Available online at www.sciencedirect.com
SCIENCE DIRECT
ICARUS
Icarus 174 (2005) 36–45
www.elsevier.com/locate/icarus

Space weathering and the low sulfur abundance of Eros

Alfred Kracher *, Derek W.G. Sears

Center for Space and Planetary Sciences and Department of Chemistry and Biochemistry, 101 Chemistry Building, University of Arkansas, Fayetteville, AR 72701, USA

Received 25 April 2003; revised 21 September 2004

Abstract

The surprisingly low S/Si ratio of Asteroid 433 Eros measured by the NEAR Shoemaker spacecraft probably reflects a surface depletion rather than a bulk property of the asteroid. The sulfur X-ray signal originates at a depth < 10 μm in the regolith. The most efficient process for vaporizing minerals at the heliocentric distance of Eros are sputtering by solar wind ions and hypervelocity impacts. These are the same processes that account for the changes in optical properties of asteroids attributed to "space weathering" of lunar surface materials, although the relative importance of sputtering and impacts need not be the same for the Moon and asteroids. Troilite, FeS, which is the most important sulfide mineral in meteorites, and presumably on S-type asteroids like Eros, can be vaporized by much less energy than other major minerals, and will therefore be preferentially lost. Within 10^6 years either process can remove sulfide from the top 10–100 μm of regolith. Sulfur will be lost into space and some sulfur will migrate to deeper regolith layers. We also consider other possible mechanisms of surficial sulfur depletion, such as mineral segregation in the regolith and perhaps even incipient melting. Although we consider solar wind sputtering the most likely cause of the sulfur depletion on Eros, we cannot entirely rule out other processes as causes of the sulfur deficiency. Laboratory simulations of the relevant processes can address some of the open questions. Simulations will have to be carried out in such a way that potential sulfur loss processes as well as resurfacing can be studied simultaneously, requiring a large and complex environmental chamber.
© 2004 Elsevier Inc. All rights reserved.

1. Introduction

Asteroid 433 Eros is the only small planetary body for which we have direct measurements of surface chemistry. Arguably the most surprising result obtained by the NEAR Shoemaker spacecraft was the lower than expected S/Si ratio (Nittler et al., 2001). Other element ratios determined by the X-ray and γ-ray spectrometers on the spacecraft are in the range of ordinary chondrites (McCoy et al., 2001). Determination of S/Si on Eros was only possible during some of the solar flares because sulfur remains below the detection limit during "quiet Sun" conditions. From an aggregate of all determinations Nittler et al. (2001) derived an upper limit of S/Si $= 0.05$ by weight. Based on the same measurements, McCoy et al. (2001) suggested S/Si $= 0.014$, with an uncertainty that was greater than the value.

The S/Si weight ratio in CI chondrites, which closely matches the spectroscopically determined solar ratio, is 0.528 (Dreibus et al., 1995). It is characteristic of chondrites that ratios of major elements to Si show only modest deviations from the CI value. Unweathered chondrites have S/Si ratios at most 4 times lower than CI, and for other major elements the depletion or enrichment factors are even smaller. By contrast, the S/Si values of Nittler et al. (2001) and McCoy et al. (2001) for Eros are less that CI values by factors of 11 and 38, respectively.

Since other element ratios are chondritic, it would seem unlikely that the low sulfur abundance is a bulk property of Eros. Thus sulfur has apparently been lost from the top layer of the regolith. Here we review possible mechanisms for the depletion of sulfur on the Eros surface, particularly the energetic processes responsible for the phenomenon known as "space weathering." As yet it is impossible to reach a

* Corresponding author. Current address: Ames Laboratory (USDOE), 227 Wilhelm Hall, Iowa State University, Ames, IA 50011-3020, USA.
E-mail address: akracher@iastate.edu (A. Kracher).

0019-1035/$ – see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2004.10.010

firm conclusion about the mechanism of sulfur depletion, and we argue that short of revisiting the asteroid the best way to make further progress on interpreting the NEAR data is to carry out laboratory simulations of asteroid surface processes.

2. Sulfur depletion on Eros

The depletion process may be physical, such as density segregation, or chemical, such as decomposition of FeS and loss of sulfur. Troilite, stoichiometric FeS, is the most common sulfur-bearing mineral in almost all anhydrous meteorites. This includes all meteorite classes potentially related to S-type asteroids (Gaffey et al., 1993a), and therefore whatever sulfur is or was present on Eros should be mostly contained in troilite.

