Ida

One of the most significant discoveries of Galileo's Ida encounter is the existence of Ida's small satellite, Dactyl, the first confirmed satellite to be discovered orbiting an asteroid (Chapman *et al.*, 1995, Belton *et al.*, 1996). Refined measurements indicate that it is 1.6 x 1.4 x 1.2 km in size (Veverka *et al.*, 1996a), an egg-shaped object oriented with its longest axis pointing towards Ida. Unlike Gaspra and Ida, Dactyl is smooth in shape, although it is cratered with a roughly saturation-density population of craters. It is interesting that about half of the dozen-or-so readily identifiable craters are in a linear chain, suggesting local origin (e.g. by crater ejecta launched from Ida).

The existence of Dactyl provided the opportunity to employ Kepler's third law in order to determine the mass of Ida and, given Thomas *et al.*'s (1996) estimate of Ida's volume as 16,100 ±1900 km^3, a bulk density for Ida. As described by Belton *et al.* (1995) and Belton *et al.* (1996), Dactyl's orbital arc was too short (and it was observed from a non-optimum perspective) to yield a definitive mass. But firm constraints on the orbit are placed by two requirements: (a) Dactyl must be on an elliptical orbit rather than a hyperbolic trajectory and (b) it cannot come too close to Ida or else its orbit would rapidly become unstable. These limits restrict Ida's bulk density between 2.0 and 3.1 g/cm^3. I emphasize that these are firm limits, not the ends of standard deviation error bars -- Ida is unlikely to have a density near the extremes, but values between 2.4 and 2.8 g/cm^3 are equally likely.

It is noteworthy that Ida's density is lower than that of any of the OC, achondritic, or more metal-rich meteorites that have been proposed as potential analogs for S-type asteroids (omitting anomalous, weathered meteorites discussed by Britt and Kring [1995]). Therefore Ida must be made of porous material, have appreciable void space, or both. Classic stony-irons (pallasites and mesosiderites) have densities near 5 g/cm^3, expected for roughly 50/50 mixtures of silicates (with densities a little more than 3 g/cm^3) and nickel-iron (with density approaching 8 g/cm^3). Noting that the porosity of a rubble pile is unlikely to be greater than 0.40 (Shoemaker *et al.*, 1979, find 20-30% reasonable), Belton *et al.* (1995) argued that such stony-iron compositions are rendered unlikely by Ida's unexpectedly low density. (The classic picture of a stony-iron core is of a metallic body with a veneer of stony-iron material from the interface with the stripped mantle -- for Ida to be such a metallic rubble pile, two-thirds of its volume would have to be void space, which is very implausible.)

How secure is this conclusion? It is conceivable that some resonance protects Dactyl against orbital instability near the upper density limit for Ida of 3.1 g/cm^3. And no one can be certain what percentage of void spaces could be sustained in a stony-iron rubble pile. Britt (Britt *et al.*, 1995; 1996) is reconsidering meteorite porosities, and these may turn out to be higher -- even for stony-irons -- than previously supposed. Moreover, some isolated samples of stony-irons have measured densities as low as 4.3 g/cm^3 (Wasson, 1974). But the fact remains that Ida's density turned out to be only *half* the density of classic stony-irons and *one-third* the density of irons, strongly suggesting that the classic stripped-core model is wrong, at least for Ida. To the degree that some meteoritic analogs for S-types have significantly lower metal abundances than classic stony-irons, they remain viable. But we must remember that McCord and Gaffey's (1974) original idea was to explain the spectral traits of S-types by high metal content. So, while Ida's density does not rule out all of the non-space-weathering alternatives that have been proposed in the past decade, it is difficult to reconcile Ida with the classic iron-core model that used to be advocated by Gaffey and his co-authors through the mid 1980's.

Spectral Properties of Ida and Dactyl

Galileo's Ida encounter has provided even stronger evidence that metal-richness cannot be invoked to explain all S-types, certainly not Ida. It has demonstrated that a space-weathering process is operating on Ida that, with time, straightens and reddens Ida's reflectance spectrum and reduces the depth of its absorption band -- just the characteristics of a process that would convert OC-like spectra to look like classic S-types. What makes this evidence particularly potent is that it is based on the same analytical technique -- visible and near-IR reflection spectroscopy -- that provided the strongest arguments against the OC alternative. No longer do we have an apples vs. oranges situation, with meteoritical and dynamical evidence having to be weighed against spectral evidence. For the first time, spectral reflectance evidence alone points toward the possibility that Koronis family material has inherent OC-like spectra and composition.

Ida's Spectral Variations

Ida shows rather prominent color variations across its surface, more prominent than on Gaspra[3]. Fig. 3 shows a false color representation of Ida, constructed from ratios in 4 Galileo SSI filters. As with the representation of Gaspra in Fig. 1, the units shown in red have a relatively reddish spectral slope and a shallow (or absent) 0.9µm absorption band. The units shown in blue are less red and have a moderately deep near-infrared absorption band. Simple inspection of Fig. 3 shows a prominent correlation of small bluish units with small, morphologically fresh craters. I believe the correlation was debatable on Gaspra due to the marginal spatial resolution, but it is secure on Ida. In addition, there are more extensive blue units, particularly prominent on the hemisphere of Ida opposite to that shown in Fig. 2 (centered near east longitude 300°) surrounding the large, morphologically fresh crater named Azzurra (Sullivan *et al.*, 1996). (Indeed, Azzurra was named -- following the grotto-and-cave nomenclature theme for Ida's craters -- for the sky-blue color of the Grotta Azzurra on the Isle of Capri.) Modelling by Geissler *et al.* (1996) has shown that the spatial distribution of the broad, bluish units on Ida corresponds very well with the irregular distribution of ejecta expected from Azzurra, given Ida's irregular shape and its complex gravity field. Just as for Gaspra, I suggest that the bluish regions on Ida are more nearly "pristine" while the reddish regions are more evolved or weathered. (On Gaspra, there is a correlation between topography and color, as the older, redder regolith migrates into low regions; on Ida, any correlation that might exist is overwhelmed by the deposition of Azzurra ejecta, which occurs on both high and low topography.)

One might imagine, instead, that there were no space weathering on Ida but that the Azzurra impact struck an underlying "lode" of material that was inherently bluer than most of Ida. (The lode would have to be small, otherwise additional craters on the same portion of Ida would have excavated blue material, too. The otherwise plausible idea that Ida's Regions 1 and 2 might be of somewhat different composition thus cannot be invoked to explain the visible color differences.) The problem, then, would be to explain the other widely separated, small, fresh, bluish craters. I cannot put together a self-consistent alternative model invoking regional differences in inherent, subsurface

---

[3]The color differences found by Galileo, however, are not nearly large enough to be compatible with the rotational variations in spectra of Ida reported by Barucci and Lazzarin (1993). I believe their telescopic data must be erroneous. Lazzarin (1996, pers. comm.) has been unable to identify a plausible source of error in her data, but the single night's observation cannot be sustained in the light of Helfenstein *et al.*'s (1996) comprehensive analysis of Galileo's SSI color data through a complete rotational cycle.

composition. The correlation of color with the relative age of features, whether large (like Azzurra) or small, seems compelling to me.

Thus, Ida's bluish units correlate with the apparent youthfulness of the surface exposure of the material and Ida's surface becomes progressively "redder" (straighter spectrum, shallower band) with time. This is the definition of a "space weathering" process: the color of a material of constant composition, exposed to the interplanetary environment at a body's surface, progressively changes color with time. Although Gaffey *et al.* (1993b) had begun to accept that *some form* of space weathering or regolith evolution was affecting asteroid colors, Ida presents a strong case that asteroidal space weathering exists.

What are the traits of Ida's space weathering? Does it operate in the sense that would evolve the spectrum of OC-material to resemble that of an S-type? This can be studied by examining the suite of spectra represented on Ida. Ideally, if Ida were an OC, the very most recent exposures of bedrock would have OC spectra. Depending on the relative rate of space weathering compared with processes (impact and otherwise) that expose fresh material at the surface, older units would show progressively more evidence of weathering, perhaps saturating (i.e. no further change in color with time) for the oldest units. Given the fact that the optical surface of Ida is exceedingly thin compared with the >100 m depth of Ida's regolith, one would expect the percentage of pure units on Ida to be very small -- it does not take long to overturn, modify, or erode the uppermost optical surface. Indeed, the bluish units represent a minority of Ida's surface and "average Ida" is only a little less red than the average reddish unit. However, the actual rate of space-weathering color changes depends on unknown attributes of the space-weathering process itself. It also depends on the rates of regolith processes (turn-over, ejection, erosion of rocks) that occur at spatial scales far smaller than can be resolved by Galileo imaging. Nevertheless, it is instructive to examine the range of spectral units on Ida to investigate whether they form a continuum along part of a space-weathering trend from pristine to completely weathered. One might then extrapolate such a trend backwards in time to infer the spectrum of the pristine end-member and see whether it is consistent with OC or some other mineral assemblage.

The most definitive published analysis of Ida's spectrum is fairly coarse for investigating whether a variety of fresh to weathered units exists on Ida. Veverka *et al.* (1996b), using the best available photometric calibration of Galileo SSI data (Helfenstein *et al*., 1996), divided all pixels on Ida into just two units on the basis of the 1μm/0.4μm ratio, called Terrain A (the redder regions) and Terrain B (the bluer regions). (In earlier work [Helfenstein *et al*., 1994b], the Cornell group had defined a third unit, Terrain C, subsequently subsumed within B.) As averages of broad regions on Ida (roughly 3/4ths and 1/4th of Ida's total surface area for A and B, respectively), the spectra shown in Fig. 4 must be regarded as *averages* themselves, rather than as reflecting the spread of end-members.

Terrain C is slightly more extreme than Terrain B in its differences from average Ida. The disk average for the color sequence centered near subspacecraft longitude 10° (Helfenstein *et al.*, 1996) is slightly more extreme than Terrain A in having an even shallower absorption band and a more linear continuum. Sullivan *et al.* (1996), also using Helfenstein *et al.*'s photometric calibration, published a spectrum for one case of a still more extreme sub-unit along the spectral continuum: a strongly reddish spot near a small bluish crater (this spot seems anomalously red, for reasons that are not clear). As plotted in Fig. 4, the range between Terrain C and Sullivan *et al.*'s "Red1" unit show, unsurprisingly, that the range of Ida spectra exceeds the range between Veverka *et al.*'s Terrains A and B.

In collaboration with E. Ryan (Ryan and Chapman, 1996) and with thanks to P. Helfenstein for providing the calibrated files, I have examined two of the Helfenstein color ratio maps for Ida in more detail (Fig. 5). For purposes of this analysis, we performed 3 x 3 pixel running boxcar averages of the ratio maps to reduce pixel-to-pixel scatter and effects of slight misregistration of the separate color images. We expect that the statistical scatter of these 3 x 3 averages is about 3%; scatter is further reduced by averaging larger regions. Units can be identified that span the range between Terrains A and B and, more significantly, extend beyond that range. There is a diversity of spectra of small- and moderate-scale units that are bluer than average Ida, extending to considerably bluer than even the Terrain B average. Few reddish spectra are more extreme than Terrain A, however, consistent with the hypothesis that Terrain A may closely approximate a mature, equilibrium spectrum.

Fig. 6 shows the spectrum of a small fresh crater near the middle of the high resolution color image. The crater is within the large crater Sterkfontein; perhaps the larger crater excavated through regolith so that it was easier for the small, more recent crater to be formed in, and reveal, "bedrock". Also shown is the spectrum for the average of several reddish regions well away from blue units, shadows, and edges, selected to represent "pure" background. The latter spectrum is only slightly redder than that for Veverka *et al.*'s Terrain A, but the fresh crater is considerably more exaggerated than Terrain B, especially in the depth of its absorption band. I suggest that the latter is the least weathered resolvable unit in the Galileo Ida data.

Fig. 6 also shows average laboratory spectra for OC meteorites of the L class (from Gaffey *et al.*, 1993a); separate average spectra for the most common petrologic grades, 5 and 6, are shown. By inspection, it is clear that the spectral trends observed on Ida are of just the character that would transform an L5 or L6 OC spectrum into an S-type spectrum: the "bend" in the visible spectrum is progressively linearized, the overall continuum is reddened, and the 1μm absorption band is weakened. Qualitatively, the Galileo Ida data alone exhibit units that span most of the variation between the pure L5 spectra and average S-type. (The pure weathered units are similar to some of the redder S-type asteroids which have a weak or absent absorption band; some less extreme S-types may well be, like Ida, a mixture of spectral units so that their disk-averaged spectra are less extreme than the pure background units found here.)

Finally, Fig. 6 shows spectra for the bluest units associated with Azzurra, chiefly near Azzurra, but also including the patch of Azzurra ejecta on the opposite side of Ida near the crater Undara (near the limb of the high-resolution color sequence). Azzurra spectra are not so extreme as for the small, fresh crater in Sterkfontein. Apparently Azzurra is older and more space weathered than the small fresh crater. Most of Terrain B, including the patch near Undara, is spectrally similar to Azzurra, consistent with the Geissler *et al.* (1996) hypothesis that large patches of Terrain B are Azzurra ejecta. Veverka *et al.*'s Terrain B average also includes an admixture of regions that are intermediate between Azzurra ejecta and pure background -- some of the larger intermediate units may be spatially unresolvable mixtures of the two terrains, or actual physical mixtures (e.g. where the younger unit is very thin), rather than units of intermediate age.

Obviously, even the smallest color pixel on Ida (10^4 m^2) must still be an average of unresolved smaller-scale heterogeneity which could have even greater spectral diversity. Presumably the purest, least space-weathered units would consist of the floors, rims, or ejected blocks from very recent (hence, most probably very small) craters formed in "bedrock" -- those not formed solely within space-weathered regolith, hence where the regolith is thin. The search for such small units can be done on Eros by the Near Earth Asteroid Rendezvous (NEAR) mission, which should attain spatial resolutions in color at least a factor of 30 better than Galileo obtained on Ida (Veverka *et al.*, 1996c).

Analogous to the expected youth and freshness of a small proportion of small craters, one would expect that a few small asteroid fragments in the main belt would have been created very recently and not had time to weather. Therefore, spectral surveys of ever smaller asteroids should eventually turn up a few nearly-pristine, unweathered OC types. This should not, however, be interpreted as a vindication of Bell *et al.*'s (1989) prediction of the existence of small Q-types as objects of inherently different composition from larger asteroids. It would be the natural expectation that some smaller, fresher asteroid fragments would not have had time to be modified by space-weathering. In fact, Binzel *et al.* (1996) have recently reported just such a spread in spectral properties, between OC-like spectra and S-type spectra, among small near-Earth asteroids. This is strong evidence for a genetic linkage between S-types and Q-types, most reasonably explained in terms of Q's gradually turning into S's with time, or -- as Binzel *et al.* say -- "through a time-dependent surface weathering process." The surveyed near-Earth asteroids are typically 3 km in diameter; I would predict that when reliable spectra can be measured for main-belt asteroids as small as 3 km, OC's (Q-types) will indeed begin to turn up, further vindicating the space-weathering hypothesis.

The qualitative correspondence between the trends observed on Ida and those required for a space-weathering process to convert OC material to look like S-types demonstrates that a *form* of space-weathering operates on Ida. Fig. 6 shows that the pristine end-member material *could* be OC, based on backwards extrapolations of the observed trends: if one assumes a pristine spectrum similar to L5 meteorites, the small fresh crater spectrum is evidently consistent with ~30% evolution toward the weathered, background spectrum, implying that L5 material *could be*, within errors, the original (unweathered) material on Ida. The L6 spectrum could be the original material if the small crater represented ~65% weathering, except that the evolution is consistent only in the infrared, not in the 0.4 - 0.55μm range (the differences between the spectra of the different petrologic grades of L chondrites are examples of how a physical process -- metamorphism -- can modify the petrological characteristics of the same material, on the same body).

Pristine Ida material probably has a spectrum that is "OC-like". However, a more quantitative demonstration that Ida's precise spectrum can be derived from OC is desired. For example, Gaffey *et al.* (1993b) have already argued that inferred regolith-mediated alteration of S-types shallows absorption bands but does *not* as systematically change the redness of the continuum, especially in the infrared longward of SSI's wavelength coverage (I will discuss such infrared data more below). Furthermore, without a more definitive characterization of the physical weathering process, one cannot prove that the observed spectra are *uniquely* diagnostic of OC mineralogy as the end-member of the trend. Other rocks dominated by mafic silicates could also be space-weathered to look S-like (Wasson and Chapman, 1996).

In detail, the spectra in Figs. 4 and 6 are not all consistent with the same inherent mineralogy, provided one ignores the typical error bars of ±3%. For instance, the values of the two longest wavelength points could be interpreted as indicating longer or shorter central wavelengths for the 1μm band. But, within error bars, the central wavelengths could all be identical.

Since Ida is not adjacent to the 3:1 resonance, neither it nor any Koronis family member is likely to be the source of known OC's. However, pristine Ida's spectrum probably matches those of observed OC's more closely, for example, than other spectral matches that have been proposed, such as Binzel *et al.*'s (1993b) claim that 3628 Božněmcová is an OC asteroid (see below). So Ida, and Koronis family members, may have OC-like mineralogy. Whether they do or not, we may conclude that any Ida-like space-weathering process operating on a *real* OC-parent body would produce something that would be classified within the broad confines of S-type asteroids (probably S(IV)), not as a Q or an O. In other words, the S-type field (not Q's or O's) becomes the domain of choice in which to search for potential parent bodies for OC's because Galileo's Ida data have demonstrated the qualitative nature of expected space-weathering trends.

I consider the above discussion to be sufficiently conclusive. However, three other matters associated with Galileo's Ida encounter bear on these important issues and must be discussed: (a) SSI spectra of Dactyl, (b) Veverka *et al.*'s (1996b) contradictory interpretations of the same Ida and Dactyl data, and (c) NIMS spectra of Ida and Dactyl.

Dactyl's Spectrum

SSI data for Dactyl (from Veverka *et al.*, 1996b) are also shown on Fig. 4. Dactyl's spectrum looks similar to, but even a little less weathered than, Terrain C. Its absorption band is deeper, its bending character in the visible stronger, and its continuum less red than, for example, Terrain B. Dactyl, is not as "pristine" as the small, fresh crater, but it is less weathered than major units on Ida. This is certainly consistent with the general expectation that bodies with as little gravity as Dactyl should accumulate minimal regolith, and whatever regolith that might exist would be expected to be immature and frequently refreshed -- hence "young". Although Dactyl has the possibility of accumulating debris in orbit around Ida (which would not be true for an independent asteroid of Dactyl's size), the expectation is that Dactyl is undergoing rapid net erosion (Geissler *et al.*, 1996; Chapman *et al.*, 1995). Therefore, despite the fact that we cannot be sure of where Dactyl fits in the relative chronology of features on Ida's surface, its spectrum (closely resembling L-type OC's of the rarer petrologic grade 4 as measured by Gaffey [1993a]) lends credence to the possibility that the Koronis parent body had OC-like mineralogy.

Veverka *et al.*'s Analysis

Analyzing the same Helfenstein data set, Veverka *et al.* (1996b) reach different conclusions from those described here. Why? First, data comparison is confused since Veverka *et al.* normalized spectra at 0.76μm rather than at the conventional 0.56μm. Then their discussion emphasizes the spectral slope between the violet and the red (0.4μm and 0.67μm), which is not a diagnostic discriminant between OC and S-types (both S-subtypes and OC sub-types span the narrow range of spectral slope, well within the noise anyway, analyzed by Veverka *et al).* What *is* relevant is the BEND parameter, which measures curvature between 0.4μm and 0.73μm. Veverka *et al.* say that "Dactyl should have a less red spectral slope" than Terrain B if there were a weathering trend, emphasizing that Terrain A has a slope similar to Dactyl's and that Terrain B (the supposed intermediate case) is the outlier, thus refuting a weathering trend. Analysis of the more appropriate parameterization of the visible spectra, however, as best

BEND can be inferred from values interpolated between the 0.67µm and 0.76µm filters, shows the appropriate trend of decreasing BEND from Dactyl to B to A.

Veverka *et al.* also claim, along with Granahan *et al.* (1994b), that Dactyl has "slightly higher pyroxene to olivine ratio than Ida," but they seem to contradict themselves by arguing that Terrain C (which closely resembles Dactyl) is so similar to Terrain B that they have chosen to subsume it *into* Terrain B. (Actually, the data in Figs. 4 and 6, if taken at face value without reference to the 3% errors, would indicate the opposite: Dactyl's longer wavelength band suggests a lower pyroxene-to-olivine ratio.) Veverka *et al.* emphasize differences in slope of the spectral curves between the violet and the red, but all such differences shown in Figs. 4 and 6, except perhaps the most extreme, are within the noise and systematic uncertainties. The minor variations seen in the violet filter are within ±0.03 of 0.82, similar to Veverka *et al.*'s plotted typical error bar of ±0.02.

I have already pointed out that Veverka *et al.* based their analysis on a division of all of Ida's surface into two spectral units, which are therefore averages. Yet their analysis -- emphasizing such parameters as single-scattering albedo (differing from only 21% to 22%!) and texture inferred from photometric parameters -- is valid only when dealing with homogeneous material. It is well known that, especially for heterogeneous materials, albedo is not a useful diagnostic. Meteorites (including undifferentiated types) and other materials with identical spectral properties often have albedos varying by 10% or more; checkerboard spatial heterogeneity (such as due to localized shock blackening) can introduce even greater differences. Albedos are also affected by particle size distributions, about which we have little independent knowledge and which may differ from place to place or body to body. Yet, Veverka *et al.* conclude that the minor spectral differences between Dactyl and Ida can be explained only by true compositional differences *because* their average albedo and photometric properties are so similar!

Most asteroid reflection spectroscopists are leery about the utility of spectral data shortward of 1.1µm for determining pyroxene-to-olivine ratios, even when the precision of the data is extremely high and the spectral resolution across the 1µm band is good (although Chapman and Salisbury [1973] showed that it was possible in the OC context). However, I am unaware of anyone previously claiming to conclude from coarse 6-color photometry across the 0.4 - 1.0µm range that they can confidently deduce pyroxene-to-olivine ratios. I think Veverka *et al.* are wrong and have overinterpreted spectral variations that are manifestly in the noise.

Finally, Veverka *et al.* build on an earlier argument by Binzel *et al.* (1993a) that individual groundbased spectra of faint, small Koronis family members vary in ways that might be interpreted as reflecting modest but real compositional differences, beyond what might be expected between petrologic (metamorphic) grades within a parent body of one of the three OC classes. I agree that there are real spectral differences among Koronis family members, but I do *not* agree that differences in the 1µm band region are large enough to warrant a tentative conclusion that parent body differentiation may need to be invoked; some differences are similar in magnitude to the error bars and other systematic errors, and larger differences suffer from the same difficulties of averaging heterogeneities (since the telescopic data are necessarily hemispheric averages) that I previously discussed. There are also uncalibratable effects of the minor terrestrial atmospheric water band within the 1µm band and the natural variability of reflectance spectra among meteorites of the same classification. (For similar reasons, until more observations are made that can reduce the error bars, I am as yet unpersuaded that minor spectral variations on opposite sides of the S(IV)-type asteroid 433 Eros, found by Murchie and Pieters [1996] from analysis of the Pieters *et al.* [1976] data actually demonstrate real mineralogical variations on Eros that span most of the extent of the S(IV) field. The variations would ostensibly imply mineralogy ranging from LL to H across Eros, which would be difficult to understand from a cosmochemical perspective.)

Another point is that Dactyl's spectrum, in an important respect, *does* fall outside the range of variation observed by Binzel *et al.* among Koronis family members, despite the contrary claim by Veverka *et al.* None of the Koronis family members shown by Binzel *et al.* have as large a BEND parameter as shown by Dactyl (compare Dactyl's upward curvature in the 0.4 - 0.73µm region with the more linear trends of other asteroids, including Ida, shown in Fig. 7). Since Dactyl is so much smaller than any of the Koronis asteroids observed by Binzel *et al.*, it is significant that it has the largest BEND parameter, deepest absorption band, and one of the bluest continua among the 6 Koronis family members studied: by the criteria I have discussed, Dactyl is *least weathered* among these asteroids.

There does remain a question about what factors influence the spectral slope between 0.4 and 0.55μm. Although Dactyl has a low 0.4 μm reflectance, the small, fresh crater, which has an even deeper infrared absorption band than Dactyl, has an 0.4 μm reflectance very similar to both Terrains A and B (actually between them). One can also ask about what property of L ordinary chondrites causes such a large difference between L5 and L6 in 0.4μm reflectivity (Fig. 6). If L6 were the starting material, one could conclude that the space weathering process on Ida raises the UV reflectivity more rapidly than it weakens the infrared absorption band; but if the starting material were L5, one would conclude, instead, that the space weathering process has negligible effect on the UV reflectivity. The answers to these questions remain to be understood, but the effects are second-order compared with the weathering trends I have described.

NIMS Data

Galileo's Near Infrared Mapping Spectrometer (NIMS) made potentially critical measurements of the reflectance spectra of Ida (and units thereon) as well as of Dactyl. Unfortunately, complex issues of calibration have not been fully resolved and exploited as of this writing (Granahan, pers. comm., Oct. 1995), although it is expected that some of them eventually will be. Calibrations of spacecraft instruments are difficult; uncertainties of several percent (which exist for SSI and, according to R. Carlson [pers. comm., 1996], for NIMS as well) render absorption band position measurements uncertain, which is why analyses of SSI images rely on spectral differences independent of absolute calibration. Earlier premature reports by NIMS investigators that Ida is an exceptionally olivine-rich object (Carlson, 1994) and that Dactyl is rich in clinopyroxene (Carlson *et al.*, 1994) have been effectively withdrawn (J. Granahan, pers. comm., 1995; R. Carlson [pers. comm., 1996] agrees that the evidence for clinopyroxene is "weak").

A preliminary reduction of NIMS data (augmented at wavelengths <1μm by SSI data, J. Granahan and F. Fanale, pers. comm.; see also Fanale and Granahan, 1995), subject to revision, is shown in Fig. 8. Channel-to-channel variations can be trusted to only ± several percent. But the general trends probably reflect reality. They hint that the infrared continuum in the 1 - 2μm range, is greatest for the reddest unit on Ida, less for the bluer units, and least of all for Dactyl. (Small units, like the fresh, bluish crater, are not spatially resolvable by NIMS.) These indications appear to reinforce my earlier conclusions of a space-weathering trend on Ida, compatible with well-documented differences in the 1 - 2.5μm continuum between OC's and S-types measured by the 52-color survey (Bell *et al.*, 1988).

Discussion of Other Recent Research

While Ida has provided the most important new evidence concerning the S-type conundrum, progress has been made on other fronts during the past few years. Some of the research has been motivated by the Gaspra and Ida results, including renewed theoretical and laboratory research on space weathering processes, new approaches to modelling the spectral signatures of S-type analog materials (especially in the 1 to 2½μm wavelength range), and more detailed studies of interesting S(IV) asteroids such as 6 Hebe and 433 Eros. Observational programs, especially the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) of R. Binzel and his co-workers, have tested the predictions of Bell *et al.* (1989) that OC parent bodies would be found among the smaller asteroids. Much of this work buttresses the inferences from the Ida encounter that some of the larger S-type asteroids (and their fragments) must be the parent bodies for the OC meteorites and are being spectrally modified by space weathering processes.