The melting point of troilite is 1468 K. It forms a eutectic with metallic nickel–iron with which it is often in contact that melts at 1261 K. The addition of Ni further lowers the melting point. Sulfide eutectic is the lowest temperature melting assemblage of all major components of a chondritic mineralogy and there are meteorites in which sulfides and a minor silicate component melted (McCoy et al., 1996, 1997; Benedix et al., 1998, 2000). Asteroids on which this occurred were called partially differentiated parent bodies by Kracher (1985). Since the taxonomy of S asteroids relies primarily on the high-melting minerals pyroxene and olivine, which are largely unaffected by partial differentiation, the spectra of partially differentiated asteroids might be practically indistinguishable from chondritic objects.

In the case of Eros segregation due to endogenous heating is unlikely. Both the chemical data (McCoy et al., 2001) and the uniform density (Miller et al., 2002) suggest that Eros is not fully differentiated, unlike Vesta, for example. However, the density data do not rule out the possibility of a partially differentiated "raisin bread" structure, in which lumps of sulfide or sulfide-metal exist scattered throughout the interior. Burbine et al. (2001) find that primitive achondrites, i.e., meteorites that come from partially differentiated parent bodies, are not a good spectral match for Eros. Furthermore, it is hard to imagine how a sulfur-depleted surface could have formed without leaving other evidence of the segregation process. It is therefore unlikely that Eros is a primitive achondrite body.

Regardless of the nature of the process, the removal of sulfur from the surface layer requires energy. Energetic processes were apparently plentiful during the first 100 Myr or so of Solar System history, as indicated by early metamorphism and differentiation of meteorite parent bodies. However, currently the only processes that deliver sufficient energy to an asteroid surface for decomposing anhydrous minerals are solar wind irradiation and high-velocity impacts. Physical separation can be achieved with low energy processes such as outgassing of volatiles, and we will consider this possibility separately.

Like all asteroids imaged from spacecraft so far, Eros is covered by ubiquitous regolith (Veverka et al., 2001; Robinson et al., 2002). According to observational data assembled from previous studies by Chapman (1995) and Murchie and Pieters (1996), Eros is an S(IV) asteroid. This subtype, as proposed by Gaffey et al. (1993a), is thought to be the type most similar to ordinary chondrites (OCs). The OC-like bulk chemistry expected for Eros on the basis of this classification was verified for most elements determined by NEAR Shoemaker, but the measured S/Si ratio proved a glaring exception (Nittler et al., 2001; McCoy et al., 2001). Regardless of the details of regolith formation on small bodies, the age of the surface layer on Eros is much younger than the age of the Solar System. An energy source that operated only during the early times of the Solar System could not account for the sulfur depletion of the Eros surface, unless it had affected the composition of the entire body, so that each successively excavated surface was similarly deficient in sulfur. Since there are no chondritic meteorites that show evidence of such a strong depletion, we will assume that it is unlikely that early Solar System processes produced bulk material of such a highly fractionated kind. Correlations of S/Si with other element ratios such as K/Si (Fig. 1) and Fe/Si (Fig. 2) show, even with the fairly large uncertainties of the XRS and GRS experiments on NEAR Shoemaker, that the composition of Eros does not fall on an extension of the trend represented by major chondrite groups. The axes of Figs. 1 and 2 are scaled so that the solar composition, represented by CI chondrites, is at unity. The spread in K/Si among chondrites (Fig. 1) is primarily due to a fractionation of volatiles, that in Fe/Si (Fig. 2) to metal/silicate fractionation. Note that the meteorites that appear to plot on a trend from CI to Eros in Fig. 1 plot far away from such a trend in Fig. 2, and vice

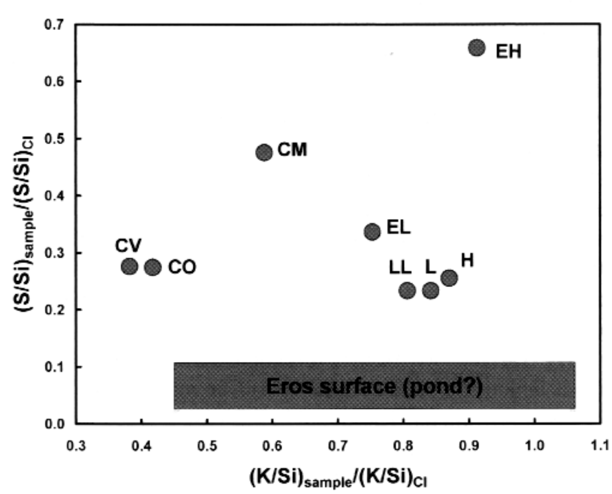

Fig. 1. S/Si versus K/Si in major chondrite groups and Eros. Meteorite data from Wasson and Kallemeyn (1988) and Dreibus et al. (1995). Eros data from Evans et al. (2001) and McCoy et al. (2001). The K value for Eros was obtained in contact with the surface, possibly in one of the structures known as ponds.

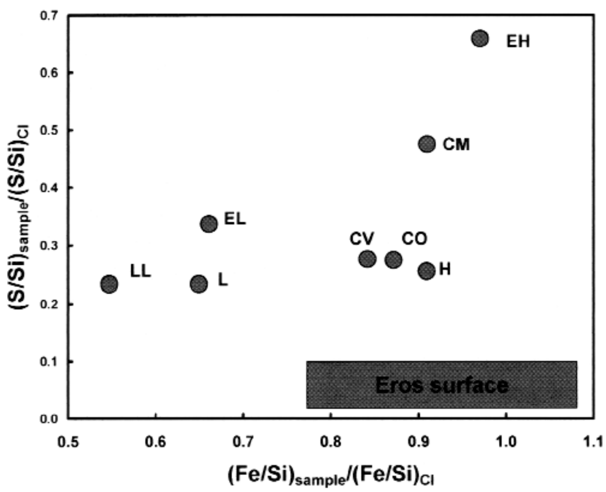

Fig. 2. S/Si versus Fe/Si in major chondrite groups and Eros. Meteorite data from Wasson and Kallemeyn (1988) and Dreibus et al. (1995). Eros data from Nittler et al. (2001) and McCoy et al. (2001).

versa. This supports the contention (McCoy et al., 2001; Kracher et al., 2003) that the S/Si ratio observed on Eros is not simply a more severe case of the kind of fractionations common to chondrites.

It has been suggested that elements such as Na and K (Wilson and Keil, 1991) and sulfur (Keil and Wilson, 1993) may be depleted from a parent body by explosive volcanism, but this would only apply to asteroids that are extensively differentiated. Even if the controversial volcanism model of Keil and Wilson (1993) is correct for other asteroids, it does not apply to Eros. Therefore the most likely energy source for sulfur depletion on Eros is one that is operative today.

Taken together, these lines of evidence make it very likely that the sulfur depletion determined by NEAR Shoemaker is a surface phenomenon rather than a bulk property of Eros. For the purpose of the following analysis we will assume that the bulk S/Si ratio of Eros is approximately that of OCs, ~ 0.13 by weight or ~ 0.11 as atomic ratio. This is approximately 4 times lower than the ratio in CI chondrites (Dreibus et al., 1995) or the solar photospheric ratio (Anders and Grevesse, 1989). Based on this assumption and the S/Si weight ratios of 0.05 (upper limit of Nittler et al., 2001) and 0.014 (nominal value of McCoy et al., 2001), between 60 and 90% of this amount of sulfur is missing from the surface of Eros.

By "surface" we mean in this context the depth of regolith from which the X-ray signal of sulfur reaches the NEAR X-ray spectrometer. The signal in this case is S Kα radiation (2.307 keV) excited by solar X-rays and cosmic radiation. Measurable intensities of S Kα were only detected during solar flares (Nittler et al., 2001). The solar spectrum "hardens," i.e., becomes more energetic, during these events, so that excitation occurs to some depth in the regolith. However, the comparatively soft S Kα X-rays emerge from only a shallow layer. The approximate depth from which the S Kα signal originates can be estimated by using the concept of attenuation length. The *characteristic attenuation length* of X-rays refers to the thickness of absorber necessary to reduce the signal to $1/e$ of its original intensity. This can be calculated for different compositions by summing the effects of absorbing elements, which have been tabulated by Henke et al. (1993).