Alternative perspectives have been developed, however, including Britt's hypothesis that low albedo asteroids are the source bodies for OC's, based on a shock darkening process. Meanwhile Bell and several of his colleagues, while acknowledging that a space weathering process is manifest on Ida, continue to deny that any of the larger S-types can be of OC composition, regarding them instead as parent bodies only for an increasing variety of minor meteorite types, including primitive achondrites, being identified in the Antarctic collections. In this section I review the 1990's research bearing, both positively and negatively, on the space-weathered OC model for such S-types as Ida.

SMASS Tests Predictions of Abundant Small Q-Types

The SMASS survey of small asteroids (Xu *et al.*, 1995) was designed, in part, to test the Bell *et al.* prediction that Q-type OC parent bodies would be found among the small main-belt asteroids that were too faint to be included in such earlier surveys as ECAS. Using a CCD detector, SMASS is restricted to the same visible and near-IR wavelengths as the Galileo SSI (0.45 - 1.0μm). Bell *et al.*'s prediction was that "small (<10 km) ordinary-chondrite source bodies (= Q-class asteroids?) will be found in the inner main belt." Although ambiguous, it appears that Bell meant 10 km *radius*, not *diameter*, since the ECAS sample was limited to asteroids larger than 20 - 25 km diameter in the inner belt. In any case, the first published sample of SMASS objects range in diameter from 4 to 20 km, with approximately half of them <10 km diameter.

One of the most widely discussed results of SMASS is the discovery of a single asteroid, 3628 Božněmcová, which shows a spectrum somewhat like that of OC material (Binzel *et al.*, 1993c). I will return to Božněmcová below, but first I want to emphasize the prime result of SMASS: of the 316 asteroids sampled, there are *no Q types* and only 2 asteroids with spectra somewhat resembling OC's. The SMASS survey is continuing, with several times as many small asteroids now sampled, and preliminary examination of much of these data reveals the same thing (R. Binzel and S.J. Bus, pers. comm., 1996): main-belt asteroids exhibiting Q-type and OC-like spectra are exceedingly rare.

Two SMASS asteroids have been put forward by Binzel and Xu as possible OC bodies. One of these, 2078 Nanking, is classified by Xu *et al.* as an unusual S-type; its spectrum has principal component values in the direction of the one well-classified Q-type (1862 Apollo). However, as shown in Fig. 9, 2078 does *not* match laboratory spectra of H chondrites, the suggested analog. In fact, it deviates from H chondrites in just the same ways -- although not as much -- as S-types in general: its spectrum is too red and too linear and its absorption band is weaker. In any case, 2078 Nanking is not relevant to the question of main-belt OC objects because it is a Mars-crosser on an inherently transient orbit, so it is just as conjectural about where it originated as are the origins of Apollo and the OC meteorites themselves.

Now let us consider 3628 Božněmcová, a small main-belt asteroid with an exceptional reflectance spectrum. Binzel *et al.* (1993b) suggest that it is an ordinary chondrite and Xu *et al.* propose it as the type example for a new taxonomic class (O, for ordinary chondrite). However, as shown in Fig. 9, Božněmcová's spectrum seems to deviate in several ways from laboratory spectra of OC meteorites. Indeed, one of the classic attributes of OC spectra -- their extreme curvature in the visible measured by the BEND parameter -- is totally missing from this asteroid's spectrum, which fails to curve at all shortward of the sharp inflection point near 0.77μm. The spectrum of Božněmcová not only deviates from the other proposed OC object in the SMASS survey (2078 Nanking, also shown in Fig. 9), but it also may deviate from OC meteorites in two other important respects. These relate to the data plotted as small dots in Fig. 9, which were published by Xu *et al.* but omitted from the original Binzel *et al.* (1993) paper due to judgement by Binzel that data toward the ends of SMASS spectra are less reproducible and reliable than the remaining data.

First, its spectrum seems to be still going down at 1.00μm, implying the band minimum is >1.00μm. This attribute alone would virtually rule out OC composition because it implies an olivine/pyroxene ratio too olivine-rich for even the most olivine-rich OC's, the LL chondrites. For example, Chapman and Salisbury (1973) demonstrated that the band center moves to longer wavelengths as a function of olivine content of OC's; it is at the longest wavelength for LL's (0.97μm) and never exceeds 1.00μm even for LL outliers; Gaffey (1976) found that band minima for LL's ranged between 0.93 and 0.99μm. Thus Božněmcová could be ruled out as an OC object (based on literal interpretation of the full data set as published by Xu *et al.*) and, indeed, would then be considered as a probable differentiated object, using the same reasoning applied to Gaspra prior to the Galileo fly-by. Binzel (1996, pers. comm.) says that new infrared data of Božněmcová are compatible with LL chondrite spectra; the disparity between the two data sets is unresolved, so the question of Božněmcová's olivine content (and likeness to ordinary chondrites) must await more definitive measurements of the asteroid's 1μm band as well as its 2μm band, if possible, to define its silicate mineralogy.

A prominent feature of OC spectra is the deep charge-transfer band, the long-wavelength wing of which is responsible for the spectra plunging toward the ultraviolet. Especially given the apparent strength of Božněmcová's 1μm band, implying an absence of opaques, one would expect a strong charge-transfer band. Instead, the reflectance data shortward of 0.5μm (which Binzel *et al.* report were consistent over the multiple observations on several nights) are much too high compared with OC meteorites, especially those (type 6) that best match the long wavelength band. The more recent data (Binzel, 1996, pers. comm.) show the same discrepancy, but less strongly.

Božněmcová certainly exhibits an extraordinary spectrum, but it is clearly *not* identical to spectra of unmodified ordinary chondrites (in making this statement, I give special weight to the apparently reliable measurements in the 0.5μm - 0.8μm wavelength range). Therefore, I conclude that SMASS has utterly disproved Bell's prediction: it has (so far) found *no Q types* in the main belt nor has it found even one indisputable, unmodified spectral analog for ordinary chondrites.

Modelling S-Type Spectra: the Role of Metal

The failure to find OC parent bodies among smaller main-belt asteroids has redirected the attention of most researchers toward trying to understand the spectra of the larger S-types. Particular attention has focussed on the infrared portion of reflectance spectra (out to ~2.5μm) because of the increasing number of high quality infrared spectra that have been measured.

The chief source of mid-IR spectra of asteroids is the still unpublished (but widely available) 52-color asteroid survey of Bell *et al.* (1984, 1988). These spectra motivated attempts by Hiroi, Takeda, and their collaborators to search the expanding collections of Antarctic meteorites for silicate assemblages that might match the IR spectra of S-type asteroids. The first laboratory spectra of several of these rare types (an acapulcoite and two lodranites) by Hiroi and Takeda (1991) failed to match S-types for the usual reasons (e.g. the absorption bands need to be weakened to match S-types), so they resorted to the traditional approach of numerically mixing these silicate assemblages with meteoritic metal as in the iron meteorite Mundrabilla (Hiroi *et al.*, 1993). While there is a cosmochemical basis for thinking that primitive achondrites may be found in association with metal (e.g. in a less completely melted parent body than for traditional stony-irons), the hypothesis is essentially *ad hoc*.

Clark (1996; see also Clark and Hiroi, 1994) has pointed out that S-type spectra are essentially flat at wavelengths longward of 1.5μm, unlike the reddening that is so prominent at shorter wavelengths. Therefore, she argues, the admixture of nickel-iron sufficient to explain the reddened aspect of S-types in the visible causes *too much reddening* at long wavelengths, because the metal component is also red at long wavelengths. The "successful" modelled fits to S-types obtained by Hiroi *et al.* were forced by unrealistic features of the experiments, including particle size and specular component. (Britt and Pieters [1988] showed that the reddened attribute of FeNi is due to the specular component, rather than the diffuse component, of reflected light.) Clark believes that metal cannot be the reddening agent for S-types.

Of course, no argument about the spectral modelling addresses the serious problem of why the most common asteroid class in the inner belt should be represented by a mere handful of rare meteorites. Most researchers are looking again to the larger S-types near the 3:1 and $\dot{\nu}_6$ resonance escape hatches. Recently, notwithstanding Clark's negative evaluation of the role of metal in reddening S-types, Gaffey (1996a,b) has proposed that the spectrum of 6 Hebe can be explained as a possibly ordinary chondritic body in which impact and regolith processes have concentrated metal on its surface. Impact production of sufficient metal on Hebe is apparently impossible (Keil *et al.*, 1996), so I would invoke space-weathering as the preferred explanation for the reddened spectra of Hebe and other S(IV)'s. Hebe has long been regarded as a prime source of meteorites due to its size and proximity to the $\dot{\nu}_6$ resonance (Morbidelli *et al.*, 1994); detailed numerical integrations of modelled ejecta from Hebe by Farinella *et al.* (1993) show that Hebe ejecta should constitute very roughly 10% of the total meteorite influx to Earth. Even if some of the modelling assumptions are greatly in error, it seems to be inescapable that some meteorites must come from Hebe.

The ultimate test of whether macroscopic metal content can explain the reddening of S-types may be the improved radar reflection surveys of asteroids expected when the upgraded Arecibo radar begins operating by 1997. Already, the evidence seems to be running against abundant metal on S-types. As reviewed by Ostro (1989), radar albedos of most asteroids are rather low with only modest average differences between the C-type asteroids (which few would believe are metal rich) and S-types; indeed the two distributions substantially overlap, and are much lower than the albedo of the large M-type asteroid 16 Psyche, which is evidently metal rich. Uncertainties in the radar cross-section of naturally occurring meteorite assemblages led Ostro to demur on making conclusions about the metal-richness of S-types.

More recently, Ostro *et al.* (1991) measured the radar albedo of an M-type Earth-approaching asteroid and found it to be 4 times greater than that of 6 Hebe, 5 times greater than the average of 30 other main-belt and Earth-approaching asteroids, and between 4 and 10 times more reflective than 3 small S-type NEA's. With radar albedo determined chiefly by metal content and bulk density (affected by inherent composition and porosity), these data seem to establish the high radar albedo of metal-rich objects. They imply that most S types have metal contents too low for the roughly 50/50 mixtures characteristic of stony-irons (unless porosities are unrealistically high, >60%). As shown in Fig. 4C of Ostro *et al.* (1991), the radar reflectivities of large, main-belt S-types like 6 Hebe are similar to those modelled (based on laboratory investigations) for powdered OC's with porosities ~40%. While radar work has not yet nailed the lid on the coffin of metal as the reddening agent for S-types, it may soon do so.

<u>Regolith Breccias and Shock Darkening</u>

One partial solution to the S-type/OC conundrum would be if some other common (non-S) asteroid type could be shown to be parent bodies for the OC's. While such a result would neither resolve what the S-types are nor why they are so poorly represented among meteorites, at least there would be a larger source for the abundant OC's than the virtually non-existent Q- and O-types. Britt and Pieters (1987) suggested that physical processes associated with impacts and exposure of asteroid surfaces to the space environment might cause OC asteroids to masquerade as C-types. In particular, they pointed to the gas-rich, shocked "black chondrites" as a possibly dominant surface component of OC parent bodies.

Britt's is a startling suggestion, indeed. The conventional view of Chapman and Salisbury (1973), Matson *et al.* (1977), and others that there might be little or no space-weathering on asteroids is turned on its head. Despite all the factors that mitigate against mature space-weathering of asteroid surfaces compared with the Moon's, Britt would have asteroid surface spectra modified and blackened to a far greater extent than even the lunar maria!

Many meteorites have attributes possibly related to parent-body surfaces. Besides the black chondrites, a variety of brecciated meteorites, composed of clasts, are interpreted to result from impacts. The traditional picture is of a lunar-like regolith in which gases from the solar wind are implanted into surficial grains, which become churned and mixed through the regolith. Then cratering impacts, perhaps including the impact that launches the meteorite from the asteroid, fragment, crush, and shock asteroidal surface rocks and soils, sometimes melting or altering grains. In addition, impact shock can actually lithify particulates into strong rocks. The clasts of a resulting breccia are generally composed of related rocks, derived from the locality of ground-zero on the target body. Often regolith breccias contain a few clasts of wholly different mineralogy and isotopic make-up (xenoliths), derived from the projectiles.

Much remains to be learned in order to verify and quantify this qualitative picture of asteroid regolith processes. The lunar regolith is actually a poor analog for asteroidal regoliths (Housen *et al.*, 1979); asteroidal regoliths are coarse and immature due to significant escape of ejecta. Recent analyses of brecciation and shock metamorphism of asteroidal surface materials have been done with better appreciation of the asteroidal context than was previously true. For example, Stöffler *et al.* (1991) have recognized that most shocked OC's are derived from "predominantly within the inner impact formations (breccia lens and crater basement) of craters large enough to penetrate through regolith into more or less coherent rock units." Keil *et al.* (1992) have emphasized that in order to salvage the Britt and Pieters hypothesis, one must rely on that fraction of blackened meteorites that are derived from the uppermost, fine grained regolith surfaces of asteroids. It is doubtful, however, that many such meteorites exist. Even candidates for such materials tend to be small dark *portions* of gas-rich meteorites having clasts with a variety of albedos.