A regolith of the composition given by McCoy et al. (2001) would have a characteristic attenuation length for S Kα radiation of about $z = 10/D$ µm, where D is the density of the absorbing medium. Assuming a highly porous regolith of $D = 1.6\ \mathrm{g\,cm^{-3}}$, $z \approx 6$ µm. The depletion factors bracketing the presumed sulfur loss, 60 to 90%, correspond to roughly one to two characteristic absorption lengths (63 and 86% attenuation, respectively). One caveat is that these parameters apply to homogeneous absorbers, whereas the regolith is granular on this scale. In fact, its typical particle size may well be larger than the characteristic absorption length. This would mean that only sulfide grains present at the very surface contribute to the sulfur X-ray signal, or at best buried sulfide grains that have an unobstructed "view" of the XRS detector through void space. Thus the depletion necessary for the sulfur signal to become undetectable need be no more than a single layer of regolith particles.

We will consider the loss of sulfur in two steps, the input of energy by impact or by solar wind sputtering, and the energy necessary to cause the loss of sulfide by vaporization.

3. Space weathering

Space weathering refers to "any surface modification process (or processes) that may tend to change the apparent traits (optical properties, physical structure, chemical or mineralogical properties) of the immediate, remotely-sensed surface of an airless body from analogous traits of the body's inherent bulk material" (Clark et al., 2002). If the bulk Eros S/Si ratio is higher than that measured at the surface by NEAR, the process responsible for the difference would, by this definition, be considered "space weathering," regardless of its nature. For our purposes we want to ask, however, whether this process is the same, or at least similar, to the space weathering process that, for example, Hapke (2001) and Pieters et al. (2000) envisage as responsible for the difference between the optical spectra of meteorites and those of asteroids. Both hypervelocity impacts and solar wind sputtering contribute to this phenomenon. It must be emphasized, however, that the relative importance of sputtering and impacts need not be the same for changes in optical properties and sulfur removal.

The concept of space weathering was originally developed on the basis of studies of the lunar regolith. The optical changes associated with soil maturation on the Moon are a significant reduction in albedo, reddening of the visual and near infrared (vis–NIR) spectrum, and a weakening of the silicate absorption features in the NIR (e.g., Matson et al., 1977). It has subsequently been found that these changes are due to the formation of metallic particles, a few nanometers to hundreds of nanometers in size. This component is referred to as *nanophase reduced iron,* $npFe^0$ (Pieters et al., 2000) or *submicroscopic metallic iron,* SMFe (Hapke, 2001). It primarily it resides on grain surfaces (Hapke, 2001), presumably in the form of vapor deposits (Hapke et al., 1975; Keller and McKay, 1993, 1997), but can also be distributed throughout agglutinates.

Originally the kind of space weathering that affects the lunar regolith was thought not to occur asteroids (Matson et al., 1977). However, laboratory measurements of vis–NIR spectra of meteorites (Gaffey, 1976) and vis–IR observations of asteroids (e.g., Chapman and Salisbury, 1973; McCord and Chapman, 1975) revealed a "mismatch" between their optical properties. Although the spectra of the common S-type asteroids and ordinary chondrites showed similar features due to olivine and pyroxene, their spectra are not identical. Gaffey et al. (1993b) suggested that comminution was responsible for the differences, since some S-type asteroids have spectra that differ from those of powdered ordinary chondrites in similar ways that mature lunar soil have spectra that differ from those of powdered samples of its source rock. Similarly, Chapman and Salisbury (1973) suggested that impact vitrification, or more generally some difference in physical state between asteroid surfaces and chondrites, was responsible for the spectral mismatch between S asteroids and ordinary chondrites, but later dismissed the idea. Thus for a number of reasons there was considerable reluctance to conclude that surface-altering processes were important on asteroids (e.g., Matson et al., 1977; Bell et al., 1989). The various arguments in the controversy are recounted in Chapman (1996).

Observations of Asteroids 951 Gaspra and 243 Ida by the Galileo spacecraft in 1991 and 1993 changed this situation. Gaspra, although only 12 km in diameter, is likely to be covered by regolith, and on Ida the spectral properties of different terrains differ in the way expected for lunar-type space weathering. Areas recently excavated by cratering appeared less "weathered" than the more mature regolith (Chapman, 1996). The results from Gaspra, Ida, and Eros show that asteroids tens of kilometers in size are covered with material that resembles the lunar regolith, although it may differ in grain size and does differ in composition. Laboratory studies summarized by Hapke (2001) have demonstrated that exposure to a simulated solar wind can change the vis–NIR spectra of chondrites and make them resemble those of S-type asteroids, notwithstanding some differences (Clark et al., 1992).

Gaffey et al. (1993a) subdivided the S-type asteroids and identified subtype S(IV)as those most closely resembling OCs. While this focused the search for potential OC-like objects as well as for mechanisms which might explain the remaining spectral mismatch, other authors (Sears, 1998; Meibom and Clark, 1999) warned that the quantitative prevalence of OCs among meteorite falls was likely to be a consequence of stochastic events and sampling bias, and did not reflect a prevalence of OC-like asteroids in the inner main asteroid belt.

Although a main motivation for studying space weathering comes from the desire to explain the spectral mismatch between chondritic meteorites and asteroids, the abundance or scarcity of OCs in the main belt is a separate issue that will not be addressed in this paper. Even if it turns out that no S-type asteroids have OC compositions, the question remains as to how their surfaces differ from the interior, and what conclusions we can and cannot draw from remote sensing data. Chondrite types other than OCs have similar sulfur abundances (cf. Figs. 1 and 2), and the arguments about sulfur depletion of Eros would apply to other bulk compositions as well, as long as the entire body was chondritic and undifferentiated.

The effects of regolith maturation or "space weathering" on the Moon are caused by two phenomena, hypervelocity impacts and exposure to solar wind, which we will now discuss as causes for the sulfur depletion on Eros.

4. Impacts

Hypervelocity impacts are a major cause of space weathering on the Moon (Hapke, 2001). However, typical impact energies in the main belt are lower than on the Moon and only marginally sufficient to produce melting (Hörz and Cintala, 1997). This may account for the virtual absence of agglutinates from meteoritic regolith breccias (McKay et al., 1989). Although at the current orbit of Eros impact energies are higher, it is still only a high-velocity tail in the velocity distribution of impactors that is responsible for most of the space weathering. Therefore our initial assumption was that sputtering was more likely to be responsible for sulfur loss than impacts.

Killen (2003) has recently concluded that impacts are capable of removing sulfide much more efficiently than other minerals and calculated erosion rates for a range of conditions. The calculated erosion rates are roughly equivalent to removing sulfide from the top 10 to 100 μm of the soil column in 10^6 years, assuming that sulfide is eroded nine times faster than average regolith. This seems rather high since below we suggest that there is only a factor of two difference in the dissociation energy of FeS and silicates. We therefore suggest that Killen's (2003) estimate represents an upper bound of impact erosion which probably overestimates the actual difference between sulfide and silicate erosion. Killen also implies this by stating that the resistance of minor phases to preferential erosion has not been taken into account in her calculation.

Impacts not only erode the surface. The larger impacts also overturn the top layers and bring fresh material to the surface. The composition of the top layer of the regolith, to the depth visible to optical spectrometry and X-ray analysis, is therefore the result of a dynamic balance between erosion and resurfacing. This situation has not yet been analyzed in detail.

In the case of Eros there is also the question how much surface modification happened at its current location and how much is inherited from its main belt history. There is a suggestion in the optical spectra that the balance between space weathering and resurfacing is different in the main belt from near-Earth orbits. The main belt asteroids Ida and Gaspra, which appear to be compositionally similar to Eros, differ from Eros in the spectral features associated with craters. Whereas Ida shows considerable differences in color (band depth and shape of the spectral continuum) with only small changes in albedo (Sullivan et al., 1996), Eros regolith is highly variable in albedo with only small color changes (Clark et al., 2001; Murchie et al., 2002; Thomas et al., 2002). This difference is tentatively ascribed by Clark et al. (2002) to "different rates of the competing processes of surface maturation and impact cratering between near-Earth orbits (Eros) and the asteroid main belt (Gaspra and Ida)."

5. Sputtering

The solar wind is a stream of charged particles with an average velocity at 1 AU of 400 $\mathrm{km\,s^{-1}}$, but varying over time from 260 to 750 $\mathrm{km\,s^{-1}}$ (Russell, 2001). The average particle density at 1 AU is $\sim 5\ \mathrm{cm^{-3}}$, which gives an average flux of $2 \times 10^8\ \mathrm{ions\,s^{-1}\,cm^{-2}}$. The velocities of solar wind particles at Eros are not substantially different from velocities at 1 AU, but the flux is approximately 50% of the 1 AU value. About 96% on the ions are protons, $\sim 3.8\%$ are He^{2+}, $\sim 0.08\%$ are C, N, and O ions, and $\sim 0.05\%$ are heavier nuclei. The kinetic energy of a proton at 400 $\mathrm{km\,s^{-1}}$ is 0.8 keV. Since the velocity of all ions is approximately the same, their kinetic energy is roughly proportional to their mass. The regime of a few keV per atomic mass unit (1 $\mathrm{keV\,amu^{-1}}$) is the most efficient energy range for ion-induced sputtering (Betz and Wehner, 1983). The ionization state of heavy ions, which is a function of the coronal electron temperature, corresponds to about 1 keV total ionization energy. As a result typical ion charges are, for example, Si^{9+} and Fe^{10+} (von Steiger et al., 2000; Bochsler, 2000), with some variation over time that is unimportant in the present context.