Britt (1996) continues to advocate that gas-rich, blackened OC meteorites might cover OC parent body surfaces, but simple geometry argues otherwise. The grains that comprise the optical surface of an asteroid are the only ones subject to gas implantation, radiation damage, micrometeorite impact, and other space weathering effects. Meteorites, however, are *volumetric* not *surficial* samples of asteroids, with a substantial contribution (due to the population index of the asteroid size distribution) from the biggest, deepest cratering events. While the dark, gas-rich portions of meteoritic regolith breccias no doubt preferentially include grains that spent time at the parent body surfaces, few if any meteorites are samples of surficial regolith powders. Even deep samples of asteroid rubble-piles/megaregoliths may include some material once at or near the surface. Meteorites must be preferentially the strongest, most lithified parts of asteroids (e.g. from crater basements, hence most likely to be shock-blackened), required for them to survive ejection from the asteroid and penetration of the Earth's atmosphere. The ejecta and unconsolidated regolith preferentially retained and redistributed across the asteroid surface must be mostly unshocked because the volume subject to shock is of the order of the volume of the projectile whereas the volume excavated from the resulting crater is typically two orders of magnitude greater. Short of a hundred-fold saturation environment, which doesn't even exist on the Moon, impacts simply cannot, and do not, blacken whole surfaces of asteroids to the degree required by the exceptionally low albedos (few percent) characteristic of C-type asteroids.

Related to the above discussion is an argument by Bell and Keil (1988) based on laboratory spectral studies of OC's classified as gas-rich regolith breccias. They contend, and Bell continues to assert, that these rocks are actual samples of OC parent-body optical surfaces. Therefore, they argue, the failure of their spectra to exhibit the classic attributes of S-type asteroids (e.g. reddening) is proof that S-types are not space-weathered OC's. However, it makes no sense to think that a lithified rock, preferentially delivered to Earth, could be representative of loose, unconsolidated soils at the optical surface of an asteroid. First and foremost, the breccias are *not soils*! To contain implanted solar gases, a portion of their constituent grains must have spent part of their lifetimes (generally a very small part, and often long ago) at the surface of the parent body. But the process that has actually lithified the grains into a solid matrix (cementing of particles by intergranular shock melting, cf. Bischoff *et al.*, 1983; Bunch and Rajan, 1988), must certainly modify the spectral signature of the material, quite apart from well-known spectral differences between particulates and solids of the same composition.

Xenolithic Clasts

Regolith breccias play another role in resolving the S-type conundrum. They contain occasional exotic clasts (xenoliths), different from the host meteorite and having other traits implying that they are fragments of projectiles that have struck the asteroid. As one might expect, given the predominance of C-type objects in the asteroid belt, about 60% of the xenoliths in OC's and achondrites are carbonaceous. But Pellas (1988) and Lipschutz *et al.* (1989), extending earlier work by Wilkening (1977) and Anders (1978), show that ~36% of xenoliths are OC's (including H's, L's, and LL's) or OC-like. Asteroid collisions are random events, not subject to most of the selectivities that Gaffey (1995a) and others have relied on to hide the OC parent bodies from astronomical surveys. The xenoliths should be approximately a volumetric representation of the composition of the main asteroid belt (note that while the parent bodies of xenolith-containing meteorites may come from limited portions of the asteroid belt, near escape hatches, the projectiles that crash into them [the parent bodies of the xenoliths] are representative of much of the asteroid population due to the appreciable eccentricities of asteroid orbits). Therefore, the H, L, LL, and other OC-like meteorites are not only common on Earth at the present epoch, but they have been the second most common constituent of the asteroid belt for aeons. (Supporting this interpretation is the fact that the two known fossil meteorites, dating from ~450 Myr ago, are probably H chondrites [A. Rubin, pers. comm., 1996].) Rare meteorite types rarely show up as xenoliths, either, so they must also be rare in the asteroid belt and cannot account for the majority of S-type asteroids, as some have proposed.

Space Weathering Processes

Since lunar rocks and soils were returned to Earth by the Apollo astronauts, it has been known that there are major optical and spectral differences between unaltered lunar rocks and the exposed surface of the lunar regolith. Qualitatively, the differences are similar to -- but more extreme than -- the differences I have discussed in this review between pristine OC meteorites and S-type asteroids: the lunar surface appears darker and its reflectance spectrum is more linear, redder, and has much weaker absorption bands than does the spectrum of its constituent rocks. The process responsible for altering the lunar surface has been called "space weathering," although there has been a long, tortured history of determining precisely what process or processes comprise space weathering (for brief reviews, see Pieters and McFadden [1994] and Clark and Johnson [1996]).

The macroscopic processes that affect lunar space weathering to various degrees include exposure to solar wind irradiation, micrometeoritic impacts, and the processes of particle segregation in the lunar regolith. What precise chemical and physical alterations in the minerals are responsible for altering their optical characteristics, and hence the resulting reflectance spectra, remains an arena of active research (Hapke, 1993). In general, it appears that formation of submicroscopic metal, through reduction of Fe^{2+} (facilitated by previously implanted solar-wind H) in the process of agglutinitic glass formation following particle impacts, is a major factor that changes the optical characteristics of the lunar soil (Allen *et al.*, 1995). Kerridge (1994) has emphasized the role of micrometeorite impact-generated vapor, which is deposited as ultrafine Fe^0 on the surfaces of regolith grains. Pieters *et al.* (1993) have shown convincingly that the optical alteration occurs chiefly in the finest fraction of lunar regolith particles, <25µm (about ¼ of the weight percent), which emphasizes the microscopic scale on which the alteration occurs.

It is a reasonable hypothesis that the space weathering process on asteroids is analogous to that on the Moon, but occurs to a lesser degree due to the lesser maturity compared with the lunar regolith, discussed above, combined with other factors that diminish the intensity of the microscopic heating events (lower impact velocities, decreased solar wind) and other mineralogical and physical differences between asteroids and the Moon. In the last few years, inspired by Galileo's Gaspra fly-by, several efforts have been made to simulate space weathering experiments in the laboratory in ways more relevant to asteroids and OC's than the lunar experiments that have been done.

For example, Clark *et al.* (1992) comminuted, melted, recrystallized, and recomminuted OC meteorites and measured the spectral changes. Qualitatively, the spectra changed in the expected directions -- albedo was lowered, absorption bands diminished, and continuum reddened. However, quantitatively the simulations failed to match S-type spectra. In particular, the albedo was lowered more, and the reddening was less, than required. In light of the Pieters *et al.* (1993) result about the predominant effect of the finest fraction in reddening and band reduction but *not* on albedo, it is clear in retrospect that the 350µm grains melted by Clark *et al.* were probably much too big. In addition, the ~10s timescales for heating and cooling, necessitated by the experimental approach (furnace heating followed by quenching by cold nitrogen gas), are far too long to accurately simulate microscopic zapping by micrometeorites and solar wind particles.

More relevant experiments have recently been carried out by Moroz *et al.* (1993, 1996) who used a 30-40 Khz pulsed laser to zap ~100µm sized spots on powdered (<75µm) samples of the L5 OC Elenkova in vacuum. Reflectance spectra were measured before and after the experiments. The results are startling and provide dramatic evidence that OC material is modified in just the ways required to make OC material have S-type characteristics. They conclude, conservatively, that "...quick melting and recrystallization can enhance the spectral similarity between S-asteroids and OC's."

As a measure of how the spectral changes conform to OC and S-type categories, Moroz *et al.* plotted their data in fields identified by Fanale *et al.* (1992) as distinguishing S-types from OC's in terms of spectral slope, band depth, and albedo. Fanale *et al.* had used these plots to highlight the spectral differences between OC's and S-types and to show that early attempts to simulate space weathering by melting failed to move OC spectra outside of the OC domains into the S-type domains. In stark contrast, the Moroz *et al.* experiments moved the spectrum of Elenkova from the OC domains into the S-type domains. In particular, spectral contrast was reduced and the spectral continuum reddened to the degrees required by typical S-type spectra; also, albedos were lowered somewhat. The fits are not perfect; for example, the experiments reddened the spectral continuum beyond 1.5µm as well as the shorter-wavelength continuum, violating the characteristics that Clark [1996] has highlighted as a problem with the reddening-by-metal hypothesis. However, the Moroz *et al.* experiments, unlike early simulations, go most of the way toward converting OC material to looking like S-types.

Since the experiments only approximate the actual physical conditions and processes on asteroid surfaces, it could hardly be expected that the spectral alterations would perfectly reproduce asteroidal space weathering. Indeed, several features of the experiment (e.g. the power of the laser) are not known, which makes it impossible to evaluate quantitatively how well the experiments truly simulate micrometeorite bombardment (L.V. Moroz, pers. comm., 1996). Nevertheless, I believe that the burden of proof must now shift to those who have previously argued that the kinds of space weathering that are observed, simulated, or otherwise deemed plausible for asteroids are very different from the OC/S-type mismatch. Now that more realistic simulations show roughly the right types of alteration, it will be difficult for nit-picks at the minor remaining discrepancies to override the larger message -- space weathering works in the laboratory.

There is another startling and potentially very significant result of the Moroz *et al.* experiments. Until now, it has been virtual dogma that space weathering processes affect spectral properties like albedo, continuum shape, and spectral contrast (including absorption band depth) but can *not* affect band center wavelengths, which are diagnostic of mineralogy. It is, therefore, unsettling that another result of the Moroz *et al.* experiments is that the short-wavelength Fe^{2+} absorption band (Band I) moved to longer wavelengths after alteration. Plotted on Gaffey *et al.*'s (1993b) field of Band II/Band I area ratio vs. Band I center wavelength, the OC meteorite Elenkova moved from the OC field (S(IV)) to SII.

It is not certain whether the apparent olivine enrichment is due to (a) dissimilar optical alteration of olivine and pyroxene grains such that the optical dominance of the olivine grains is enhanced while the underlying mineralogy is unchanged, (b) if there is actually a change in mineralogy of a fraction of the grains that contribute to the reflection spectrum, or (c) if vitrification of some of the material is changing the Band I center. (Moroz *et al.* propose explanation [a], arguing that the rapid quenching of the micromelts results in recrystallization of olivine while some pyroxene accumulates in a glassy mesostasis, weakening the strength of the pyroxene band compared with olivine.) If the effect is real, it would undercut a major pillar supporting the utility of remote-sensing of mineral composition on asteroids and, perhaps, other bodies. It may not be, as most researchers have assumed since the Gaffey *et al.* (1993b) work, that the search for OC-parent bodies among the S-types must be restricted to those, the S(IV)'s, with the "correct" inferred silicate mineralogy, but could now include as well the apparently more olivine-rich S-types SIII, SII, and perhaps even SI. The long-standing problem that most S-types are too olivine-rich to be OC parent bodies (Feierberg *et al.*, 1982) may be resolved by invoking this possible olivine-enrichment aspect of space weathering. It is even possible that *most* S-types could be OC parent bodies! Naturally, much more laboratory experimentation is required before this paradigm-altering suggestion can be given much weight.

Among the issues that have been incompletely investigated recently is the degree to which the migration of particles of different sizes and properties within the regolith might alter the proportions at the optical surface compared with the rest of the regolith. The earliest idea that simple differential comminution and aggregation might differentiate metallic grains from silicate grains in asteroidal regoliths proved unworkable. But recent considerations of electrostatic levitation of fines on the Moon and asteroids (Horanyi *et al.*, 1994; Lee, 1995) highlights the potential that other processes are probably at work. The conclusion of Pieters *et al.* (1993) that "space weathering optical properties are controlled by a magnetic component on or in the soil grains" is particularly interesting in this regard.

The Skeptics (J. F. Bell and Others)

My thesis in the present review article is that at least a significant fraction of the larger S-type main-belt asteroids are likely to be parent bodies of OC and OC-like meteorites and, further, that the spectra of those asteroids have been altered by space weathering. Lately, an increasing number of researchers have been persuaded to consider this idea by the results for Ida and other research reviewed above. Several hold-outs remain, however, most notably J. F. Bell of the University of Hawaii. His paradigm on the compositional structure of the asteroid belt and the nature of S-types (Bell *et al.*, 1989) is seemingly undermined by the new, emerging view.

Since 1989, Bell has co-authored several papers bearing tangentially on these issues. However, he has not yet published a full paper on his current views of the S-type conundrum, so I rely in what follows on a series of abstracts by Bell (1994, 1995a, 1995b, 1995c, and others), supplemented by additional materials which Bell has kindly provided to me. In addition, I discuss some of the arguments raised by F. Fanale and by M. Gaffey, although they have recently moved toward more centrist positions (cf. Fanale and Clark, 1993; Fanale and Granahan, 1995; Gaffey, 1995b, 1996a,b).

A central difference between my approach to the conundrum, on the one hand, and Bell's and Gaffey's, on the other, is our philosophical perspectives on whether one should *expect* some degree of representation of meteorites that is proportional to the abundance of parent bodies in the asteroid belt. There are, to be sure, a variety of processes involved in the delivery of meteorites to the Earth that discriminate between meteorites of different composition (e.g. strength-dependent effects that affect proportions of irons to stones to weak carbonaceous materials) or between parent bodies of different sizes or in different locations of the main belt (e.g. proximity to resonances). As co-author of an early evaluation of such biases (Greenberg and Chapman, 1983), I appreciate them. But I find it incredible to dismiss a discrepancy that Gaffey (1995a) himself has estimated at ~2500:1 between the proportion of OC meteorites among falls and the percentage of OC asteroids (unlike me, Gaffey accepts Božněmcová as a plausible OC).

It has long been appreciated that carbonaceous chondrites are severely underrepresented in meteorite collections, relative to their abundance in Earth-crossing orbits, due to their weakness and difficulty in surviving atmospheric passage. However, biases work both ways as they affect the ratio of irons to stones (the strength of iron both preserves it against destruction, but also hinders the ease of excavating it from a parent body). To me it seems no more credible that OC's can come from a few small main-belt OC asteroids (none yet discovered) than that most of the pebbles in a stream could be derived from some tiny, unobservable mineral lode in distant cliffs along the stream's headwaters. I think it is unfounded to dismiss the order-of-magnitude validity of such calculations of yield as those of Farinella *et al.* (1993). But for Gaffey (1995a), "there is no expectation that there should be **any** correlation between the abundance of lithologic types in the asteroid belt and the abundance of equivalent meteorite types [boldface is Gaffey's]."