At these energies both sputtering and ion implantation occurs at the target. Since the majority of ions in the solar wind are protons, it was originally assumed that the formation of metallic Fe is due to a chemical reduction process. However, Hapke (2001) argues that chemical effects do not play a significant role in the formation of SMFe from Fe-bearing silicates and the experiments of Dukes et al. (1999) confirm this. Dukes et al. (1999) bombarded San Carlos olivine with 1 kV H^+ and 4 kV He^+ ions while observing the X-ray photoelectron (XPS) spectrum. In both cases a Fe^0 signal was observed, but it was much stronger under He bombardment. This is probably due to both the higher energy of the He^+ ions and the fact that each ion–atom collision can transfer a larger amount of energy. A similar conclusion has been reached by Bibring et al. (1974) and Maurette and Price (1975) who report that He^+ is ~ 100 times more efficient that H^+ in producing macroscopically visible changes in mineral grains. Since sputtering is not a classical process, a "billiard ball" analysis is only a very rough approximation, but it nonetheless indicates that a 4 kV He^+ ion transfers some 12–15 times as much energy onto a target atom of mass $\geqslant 16$ as a 1 kV H^+ ion. The higher thermal energy of the sputtered atoms and ions may be responsible for a more efficient escape of sputtered oxygen, and hence an increased production of Fe^0. This would indicate that alpha particles, which account for $\sim 4\%$ of the solar wind particles, or $\sim 13\%$ of its total energy, contribute significantly to space weathering.

The ion energies used by Dukes et al. (1999) correspond to velocities of about 450 $\mathrm{km\,s^{-1}}$, typical of the average velocity in the solar wind (Russell, 2001). However, helium ions in the experiment were He^+, whereas the solar wind contains He^{2+}, which we expect to be even more efficient in sputtering, since they carry additional energy in the form of ionization. However, we know of no experiments that compare sputtering yields of ions with the same kinetic energy but different ionization states in this mass and energy range.

Solar wind protons apparently do not produce H_2O, and we assume that they do not produce H_2S. However, oxygen in Fe-bearing silicates and sulfur in FeS might behave very differently during sputtering. Solar wind energies and Eros surface temperatures generally fall in the regime called "chemically enhanced physical sputtering" (Roth, 1983), in which some molecule formation may take place (true chemical sputtering only occurs at target temperature > 500 K). The proton flux at Eros could destroy at most 0.5 nm FeS per year by removal of H_2S, if the process were 100% efficient. Although Hapke (2001) considers this mechanism improbable, this value is similar to the erosion rate by physical sputtering estimated below. Therefore our conclusions do not depend on the particular mechanism by which solar wind interacts with surficial sulfide.

There remains, however, a major uncertainty in how solar wind contributes to chemical changes on asteroid surfaces. So far we have only considered the major species H and He. Even though ions with $Z > 2$ are much less abundant than protons and He^{2+} ions, they carry considerable energy, and are likely to be much more efficient in sputtering than protons. We will return to this issue at the end of the following section.

6. Energetics of erosion

One way of estimating the effect of any energetic surface process on mineral abundances is to ask the question how much energy it would take to destroy a given volume, for ex-

Table 1
Specific dissociation enthalpies of major minerals in meteorites

	ΔH_f^{298} kJ mol^{-1}	E_{conv} kJ mol^{-1}	E_{diss} kJ mol^{-1}	MW g mol^{-1}	ρ	V_0 cm^3	E_{diss}/V_0 kJ cm^{-3}	E^*_{diss} kJ kg^{-1}
Mg_2SiO_4	2170	1741	3911	140.69	3.21	43.79	89.32	27800
Fe_2SiO_4	1497	2278	3775	203.78	4.39	46.39	81.38	18530
$MgSiO_3^*$	1548	1345	2892	100.39	3.19	31.47	91.91	28810
$MgCaSi_2O_6$	3211	2720	5931	216.55	3.28	66.09	89.74	27390
$NaAlSi_3O_8$	3935	3781	7716	262.22	2.62	100.09	77.09	29430
$CaAl_2Si_2O_8$	4243	3731	7974	278.21	2.76	100.79	79.12	28660
Fe		415.5	415.5	55.85	7.874	7.093	58.58	7440
FeS	101.0	692.7	793.6	87.91	4.74	18.55	42.79	9027

ΔH_f^{298}—standard enthalpy of formation from the elements (Robie et al., 1978). E_{conv}—enthalpy of conversion from element standard state to monoatomic vapor (Lide, 1996). E_{diss}—dissociation enthalpy; sum of ΔH_f^{298} and E_{conv}. MW—formula weight. ρ—specific gravity. V_0—molar volume (Robie et al., 1978, or calculated from densities in Tröger, 1979). E_{diss}/V_0—volume-normalized dissociation enthalpy. E^*_{diss}—weight-normalized dissociation enthalpy.

ample a 1 cm^3 cube, of each major mineral. One may think of this as "energy density (J cm^{-2}) required for 1 cm of erosion." We can then compare the required energy to various processes, including those responsible for space weathering.

If we assume that the main product of the energetic process is the production of monoatomic vapor (Hapke, 2001), we can approximate the required energy for each mineral by adding up its enthalpy of formation from the standard states of the constituent elements, plus the enthalpy required for converting the standard state to a monoatomic gas (dissociation enthalpy). This value does not include the additional thermal energy imparted on the vaporized atoms, but it quantifies at least approximately the process of erosion by vaporization. Using formation enthalpies and molar volumes for silicates and FeS tabulated by Robie et al. (1978) and dissociation enthalpies from Lide (1996, 9–63), we calculate that volume-normalized dissociation energies for typical meteoritic silicates fall within a narrow range of 77 kJ cm^{-3} for $NaAlSi_3O_8$ to 92 kJ cm^{-3} for $MgSiO_3$ (Table 1). The dissociation energy of olivine, $\sim$ 89 kJ cm^{-3}, is only weakly dependent on Fe content. The energy required to vaporize 1 cm^3 of FeS is much smaller than these values, only 42.8 kJ. Thus it takes only about half the energy to vaporize a given volume of troilite compared to the same volume of olivine. Expressed in terms of erosion, a mineralogically unspecific energetic process could remove troilite twice as fast as olivine. The conclusion is that any energetic process acting at the regolith surface can potentially erode sulfide to a greater depth than any other mineral (Fig. 3). This applies to metal as well, pure Fe requiring 58.6 kJ cm^{-3} for conversion to a monoatomic gas at room temperature. Erosion and redeposition of metal does not involve any change in chemistry, although it may change the optical properties of the regolith. Since our concern here is mostly with chemistry, we will ignore the behavior of metal.

Actual erosional processes may not be entirely unspecific. For example, some fraction of Si may be sputtered or vaporized as SiO rather than separate Si and O atoms, which would reduce the energy required for eroding olivine by up to $\sim$ 20%. But this is a small change compared to the factor of two difference between olivine and troilite, and does not alter the conclusion that any process capable of vaporizing surface material may act more efficiently on FeS than on any other major mineral in the regolith.

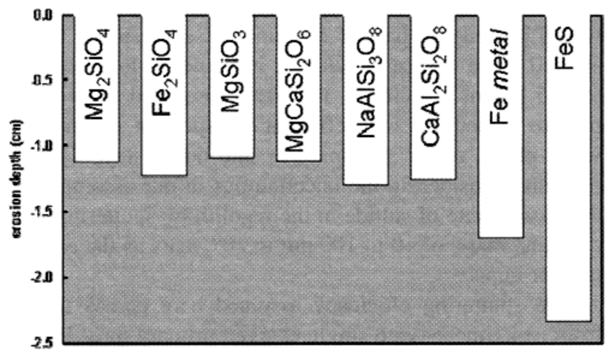

Fig. 3. Depth of erosion for different minerals caused by expending 100 kJ on complete dissociation.