As for Bell, he counts *types* of meteorites (even if represented by only 1 or 2 examples) instead of numbers (or cumulative masses) of all examples of meteorites of the different types. Thus Bell is comfortable with having all of the larger S-type asteroids being parent bodies for rare meteorites like pallasites, mesosiderites, and IAB irons as well as for the very rare R chondrites, lodranites, winonaites, acapulcoites, and various other "primitive achondrites" without being concerned about why their yield on Earth should be so suppressed. I would guess, instead, that most of the rare meteorites come from bodies far from resonances or from parent bodies that have largely been comminuted by collisions so that only small pieces remain.

Considerable non-representative selectivity favoring OC's might seem to be implied by two facts: (1) most OC's are interpreted to be derived from just three parent bodies and (2) ~10^2 parent bodies appear to be represented in our meteorite collection. Most of the inferred separate parent bodies are for metallic meteorites; if one interpreted such irons to be derived from the cores of dozens of (perhaps large) broken-up asteroids, it might seem that the dominance of our collections by just three unmelted (perhaps smaller) OC parent bodies proves non-representative sampling. However, it is more likely that most of the inferred parent bodies for the numerous different groups and "grouplets" of irons were actually km-scale bodies in an earlier, hotter stage of planetesimal evolution, some of which have survived due to their strength and others of which were subsequently incorporated into just a few 100-km-scale parent bodies which might remain as observable asteroids today (see discussion by Scott, 1979). (There are hardly enough M-type asteroids or asteroid families to account for scores of large broken-up asteroidal parent bodies.) It is reasonable, in my view, to generally interpret very rare meteorite (or xenolith) types as being derived from small, rare parent bodies (or small portions of larger parent bodies), although occasionally low representation must instead reflect biases against sampling (e.g. great distance from resonances or the physical impediments to efficiently extracting SNC's from the surface of Mars).

Bell has stressed recent findings that OC material constitutes only 1% - 3% of "asteroidal" interplanetary dust particles (IDP's), which would seem incompatible with the results of modelling that suggest that 5% - 10% of IDP's should come from the Koronis family itself (Flynn, 1996). Yet such IDP's are derived from the *whole* asteroid belt, which is dominated by C-types not S-types, by well-known (e.g. Poynting-Robertson) processes very different from those that extract meteorites only from resonances in the inner belt. My view is that our understanding of IDP collection statistics and compositions is too premature to have probative value concerning the OC/S-type conundrum. Even the predominant C-like IDP's have mineralogical differences from carbonaceous chondritic meteorites (Brownlee, 1995).

The traditional Dohnanyi (1971) perspective of a universal equilibrium population index for interplanetary debris has been found wanting, in some respects (reasonable explanations have been proposed; cf. Campo Bagatin *et al*, 1994). Bell appeals to this situation to justify having gross differences in the compositional mix of small asteroids compared with large ones. But no self-consistent model for asteroid comminution can generate and sustain orders of magnitude more objects at one size range compared with the equilibrium extrapolation from another size range. Nor is there support for Bell's opinion -- so far unsupported by any quantitative model -- that the population index of debris should be a function of material strength.

There has been much controversy in recent years, beyond the scope of this review, about the degree to which the proportions of meteorites in contemporaneous falls are the same as in the Antarctic collection, and about whether there are much larger stochastic variations over timescales of 10's or 100's of Myr. As described in an earlier section, however, the abundances of xenolithic clasts in meteorites are not subject to the controversial effects of delivery to Earth and must be much more representative of the materials in the asteroid belt. It is simply not true, once the statistics are corrected for atmospheric penetration, that ordinary chondritic matter is substantially over-represented in meteorite collections compared with its abundance in the asteroid belt.

Bell has occasionally argued that OC material was more abundant at earlier times, and present in larger objects than the <10 km objects he now prefers, which might explain the xenoliths. His model would seem to be fortuitous, then, that OC objects have now become so small that, in the near future (the order of a few percent of the age of the solar system) they would be expected to be catastrophically disrupted by collision and their fragments rapidly comminuted and lost from the solar system forever. (Collisional lifetimes vary roughly as the square-root of asteroid size, so that small asteroids must be pieces from larger reservoirs; the odds are against the "last" three large reservoirs of OC material, required to explain the preservation of the three major OC types for 4½ Byr, all having been just broken up in the last few hundred million years with their debris soon to disappear from the system altogether.)

Bell (1995a) continues to cite meteoritical references in support of his contention that more recent parent-body cooling models than those in the classic work on metallographic cooling rates of Wood (1967) imply that OC parent body "sizes" must be <50 km due to insulating regolith. Unfortunately, Bell apparently has mistaken *depth* in a parent body for diameter and he has reversed the direction of the inequality. For example concerning the L parent body, Haack *et al.* (1996) write that "the slow cooling rates seem to require that the *radius* of the original parent body was *more* than 50 km even if the surface was covered with a layer of insulating regolith [my italics]." Taylor *et al.* (1987; see also Keil *et al.*, 1994) argue that the wide range of cooling rates for individual taenite grains in H and L meteorites imply parent body diameters at least 200 km in diameter. McSween and Bennett (1995) derive a 175 km diameter for the H chondrite parent body. Pellas and Storzer (1981), considering ^{244}Pu fission track thermometry, conclude that the parent bodies of the H, L, and LL OC's were 100 to 300 km in diameter. Such bodies are large enough so that catastrophic disruption and dispersal is difficult; either rubble-pile versions of their former selves, families, or other large remnants should still exist as large, readily observable asteroids.

One question that has persisted throughout the S-type debates (cf. Matson *et al.*, 1976) is how space weathering can be claimed to operate when Vesta, one of the very largest asteroids, shows "no evidence" of space weathering (Fanale and Clark, 1993). It is *not* strictly true that it isn't weathered, inasmuch as its spectral features -- while strong compared with spectra of most asteroids -- are subdued compared with those of most measured HED meteorites (Wasson *et al.*, 1996). Vesta is nevertheless a puzzle, but my view is that the solution will prove to be unrelated to weathering of S-type asteroids. It is more plausible to me that Vesta's surface is unexpectedly and anomalously young, an idea that has occurred to others (Pieters and Binzel, 1994; Davis *et al.*, 1985; Wasson *et al.* 1996).

A final set of arguments against S-types as space weathered OC's involves correlations among various parameters. There are tendencies for S-types at smaller semi-major axes to have mineralogies interpreted to be more olivine rich, opposite to the expected trend of oxidation of OC parent bodies. (The correlation is difficult to disentangle from the tendency for smaller S-types to be more olivine-rich than larger ones, due to observational selection effects favoring asteroids that are closer to the Earth [Chapman, 1987].) Possibly this correlation is, instead, due to the effect found by Moroz *et al*. (1996) of increasing *apparent* olivine content with space weathering, given that S-types with smaller semi-major axes (which are plausibly subject to more space weathering due to proximity to the sun and higher average impact velocities) exhibit such weathering attributes as redder colors (see Fig. 2 in Chapman, 1979; Dermott *et al.*, 1985). Apparently opposing this trend is the tendency for S-type absorption band depths to be *deeper* (implying less weathering) at small semi-major axes (Fig. 2 in Chapman, 1979), but that correlation is confounded by the fact that those same asteroids in the observed sample are much smaller than average and absorption band depths apparently vary inversely with asteroid diameter (Gaffey *et al.*, 1993b), as would be expected for a space-weathering model. A careful study of all these correlations has yet to be made using data corrected for sampling bias. Any conclusions based on supposedly expected correlations are highly model-dependent, anyway. Therefore, while I consider the correlations to be interesting and deserving of further study, I do not consider them to weigh heavily one way or the other in the space weathering controversy.

Conclusion

The Galileo Ida data give the strongest evidence to date that space weathering operates in the asteroid belt. Observed spectral differences, correlated with relative age of geological features on Ida, span a large fraction of the range required to convert laboratory spectra of ordinary chondrites to look like typical S-type asteroids. Although it is not yet proven that the starting end-member of this trend on Ida is uniquely OC, the observations must cause anyone who has doubted the efficacy of asteroidal space weathering to pause. Appropriately, as has long been expected, the observed degree of space weathering on asteroids is very modest compared with that well documented (but incompletely understood) on the Moon. Reassuringly, the most realistic laboratory simulations of likely space weathering processes (e.g. Moroz *et al.*, 1996) do an excellent, though not perfect, job of converting the reflectance spectrum of an OC meteorite to fit within spectral parameter domains of S-type asteroids, domains which had only a few years earlier been defined by Fanale *et al.* (1992) and used to argue against space weathering.

While the case for space-weathering of OC parent bodies has strengthened, the alternative, once widely accepted paradigm of Bell *et al.* (1989) has failed its most important prediction. Despite the premature claim of Binzel *et al.* (1993b, 1993c) that Božněmcová is an OC analog (I argue above that it is not), the undisputed result of SMASS is that Bell's predicted abundance of small Q-types is plainly refuted: there are *none* in the main belt among the hundreds that have been surveyed.

Certain other results and arguments from meteoritics (e.g. the abundance of OC xenoliths and the appreciable inferred sizes of OC parent bodies), dynamics (the discovery by Wisdom of an effective resonant escape hatch from the inner asteroid belt), and asteroid collisional modelling all remain as potent as when they were first proposed. Jeff Bell, the chief opponent of a connection between S-types and OC meteorites, has recently declared his "independence" from meteoritics and has suggested that asteroid spectroscopists "could have made much faster progress if they had worked in total isolation from meteoritics;" he now advocates that it is time that "meteoritics plays a supplementary role to direct studies of asteroids" (Bell, 1995b). However, it is manifest that the evidence from all of the multiple disciplines that bear on this problem must be considered, treated seriously, and reconciled. One cannot simply dismiss the meteoritical evidence. Fortunately, asteroid reflectance spectroscopy is now pointing the way to a new perspective that reconciles the long-standing interdisciplinary contradictions.

Very likely, among the larger S-types will be found the parent bodies of the major OC meteorite classes (H, L, and LL) as well as other asteroids of OC-like composition (e.g. fitting within the gaps between the three major OC types in compositional plots). It is not yet clear, however, what fraction of S-types are OC, what fraction are classic stony-irons, and what fraction are other kinds of silicaceous assemblages (primitive achondrites, as-yet-unsampled materials, etc.). The S-types clearly span a considerable diversity in composition. If the composition of the silicates can be reliably inferred from absorption band centers (despite the questions raised by the work of Moroz *et al.*), then OC parent bodies are restricted to those ~25% of S-types that Gaffey *et al.* (1993b) classify as S(IV)'s. Perhaps (e.g. if NEAR shows that Eros is differentiated) some of the S(IV)'s will be proven not to be OC's and the overall fraction of S-types that are OC will turn out to be modest, say only 5% or 10%. On the other hand, if the methods traditionally used to infer silicate chemistry are affected by space weathering, it is plausible that even the majority of S-types will turn out to have OC affinities. I would guess that the percentage of OC-like S-types will turn out to be at least 25% and perhaps as much as 50%, but the proof is not yet in. Certainly the broad S asteroid class contains a grab-bag of diverse silicate-bearing objects, whatever the final proportions turn out to be.

This, I suggest, should be the new paradigm. Insofar as the ordinary chondritic meteorites are concerned, we still face the task of finding out just *which* S-types (or S-type families) are the parent bodies for the well studied H, L, and LL meteorites. The task may not prove to be easy, but at least now we can accept that a lot of the progress that Anders (1971) expected would be made rapidly has, at length, finally been made.

Acknowledgements

This research was supported by the Galileo Project at the Jet Propulsion Laboratory. I thank numerous colleagues for helpful discussions, especially E. Anders, J. Bell, R. Binzel, D. Britt, D. Brownlee, R. Carlson, B. Clark, M. Gaffey, P. Geissler, J. Granahan, H. Haack, J. Kerridge, A. McEwen, L. McFadden, H. McSween, L. Moroz, D. Morrison, S. Murchie, C. Pieters, A. Rubin, E. Ryan, R. Sullivan, T. Swindle, J. Wasson, G. Wetherill, and V. Zappalà. W. Merline provided essential assistance. P. Helfenstein kindly provided files of reduced photometric data for further analysis.

References

Allen C.C., Morris R.V., and McKay D.S. (1995) Experimental space weathering of lunar soils (abstract). *Meteoritics* **30**, 479-480.

Anders E. (1971) Reasons for not having an early asteroid mission. In *Physical Studies of Minor Planets* (ed. T. Gehrels), pp. 479-487. NASA SP-267.

Anders, E. (1975) Do stony meteorites come from comets? *Icarus* **24**, 363-371.

Anders E. (1978) Most stony meteorites come from the asteroid belt. In *Asteroids: An Exploration Assessment* (eds. D. Morrison and W.C. Wells), pp. 57-75. NASA Conf. Publ. 2053.

Asphaug E., Moore J.M., Morrison D., Benz W., Nolan M.C., and Sullivan R.J. (1996) Mechanical and geological effects of impact cratering on Ida. *Icarus* **120**, 158-184.

Barucci M.A. and Lazzarin M. (1993) Koronis family: reflectance spectra of 243 Ida, 1442 Corvina and 2226 Cunitza. *Planet. Space Sci.* **41**, 641-646.

Bell J.F. (1986) Mineralogical evolution of the asteroid belt (abstract). *Meteoritics* **21**, 333-334.

Bell J.F. (1994) Ordinary chondrites in space and time (abstract). *LPSC XXV*, 89-90.

Bell J.F. (1995a) Q-class asteroids and ordinary chondrites (abstract). *LPSC XXVI*, 93-94.

Bell J.F. (1995b) Asteroid spectroscopy: a declaration of independence (abstract). *Meteoritics* **30**, 484-485.

Bell J.F. (1995c) Invited debate, "Do ordinary chondrites come from S-class asteroids?", AAS Div. for Planetary Sciences 27th annual meeting, Kona, HI, 9 Oct. 1995.

Bell J.F., Hawke B.R., Gaffey M.J., Owensby P.D. (1984) The 52-color asteroid survey: preliminary results (abstract). *Bull. Am. Astron. Soc.* **16**, 692.

Bell J.F. and Keil K. (1988) Spectral alteration effects in chondritic gas-rich breccias: implications for S-class and Q-class asteroids. *Proc. Lunar Planet. Sci. Conf. 18th*, 573-580.

Bell J.F., Hawke B.R., Owensby P.D., and Gaffey M.J. (1988) The 52-color asteroid survey: final results and interpretations (abstract). *LPSC XIX*, 57-58.

Bell J.F., Davis D.R., Hartmann W.K., and Gaffey M.J. (1989) Asteroids: the big picture. In *Asteroids II* (eds. R.P. Binzel, T. Gehrels, and M.S. Matthews), pp. 921-945. Univ. Ariz. Press, Tucson.

Belton M.J.S., Klaasen K.P., Clary M.C., Anderson J.L., Anger C.D., Carr M.H., Chapman C.R., Davies M.E., Greeley R., Anderson D., Bolef L.K., Townsend T.E., Greenberg R., Head J.W. III, Neukum G., Pilcher C.B., Veverka J., Gierasch P.J., Fanale F.P., Ingersoll A.P., Masursky H., Morrison D., and Pollack J.B. (1992a) The Galileo Solid-State Imaging experiment. *Space Sci. Revs.* **60**, 413-455.

Belton M.J.S., Veverka J., Thomas P., Helfenstein P., Simonelli D., Chapman C., Davies M.E., Greeley R., Greenberg R., Head J., Murchie S., Klaasen K., Johnson T.V., McEwen A., Morrison D., Neukum G., Fanale F., Anger A., Carr M., Pilcher C. (1992b) Galileo encounter with 951 Gaspra: first pictures of an asteroid. *Science* **257**, 1647-1652.

Belton M.J.S. and Carlson R. (1994) 1993(243)1. *IAU Circ.* 5948.

Belton M.J.S., Chapman C.R., Veverka J., Klaasen K.P., Harch A., Greeley R., Greenberg R., Head J.W. III, McEwen A., Morrison D., Thomas P.C., Davies M.E., Carr M.H., Neukum G., Fanale F.P., Davis D.R., Anger C., Gierasch P.J., Ingersoll A.P., and Pilcher C.B. (1994) First images of asteroid 243 Ida. *Science* **265**, 1543-1547.

Belton M.J.S., Chapman C.R., Thomas P.C., Davies M.E., Greenberg R., Klaasen K., Byrnes D., D'Amario L., Synnott S., Johnson T.V., McEwen A., Merline W., Davis D.R., Petit J-M., Storrs A., and Zellner B. (1995) Bulk density of asteroid 243 Ida from the orbit of its satellite Dactyl. *Nature* **374**, 785-788.

Belton M.J.S., Mueller B.E.A., D'Amario L.A., Byrnes D.V., Klaasen K.P., Synott S., Breneman H., Johnson T.V., Thomas P.C., Veverka J., Harch A.P., Davies M.E., Merline W.J., Chapman C.R., Davis D., Denk T., Neukum G., Petit J-M., Greenberg R., Storrs A., and Zellner B. (1996). The discovery and orbit of 1993 (243)1 Dactyl. *Icarus* **120**, 185-199.

Binzel, R.P. (1988) Collisional evolution in the Eos and Koronis asteroid families: observational and numerical results. *Icarus* **73**, 303-313.

Binzel, R.P. (1995) An early heavy bombardment period for 243 Ida (abstract). *EOS* **76**, 198.

Binzel R.P., Xu S., and Bus S.J. (1993a) Spectral variations within the Koronis family: possible implications for the surface colors of asteroid 243 Ida. *Icarus* **106**, 608-611.

Binzel R.P., Xu S., Bus S.J., Skrutskie M.F., Meyer M., Knezek P., and Barker E.S. (1993b) The discovery of a main-belt ordinary chondrite asteroid (abstract). *Bull. Am. Astron. Soc.* **25**, 1133.

Binzel R.P., Xu S., Bus S.J., Skrutskie M.F., Meyer M.R., Knezek P., and Barker E.S. (1993c) Discovery of a main-belt asteroid resembling ordinary chondrite meteorites. *Science* **262**, 1541-1543.

Binzel R.P., Bus S.J., Burbine T.H., and Sunshine J.M. (1996) Spectral properties of near-Earth asteroids: Evidence for sources of ordinary chondrite meteorites. *Science* **273**, 946-948.

Bischoff A., Rubin A.E., Keil K., and Stöffler D. (1983) Lithification of gas-rich chondrite regolith breccias by grain boundary and localized shock melting. *Earth Planet. Sci. Lett.* **66**, 1-10.

Bobrovnikoff N.T. (1929) The spectra of minor planets. *Lick Observatory Bull.*, **14**, No. 407, 18-27.

Bowell E., Chapman C.R., Gradie J.C., Morrison D., and Zellner B. (1978) Taxonomy of asteroids. *Icarus* **35**, 313-335.

Britt D.T. and Kring D.A. (1995) The problem with porosity (abstract). 27th Annual AAS/DPS Meeting, Kona.

Britt D.T., Kring D.A., Bell J.F. (1995) The density/porosity of asteroids (abstract). *LPSC XXVI*, 177-178.

Britt D.T. (1996). The parent asteroids of ordinary chondrite meteorites (abstract). *LPSC XXVII*, 167-168.

Britt D.T. and Pieters C.M. (1987) The optical effects of surface processes on small bodies (abstract). *Meteoritics* **22**, 340-342.

Britt D.T. and Pieters C.M. (1988) Bidirectional reflectance properties of iron-nickel meteorites. *Proc. Lunar Planet. Sci. Conf. 18th*, 503-512.

Brownlee D.E. (1995) Chemistry of interplanetary dust (abstract). Presented at IAU Colloq. 150 (Physics, Chemistry, and Dynamics of Interplanetary Dust), Gainesville, FL, 14-18 Aug. 1995.

Bunch T.E. and Rajan R.S. (1988) Meteorite regolith breccias. In *Meteorites and the Early Solar System* (ed. J.F. Kerridge and M.S. Matthews), 144-164. Univ. Ariz. Press, Tucson).

Campo Bagatin A., Cellino A., Davis D.R., Farinella P., and Paolicchi P. (1994) Wavy size distributions for collisional systems with a small-size cutoff. *Planet. Space Sci.* **42**, 1079-1092.

Carlson R.W. (1994) Invited talk and press conference at Spring Meeting, American Geophys. Union, Baltimore, MD, 26 May 1994.

Carlson R.W., Weissman P.R., Smythe W.D., Mahoney J.C., and the NIMS Science and Engineering Teams (1992) Near-Infrared Mapping Spectrometer experiment on Galileo. *Spa. Sci. Rev.* **60**, 457-502.

Carlson R.W., Weissman P.W., Segura M., Kamp L.W., Smythe W.D., Johnson T.V., Matson D., Leader F.E., Mehlman R., Fanale F.P., Granahan J.C., Kieffer H.H., Soderblom L.A., McCord T.B. (1994) Infrared imaging spectroscopy of asteroid 243 Ida and discovery spectra of satellite 1993 (243) 1. *Bull. Am. Astron. Soc.* **26**, 1156.

Carr M.H., Kirk R.L., McEwen A., Veverka J., Thomas P., Head J.W., and Murchie S.M. (1994) The geology of Gaspra. *Icarus* **107**, 61-71.

Cellino A., Di Martino M., Migliorini F., Paolicchi P., and Zappalà V. (1996) Maria's family as the possible origin of "giant" near-Earth asteroids. *Nature*, submitted.

Chapman C.R. (1972). *Surface Properties of Asteroids*. Ph.D. Dissertation, Mass. Inst. of Tech.

Chapman C.R. (1974) Asteroid size distribution: Implications for the origin of stony-iron and iron meteorites. *Geophys. Res. Lett.* **1** 341-344.

Chapman C.R. (1976) Asteroids as meteorite parent bodies: the astronomical perspective. *Geochim. Cosmochim. Acta* **40,** 701-719.

Chapman C.R. (1978) Asteroid collisions, craters, regoliths, and lifetimes. In *Asteroids: An Exploration Assessment* (eds. D. Morrison and W.C. Wells), pp. 145-160. NASA Conf. Publ. 2053.

Chapman C.R. (1979) Asteroids: Nature, interrelations, origin, and evolution. In *Asteroids* (ed. T. Gehrels), pp. 25-60. Univ. of Arizona Press, Tucson.

Chapman C.R. (1987) Distributions of asteroid compositional types with solar distance, body diameter, and family membership (extended abstract). *Meteoritics* **22**, 353-354.

Chapman C.R. (1991) Will Gaspra data solve the S-asteroid controversy? (abstract). *Bull. AAS* **23**, 1141.

Chapman C.R. (1996) Children of the asteroids. *The New Scientist*, **149** (No. 2016, 10 Feb. 1996), 22-25.

Chapman C.R., Johnson T.V., McCord T.B. (1971) A review of spectrophotometric studies of asteroids. In *Physical Studies of Minor Planets* (ed. T. Gehrels), pp. 51-65. NASA SP-267.

Chapman C.R. and Salisbury J.W. (1973) Comparisons of meteorite and asteroid spectral reflectivities. *Icarus* **19,** 507-522.

Chapman C.R., McCord T.B., and Pieters C. (1973) Minor planets and related objects: X. Spectrophotometric study of the composition of (1685) Toro. *Astron. J.* **78,** 502-505.

Chapman C.R., Morrison D., Zellner B. (1975) Surface properties of asteroids: A synthesis of polarimetry, radiometry, and spectrophotometry. *Icarus* **25,** 104-130.

Chapman C.R., Williams J.G., and Hartmann W.K. (1978) The asteroids. *Ann. Rev. Astron. and Astrophys.* **16,** 33-75.

Chapman C.R. and Gaffey M.J. (1979) Reflectance spectra for 277 asteroids. In *Asteroids* (ed. T. Gehrels), pp. 655-687. Univ. of Arizona Press, Tucson.

Chapman C.R. and Davis D.R. (1991) Gaspra: the scientific issues (abstract). Presented at Asteroids, Comets, Meteors 1991, Flagstaff, AZ, June 1991.

Chapman C.R., Veverka J., Thomas P.C., Klaasen K., Belton M.J.S., Harch A., McEwen A., Johnson T.V., Helfenstein P., Davies M.E., Merline W.J., and Denk T. (1995) Discovery and physical properties of Dactyl, a satellite of asteroid 243 Ida. *Nature* **374**, 783-785.

Chapman C.R., Veverka J., Belton M.J.S., Neukum G., and Morrison D. (1996a) Cratering on Gaspra. *Icarus* **120**, 231-245.

Chapman C.R., Ryan E.V., Merline W.J., Neukum G., Wagner R., Thomas P.C., Veverka J., and Sullivan R.J. (1996b) Cratering on Ida. *Icarus* **120**, 77-86.

Clark B.E. 1996 On the interpretation of the S-type asteroid spectral continuum. *Icarus*, in press.

Clark B.E., Fanale F.P., Salisbury J.W. (1992) Meteorite-asteroid spectral comparison: the effects of comminution, melting, and recrystallization. *Icarus* **97**, 288-297.

Clark B.E. and Hiroi T. (1994) S-type asteroid spectral continua: redness and Fe,Ni metal (abstract). *Bull. Am. Astron. Soc.* **26**, 1172.

Clark B.E. and Johnson R.E. (1996) Interplanetary weathering: surface erosion in outer space. *EOS* **77**, 141-145.

Cloutis E.A., Gaffey M.J., Jackowski T.L., and Reed K.L. (1986) Calibrations of phase abundances, compositions, and particle size distribution for olivine-orthopyroxene mixtures from reflectance spectra. *J. Geophys. Res.* **91**, 11641-11653.

Davis D.R. and Chapman C.R. (1977) Collisional evolution of asteroid compositional classes. *Lunar Sci. VIII*, 224-226.

Davis D.R., Chapman C.R., Greenberg R., Weidenschilling S.J., and Harris A.W. (1979) Collisional evolution of asteroids: populations, rotations, and velocities. In *Asteroids* (ed. T. Gehrels), pp. 528-537. Univ. Ariz. Press, Tucson.

Davis D.R., Chapman C.R., Weidenschilling S.J., and Greenberg R. (1985) Collisional history of asteroids: evidence from Vesta and the Hirayama families. *Icarus* **62**, 30-53.

Davis D.R., Chapman C.R., Durda D.D., Farinella P., and Marzari F. (1996) The formation and collisional/dynamical evolution of the Ida/Dactyl system as part of the Koronis family. *Icarus* **120**, 220-230.

Dermott S.F., Gradie J., Murray C.D. (1985) Variation of the UBV colors of S class asteroids with semimajor axis and diameter. *Icarus* **62**, 289-297.

Dohnanyi J.S. (1971). Fragmentation and distribution of asteroids. In *Physical Studies of Minor Planets* (ed. T. Gehrels), pp. 263-295. NASA SP-267.

Durda D.D. (1996) The formation of asteroidal satellites in catastrophic collisions. *Icarus* **120**, 212-219.

Egan W.G., Veverka J., Noland M., and Hilgeman T. (1973) Photometric and polarimetric properties of the Bruderheim chondritic meteorite. *Icarus* **19**, 358-371.

Fanale F.P., Clark B.E., and Bell J.F. (1992) A spectral analysis of ordinary chondrites, S-type asteroids, and their component minerals: genetic implications. *J. Geophys. Res.* **97**, 20863-20874.

Fanale F.P. and Clark B.E. (1993) Chondrites, S asteroids, and "space weathering": thumping noises from the coffin? (abstract) *LPSC XXIV*, 463-464.

Fanale F.P. and Granahan J.C. (1995) The "ordinary chondrite - S asteroid controversy"; still going, still going (abstract). *LPSC XXVI*, 389-390.

Farinella P., Froeschlé C., Conczi R. (1993) Meteorites from the asteroid 6 Hebe. *Celest. Mech.* **56**, 287-305.

Feierberg M.A., Larson H.P., Fink U., and Smith H.A. (1980) Spectroscopic evidence for two achondrite parent bodies: asteroids 349 Dembowska and 4 Vesta. *Geochim. Cosmochim. Acta* **44**, 513-524.

Feierberg M.A., Larson H.P., Chapman C.R. (1982) Spectroscopic evidence for undifferentiated S-type asteroids. *Astrophys. J.* **257**, 361-372.

Flynn G.J. (1996) Are the S-asteroids the parent bodies of the ordinary chondrite meteorites? (abstract). Presented at ACM 96: COSPAR Colloq. 10, Versailles, France, 8-12 July 1996.

Gaffey M.J. (1974) *A systematic study of the spectral reflectivity characteristics of the meteorite classes with applications to the interpretation of asteroid spectra for mineralogical and petrological information*. PhD thesis, Mass. Inst. of Technology.

Gaffey M.J. (1976) Spectral reflectance characteristics of the meteorite classes. *J. Geophys. Res.* **81**, 905-920.

Gaffey M.J. (1984) Rotational spectral variations of asteroid (8) Flora: implications for the nature of the S-type asteroids and for the parent bodies of the ordinary chondrites. *Icarus* **60**, 83-114.

Gaffey M.J. (1985a) Thermal and collisional history of asteroids of the inner belt: evidence from the S-type asteroids (abstract). *Asteroids, Comets, Meteors II* (Uppsala, Sweden).

Gaffey M.J. (1985b) A paradigm for the S-type asteroids: implications for the evolutionary history of the inner belt and the search for the ordinary chondrite parent bodies (abstract). *LPSC XVI*, 258-259.

Gaffey M.J. (1986) The spectral and physical properties of metal in meteorite assemblages: implications for asteroid surface materials. *Icarus* **66**, 468-486.

Gaffey M.J. (1992) Narrowing the search for ordinary chondrites among the large S-type asteroids: identification and tests of three prime candidates (abstract). *LPSC XXIII*, 393-394.

Gaffey M.J. (1995a) Meteoritic aspects of the S-asteroid issue: a perspective for the NEAR mission (abstract). *LPSC XXVI*, 439-440.

Gaffey M.J.(1995b) The S(IV)-type asteroids as ordinary chondrite parent body candidates: implications for the completeness of the meteorite sample of asteroids (abstract). *Meteoritics* **30**, 507-508.

Gaffey M.J. (1996a) Asteroid 6 Hebe: spectral evaluation of the prime large mainbelt ordinary chondrite parent body candidate with implications from space weathering of Gaspra and the Ida-Dactyl system (abstract). *LPSC XXVII*, 391-392.

Gaffey M.J. (1996b) Spectral identification of asteroid 6 Hebe as the main-belt parent body of the H-type ordinary chondrites (abstract). *Meteoritics & Planet. Sci.* **31**, A47.

Gaffey M.J. and McCord T.B. (1978) Astroid surface materials: mineralogical characterizations from reflectance spectra. *Space Sci. Rev.* **21**, 555-628.

Gaffey M.J., Bell J.F., and Cruikshank D.P. (1989) Reflectance spectroscopy and asteroid surface mineralogy. In *Asteroids II* (eds. R.P. Binzel, T. Gehrels, and M.S. Matthews), pp. 98-127. Univ. Ariz. Press, Tucson.

Gaffey M.J., Burbine T.H., Binzel R.P. (1993a) Asteroid spectroscopy: progress and perspectives. *Meteoritics* **28**, 161-187.

Gaffey M.J., Bell J.F., Brown R.H., Burbine T.H., Piatek J.L., Reed K., and Chaky D.A. (1993b) Mineralogical variations within the S-type asteroid class. *Icarus* **106**, 573-602.

Geissler P., Petit J-M., Durda D.D., Greenberg R., Bottke W., and Nolan M. (1996) Erosion and ejecta reaccretion on 243 Ida and its moon. *Icarus* **120**, 140-157.

Gradie J.C. (1978) *An astrophysical study of the minor planets in the Eos and Koronis asteroid families*. PhD thesis, Univ. of Arizona.

Gradie J.C., Chapman C.R., and Williams J.G. (1979) Families of minor planets. In *Asteroids* (ed. T. Gehrels), pp. 359-390. Univ. Ariz. Press, Tucson.

Gradie J. and Tedesco E. (1982) Compositional structure of the asteroid belt. *Science* **216**, 1405-1407.

Gradie J.C., Chapman C.R., and Tedesco E.F. (1989) Distribution of taxonomic classes and the compositional structure of the asteroid belt. In *Asteroids II* (eds. R.P. Binzel, T. Gehrels, and M.S. Matthews), pp. 316-335. Univ. Ariz. Press, Tucson.

Granahan J.C., Fanale F.P., Robinson M., Carlson R.W., Kamp L.W., Klaasen K.P., Smythe W.D., Weissman P.R., Belton M., Cook D., Edwards K., McEwen A.S., Soderblom L.A., Carcich B.T., Helfenstein P., Simonelli D., Thomas P., and Veverka J. (1994a) A Galileo multi-instrument spectral analysis of 951 Gaspra (abstract). *LPSC XXV*, 453-454.

Granahan J.C., Fanale F.P., Carlson R.W., Kamp L.W., Klaasen K.P., Belton M., Chapman C.R., McEwen A.S. and the Galileo NIMS and SSI instrument teams (1994b) A Galileo multi-instrument spectral view of 243 Ida and 1993 (243) 1 (abstract). *Bull. Am. Astron. Soc.* **26**, 1156.

Greenberg R. and Chapman C.R. (1983) Asteroids and meteorites: parent bodies and delivered samples. *Icarus* **55**, 455-481.

Haack H., Farinella P., Scott E.R.D., and Keil K. (1996). Meteoritic, asteroidal, and theoretical constraints on the 500 Ma disruption of the L chondrite parent body. *Icarus* **119**, 182-191.

Hapke B. (1971) Inferences from optical properties concerning the surface texture and composition of asteroids. In *Physical Studies of Minor Planets* (ed. T. Gehrels), pp. 67-77. NASA SP-267.

Hapke B. (1993) Laboratory simulations of lunar darkening processes. In *Workshop of the Space Environment: The Effects on the Optical Properties of Airless Bodies* (eds. B. Hapke, B. Clark, G. Benedix, D. Domingue, and M. Cintala), 8-9. LPI Tech. Rept. No. 93-01.

Helfenstein P., Veverka J., Thomas P.C., Simonelli D.P., Lee P., Klaasen K., Johnson T.V., Breneman H., Head J.W., Murchie S., Fanale F., Robinson M., Clark B., Granahan J., Garbeil H., McEwen A.S., Kirk R.L., Davies M., Neukum G., Mottola S., Wagner R., Belton M., Chapman C., Pilcher C. (1994a) Galileo photometry of asteroid 951 Gaspra. *Icarus* **107**, 37-60.

Helfenstein P., Veverka J., Thomas P., Johnson T.V., McEwen A., Granahan J., Fanale F., Geissler P., Belton M., Chapman C., and the Galileo Imaging Team (1994b) Regolith and composition of Ida: Clues from color and photometry (abstract). *Bull. Am. Astron. Soc.* **26**, 1158.

Helfenstein P., Veverka J., Thomas P.C., Simonelli D.P., Klaasen K., Johnson T.V., Fanale F., Granahan J., McEwen A.S., Belton M., and Chapman C. (1996) Galileo photometry of asteroid 243 Ida. *Icarus* **120**, 48-65.

Hirayama K. (1918) Groups of asteroids probably of common origin. *Astron. J.* **31**, 185-188.

Hiroi T. and Takeda H. (1991) Reflectance spectroscopy and mineralogy of primitive achondrites-lodranites. *Proc. NIPR Symp. Antarct. Meteorites* **4**, 163-177.

Hiroi T., Bell J.F., Takeda H., and Pieters C.M. (1993) Modeling of S-type asteroid spectra using primitive achondrites and iron meteorites. *Icarus* **102**, 107-116.

Hood L.L. and Sonett C.P. (1994) Galileo magnetic field signature: no evidence that Gaspra is differentiated (abstract). *LPSC XXV*, 561-562.

Horanyi M., Robertson S., and Walch R. (1994) Electrostatic charging properties of simulated lunar dust (abstract). *EOS* **75**, 400.

Housen K.R. (1992) Crater ejecta velocities for impacts on rocky bodies (abstract). *LPSC XXIII*, 555-556.

Housen K.R., Wilkening L.L., Chapman C.R., Greenberg R.J. (1979). Regolith development and evolution on asteroids and the Moon. In *Asteroids* (ed. T. Gehrels), pp. 601-627. Univ. of Ariz. Press, Tucson.

Howell E.S., Merényi E., and Lebofsky L.A. (1994) Classification of asteroid spectra using a neural network. *J. Geophys. Res.* **99**, 10,847-10,865.

Hudson R.S. and Ostro S.J. (1995) Shape and non-principal axis spin state of asteroid 4179 Toutatis. *Science* **270**, 84-86.

Johnson T.V. and Matson D.L. (1973) Spectrophotometry of (43) Ariadne: a possible chondritic composition (abstract). *Bull. Am. Astron. Soc.* **??**, ???.

Johnson T.V., Yeates C.M., and Young R. (1992) Space Science Reviews volume on Galileo mission overview. *Spa. Sci. Rev.* **60**, 3-21.

Keil K., Bell J.F., Britt D.T. (1992) Reflection spectra of shocked ordinary chondrites and their relationship to asteroids. *Icarus* **98**, 43-53.

Keil K., Haack H., Scott E.R.D. (1994) Catastrophic fragmentation of asteroids: evidence from meteorites. *Planet. Space Sci.* **42**, 1109-1122.

Keil K., Stöffler D., Love S.G., and Scott E.R.D. (1996) Constraints on the role of impact heating and melting in asteroids (abstract). *Meteoritics & Planet. Sci.* **31**, A69-A70.

Kerridge J.F. (1964) Production of superparamagnetic Fe^0 on the lunar surface (abstract). *LPSC XXV*, 695-696.

Kivelson M.G., Bargatze L.F., Khurana K.K., Southwood D.J., Walker R.J., and Coleman P.J., Jr. (1993) Magnetic field signatures near Galileo's closest approach to Gaspra. *Science* **261**, 331-334.

Kuiper G.P. (1971) Discussion. In *Physical Studies of Minor Planets* (ed. T. Gehrels), p. 485. NASA SP-267.

Larson H.P. and Veeder G.J. (1979) Infrared spectral reflectances of asteroid surfaces. In *Asteroids* (ed. T. Gehrels), pp. 724-744. Univ. of Ariz. Press, Tucson.

Lee P. (1995) Electrostatic levitation of fines on asteroids (abstract). *Meteoritics* **30**, 535.

Lee P., Veverka J., Thomas P.C., Helfenstein P., Belton M.J.S., Chapman C.R., Greeley R., Pappalardo R.T., Sullivan R., and Head J.W., III (1996) Ejecta blocks on 243 Ida and on other asteroids. *Icarus* **120**, 87-105.

Lipschutz M.E., Gaffey M.J., and Pellas P. (1989) Meteoritic parent bodies: nature, number, size and relation to present-day asteroids. In *Asteroids II* (eds. R.P. Binzel, T. Gehrels, and M.S. Matthews), pp. 740-777. Univ. Ariz. Press, Tucson.

Love S.G. and Ahrens T.J. (1996) Gravity dominance in catastrophic impacts onto asteroids (abstract). Presented at ACM 96: COSPAR Colloq. 10, Versailles, France, 8-12 July 1996.

Martelli G., Rothwell P., Smith P.N., Giblin I., Di Martino M., and Farinella P. (1993) Fragment jets from catastrophic break-up events and the formation of asteroid binaries and families. *Astron. Astrophys.* **271**, 315-318.

Marzari F., Davis D., and Vanzani V. (1995) Collisional evolution of asteroid families. *Icarus* **113**, 168-187.

Matson D.L., Fanale F.P., Johnson T.V., Veeder G.J. (1976) Asteroids and comparative planetology. *Proc. Lunar Sci. Conf. 7th*, 3603-3627.

Matson D.L., Johnson T.V., and Veeder G.J. (1977) Soil maturity and planetary regoliths: the moon, Mercury, and the asteroids. *Proc. Lunar Sci. Conf. VIII*, 1001-1011.

McCord T.B., Adams J.B., and Johnson T.V. (1970) Asteroid Vesta: spectral reflectivity and compositional implications. *Science* **168**, 1445-1447.

McCord T.B. and Gaffey M.J. (1974) Asteroids: surface composition from reflection spectroscopy. *Science* **186**, 352-355.

McCord T.B. and Chapman C.R. (1975a) Asteroids: spectral reflectance and color characteristics. *Astrophys. J.* **195**, 553-562.

McCord T.B. and Chapman C.R. (1975b) Asteroids: spectral reflectance and color characteristics II. *Astrophys. J.* **197**, 781-790.

McFadden L.A. (1983) Spectral reflectance of near-Earth asteroids: implications for composition, origin, and evolution. PhD dissertation, Univ. of Hawaii.

McFadden L.A., Gaffey M.J., and McCord T.B. (1985) Near-Earth asteroids: Possible sources from reflectance spectroscopy. *Science* **229**, 160-163.

McSween H.Y. (1992) Redox effects in ordinary chondrites and implications for asteroid spectrophotometry. *Icarus* **95**, 239-243.

McSween H.Y. and Bennett M.E. (1995) Hotter, faster: A thermal model for the H-chondrite parent body consistent with chronology and cooling rates (abstract). *Meteoritics* **30**, 544.

Morbidelli A., Gonczi R., Froeschlé Ch., and Farinella P. (1994) Delivery of meteorites through the ν_6 secular resonance. *Astron. Astrophys.* **282**, 955-979.

Moroz L.V., Fisenko A.V., Semjonova L.F., Pieters C.M. (1993) Optical effects of regolith processes on S asteroids as simulated by laser impulse alteration of ordinary chondrite (abstract). *LPSC XXIV*, 1011-1012.

Moroz L.V., Fisenko A.V., Semjonova L.F., Pieters C.M., Korotaeva N.N. (1996) Optical effects of regolith processes on S-asteroids as simulated by laser shots on ordinary chondrite and other mafic materials. *Icarus*, in press.

Morrison D. (1974) Radiometric diameters and albedos of 40 asteroids. *Astrophys. J.* **194**, 203-212.

Morrison D. (1978) General discussion on session 1. In *Asteroids: An Exploration Assessment* (eds. D. Morrison and W.C. Wells), p. 77. NASA Conf. Publ. 2053.

Murchie S.L. and Pieters C.M. (1996) Spectral properties and rotational spectral heterogeneity of 433 Eros. *J. Geophys. Res.* **101**, 2201-2214.

NASA Solar System Exploration Division (1984) Proposed NASA policy on asteroid fly-bys. In *Report of the Galileo Asteroid Flyby Working Group*, pp. 21-22. August 1984.

Ostro S.J. (1989) Radar observations of asteroids. In *Asteroids II* (eds. R.P. Binzel, T. Gehrels, and M.S. Matthews), pp. 192-212. Univ. Ariz. Press, Tucson.

Ostro S.J. (1993) Planetary radar astronomy. *Rev. Modern Phys.* **65**, 1235-1279.

Ostro S.J., Campbell D.B., Chandler J.F., Hine A.A., Hudson R.S., Rosema K.D., Shapiro I.I. (1991) Asteroid 1986 DA: radar evidence for a metallic composition. *Science* **252**, 1399-1404.

Pellas P. (1988) Foreign OC-type clasts in meteoritic breccias: what they tell us about the abundance of OC-type asteroids in the main belt. *Meteoritics* **23**, 296.

Pellas P. and Storzer D. (1981) ^{244}Pu fission track thermometry and its application to stony meteorites. *Proc. R. Soc. Lond.* A **374**, 253-270.

Pieters C., Gaffey M.J., Chapman C.R., and McCord T.B. (1976) Spectrophotometry (0.33 to 1.07μm) of 433 Eros and compositional implications. *Icarus* **28**, 105-115.

Pieters C.M., Fischer E.M., Rode O., and Basu A. (1993) Optical effects of space weathering: the role of the finest fraction. *J. Geophys. Res.* **98**, 20817-20824.

Pieters C.M. and Binzel R.P. (1994) Young Vesta (regolith)? (abstract). *LPSC XXV*, 1083-1084.

Pieters C.M. and McFadden L.A. (1994) Meteorite and asteroid reflectance spectroscopy: clues to early solar system processes. *Annu. Rev. Earth Planet. Sci.* **22**, 457-497.

Rabinowitz D.L. (1993) The size distribution of the Earth-approaching asteroids. *Astrophys. J.* **407**, 412-427.

Ryan E.V. and Melosh H.J. (1995) Asteroids: Shattered but not dispersed (abstract). *EOS* **76** (46), F336.

Ryan E.V. and Chapman (1996) Spectral variations on Ida: A space weathering trend? (abstract). *Meteoritics & Planet. Sci.* **31**, A120-A121.

Scott E.R.D. (1979) Origin of iron meteorites. In *Asteroids* (ed. T. Gehrels), pp. 892-925. Univ. Ariz. Press, Tucson.

Shoemaker E.M., Williams J.G., Helin E.F., and Wolfe R.F. (1979) Earth-crossing asteroids: orbital classes, collision rates with Earth, and origin. In *Asteroids* (ed. T. Gehrels), pp. 253-282. Univ. Ariz. Press, Tucson.

Stöffler D., Keil K., Scott E.R.D. (1991) Shock metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta* **55**, 3845-3867.

Sullivan R., Greeley R., Pappalardo R., Asphaug E., Moore J.M., Morrison D., Belton M.J.S., Carr M., Chapman C.R., Geissler P., Greenberg R., Granahan J., Head J.R. III, Kirk R., McEwen A., Lee P., Thomas P.C., and Veverka J. (1996) Geology of 243 Ida. *Icarus* **120**, 119-139.

Sykes M.V., Greenberg R., Dermott S.F., Nicholson P.D., and Burns J.A. (1989) Dust bands in the asteroid belt. In *Asteroids II* (ed. R.P. Binzel, T. Gehrels, M.S. Matthews), pp. 336-367. Univ. Ariz. Press, Tucson.

Taylor G.J., Maggiore P., Scott E.R.D., Rubin A.E., Keil K. (1987). Original structures, and fragmentation and reassembly histories of asteroids: evidence from meteorites. *Icarus* **69**, 1-13.

Tholen D.J. (1984) *Asteroid taxonomy from cluster analysis of photometry*. Ph.D. dissertation, Univ. of Arizona.

Thomas P.C., Veverka J., Simonelli D., Helfenstein P., Carcich B., Belton M.J.S., Davies M.E., and Chapman C. (1994) The shape of Gaspra. *Icarus* **107**, 23-36.

Thomas P.C., Belton M.J.S., Carcich B., Chapman C.R., Davies M.E., Sullivan R., and Veverka J. (1996) The shape of Ida. *Icarus* **120**, 20-32.

Veverka J., Belton M., Klaasen K., and Chapman C. (1994a) Galileo's encounter with 951 Gaspra: overview. *Icarus* **107**, 2-17.

Veverka J., Thomas P., Simonelli D., Belton M.J.S., Carr M., Chapman C., Davies M.E., Greeley R., Head J., Klaasen K., Johnson T.V., Morrison D., Neukum G. (1994b) Discovery of grooves on Gaspra. *Icarus* **107**, 72-83.

Veverka J., Thomas P.C., Helfenstein P., Lee P., Harch A., Calvo S., Chapman C., Belton M.J.S., Klaasen K., Johnson T.V., and Davies M.E. (1996a) Dactyl: Galileo observations of Ida's satellite. *Icarus* **120**, 200-211.

Veverka J., Helfenstein P., Lee P., Thomas P., McEwen A., Belton M., Klaasen K., Johnson T.V., Granahan J., Fanale F., Geissler P., and Head J.W., III (1996b) Ida and Dactyl: spectral reflectance and color variations. *Icarus* **120**, 66-76.

Veverka J., Bell J.F. III, Thomas P., Harch A., Murchie S., Hawkins S.E. III, Warren J.W., Darlington H., Peacock K., Chapman C.R., McFadden L.A., Malin M.C., and Robinson M.S. (1996c) An overview of the NEAR Multispectral Imager (MSI)--Near Infrared Spectrometer (NIS) investigation. *J. Geophys Res.*, submitted.

Wasson, J.T. (1974) *Meteorites*, p. 175, Springer-Verlag, New York/Heidelberg/Berlin.

Wasson J.T. and Wetherill G.W. (1979) Dynamical, chemical and isotopic evidence regarding the formation locations of asteroids and meteorites. In *Asteroids* (ed. T. Gehrels), pp. 926-974. Univ. of Ariz. Press, Tucson.

Wasson J.T., Chapman C.R., Grogan K., and Dermott S.F. (1996) Possible formation of the Vesta-family asteroids and the main IRAS dust band by an oblique impact on Vesta (abstract). *LPSC XXVII*, 1387-1388.

Wasson J.T. and Chapman C.R. (1996) Space weathering of basalt-covered asteroids: Vesta an unlikely source of the HED meteorites (abstract). Submitted to Workshop on Evolution of Igneous Asteroids: Focus on Vesta and the HED Meteorites, Lunar & Planet. Inst., Houston, TX, 16-18 Oct. 1996.

Wetherill G.W. (1985) Asteroidal source of ordinary chondrites. *Meteoritics* **20**, 1-22.

Wetherill G.W. (1988) Where do the Apollo objects come from? *Icarus* **76**, 1-18.

Wetherill G.W. and Chapman C.R. (1988) Asteroids and meteorites. In *Meteorites and the Early Solar System* (eds. J. Kerridge and M.S. Matthews), 35-67. Univ. of Ariz. Press, Tucson.

Wilkening L.L. (1977) Meteorites in meteorites: evidence for mixing among the asteroids. In *Comets, Asteroids, Meteorites* (ed. A.H. Delsemme), pp. 389-396. Univ. Toledo Press, Toledo, Ohio.

Wilkening L.L. (1979) The asteroids: accretion, differentiation, fragmentation, and irradiation. In *Asteroids* (ed. T. Gehrels), pp. 61-74. Univ. of Ariz. Press, Tucson.

Wisdom J. (1985) Meteorites may follow a chaotic route to Earth. *Nature* **315**, 731-733.

Wood J.A. (1967) Chondrites: their metallic minerals, thermal histories, and parent planets. *Icarus* **6**, 1-49.

Xu S., Binzel R.P., Burbine T.H., and Bus S.J. (1995) Small main-belt asteroid spectroscopic survey: initial results. *Icarus* **115**, 1-35.

Zellner B., Gehrels T., and Gradie J (1974) Minor planets and related objects. XVI. Polarimetric diameters. *Astron. J.* **79**, 1100-1110.

Zellner B., Tholen D.J., Tedesco E.F. (1985) The Eight-Color Asteroid Survey: results for 589 minor planets. *Icarus* **61**, 355-416.

Figure Captions

Fig. 1. The highest resolution color data from Gaspra (enhanced false color from the violet, green, and 0.99μm filters) are reprojected onto the highest resolution monochrome image of Gaspra (~54 m/pixel) to illustrate correlation between colors, topography, and smaller features. J.P.L. photo P-40450-C.

Fig. 2. The highest resolution monochrome picture of Ida, mosaicked from 5 images taken between 4 and 2.5 min. before encounter. Resolution varies between 38 and 31 m/pixel. The highest resolution image of Gaspra is shown at approximately the same scale.

Fig. 3. An enhanced false-color view of Ida constructed from the violet, 0.76μm, and 0.99μm images, illustrating the correlation of bluish regions with small fresh craters and Azzurra ejecta. J.P.L. photo P-44131.

Fig. 4. Reflection spectra of Terrain A, Terrain B, Terrain C, Dactyl, whole Ida (near 10° longitude), and from unit "Red1" of Sullivan *et al.* (1996). Error bars are typically ±2-3%. See text for details and interpretation.

Fig. 5. False color representations of major color units evaluated in this paper. Light blue represents typical Azzurra ejecta; dark blue the "freshest" and bluest units; red represents the background redder units and intermediate areas. (a) The highest resolution color sequence, with subspacecraft longitude near 50°. The small fresh crater discussed in the text is indicated, as well as the most representative background regions, and the single patch of Azzurra ejecta on this hemisphere. (b) The "back side" of Ida, near subspacecraft longitude 340°, showing the bluish regions near Azzurra.

Fig. 6. Reflection spectra for the small fresh crater, typical Azzurra ejecta, and typical background (from both image sequences shown in Fig. 5). Typical error bars are ±2-3%. Also shown are average laboratory spectra, from Gaffey, for L5 and L6 ordinary chondrites (OC's). There is an apparent weathering trend from either of the OC spectra to the fresh crater spectrum to the Azzurra spectrum, culminating in the reddish general background spectrum.

Fig. 7. Reflection spectra for Terrains A and B and for Dactyl, divided by average Ida (from Veverka *et al.*, 1996b), are plotted on top of an equivalent plot (from Binzel *et al.*, 1993a) showing deviations of Koronis family members from Ida. Note that none of the Koronis family members are quite as red as Terrain A, nor do any of them show a spectrum that curves as much between 0.45μm and 0.75μm as Dactyl.

Fig. 8. Preliminary NIMS spectra of Ida and Dactyl are shown on this plot, courtesy of J. Granahan and F. Fanale. The short wavelength data are based on SSI data, from an early calibration.

Fig. 9. Reflection spectra for 2078 Nanking (a Mars-crosser) and 3628 Božněmcová, compared with various meteorites. The figure, graciously provided by R. Binzel, is based partly on that of Xu *et al.* (1995). Data for Božněmcová from Binzel *et al.* (1993b) are shown as solid squares, with data at additional wavelengths (as published by Xu *et al.*) shown as small points. Question marks highlight some regions of disagreement between the spectrum of Božněmcová and those for OC analogs. The short wavelength reflectance of the asteroid (near 0.45μm) is too bright compared with the meteorites and the long wavelength absorption band center may be beyond 1.00μm, unlike the OC meteorites.

[Click on "Short Abstract" button on my Available Preprints page to see most figures]