7. The solar wind as energy source

The total energy available from the solar wind can only be roughly estimated. Although there is considerable information from the SOHO and Ulysses spacecrafts, and more recently from Genesis, these measurements have shown strong variations in velocity, flux, and ionization state of solar wind particles (von Steiger et al., 2000; Bochsler, 2000; Russell, 2001). What is relevant for space weathering is the average energy flux over 10^3 to 10^6 years, whereas the database for direct measurements does not even cover one complete solar cycle.

Nonetheless we can make a conservative estimate of the energy deposited by the various components of the solar wind by making some simplifying assumptions. First, the flux and energy of protons given above amounts to an energy flux of 0.3 to 0.6 J cm^{-2} yr^{-1} at the heliocentric distance of Eros. Assuming that all ions have the same velocity, and hence kinetic energy is proportional to mass, the kinetic energy of He^{2+} contributes roughly 13%, C, N, and O ions about 1%, and all heavier ions ($Z > 8$) also about 1%.

From Fig. 3 the difference in erosion depth between silicates and FeS for a given amount of energy expended on dissociation is $\sim 0.1\ \mu m\,J^{-1}\,cm^{-2}$. A comparison of sputtering yields for ions of various energies with average binding energies per atom, which are 4–6 eV, indicates that the energy conversion factor, i.e., the fraction of the kinetic energy of incident ions expended on dissociation of target material, varies from a few times 10^{-4} to 10^{-2}. Maurette and Price (1975) estimate the erosion rate of lunar mineral grains at $0.5 \times 10^{-4}\ \mu m\,yr^{-1}$. Although some other authors have estimated lower rates, summarized by Hapke (2001, Table 2), this value corresponds to a reasonable energy conversion factor of roughly 0.1%, assuming a typical energy flux of $0.5\ J\,cm^{-2}\,yr^{-1}$. At the location of Eros the erosion rate would be roughly half of the lunar case. If sulfide is destroyed twice as fast as silicate, it would be lost from the top 25 μm of regolith in 10^6 years, provided the erosion process is coupled with efficient transport of the ensuing vapor phase, either into space or into deeper layers of the regolith. Considering the uncertainties in our assumptions, the erosion rate of sulfide in the regolith by sputtering is in the same range of 10 to 100 μm in 10^6 years as the erosion rate for impacts.

The sputtering efficiency assumed here comes mostly from experiments with single charged primary ions. Highly charged ions, such as the heavier components of the solar wind, have been found to be much more efficient in sputtering, in some cases by more than an order of magnitude for the energies and charge states relevant to the solar wind (Arnau et al., 1997). Thus the erosion rates on asteroid surfaces may well be higher than our conservative estimate. Killen (2003) also estimates similar erosion rates for sputtering and impacts, although she considered only sputtering by protons. Since this significantly underestimates the effects of sputtering and her impact erosion rate is probably an upper limit, we conclude that sputtering is most likely the dominant process that removes sulfur from the upper layer of the Eros regolith.

There are, however, problems with this simple picture of sulfide erosion. The layer within which FeS is destroyed may be relatively shallow, but within this layer the change in bulk chemistry is massive. If we assume that the primary erosion process is the conversion of FeS into metallic iron and some volatile species of sulfur, at least 2.4% Fe^0 would be added to the regolith. This amount of metal cannot be present as SMFe in the asteroid regolith. Hapke (2001) has developed a model for the influence of SMFe on regolith spectra (e.g., Fig. 26 in Hapke, 2001). For amounts of SMFe on the order of 0.1% the spectra show the convex-upward curvature in the visual quantified in asteroid spectra by McCord and Chapman (1975) and used by Chapman (1996) to infer the extent of asteroid space weathering. At higher SMFe contents, however, the spectrum becomes saturated, absorption bands disappear completely, and reflectance in the visual range is uniformly depressed (curves for 0.5 and 2% SMFe in Fig. 26 of Hapke, 2001). Measurements of lunar samples and a lunar soil analog essentially confirm the validity of Hapke's model (Noble et al., 2001). Even the most mature lunar soils contain less than 1% by weight of SMFe ($npFe^0$ of Noble et al., 2001), and absorption features of silicates are entirely obscured at SMFe contents of 0.5% or less in both actual lunar soil and simulant (Fig. 10 of Noble et al., 2001). This is very different from the actually observed spectra of Gaspra, Ida, and Eros. Even if the lunar situation with its different energy environment and grain sizes should lead us to overestimate the effect of SMFe on asteroid spectra, a content of 2.4% SMFe is simply not realistic for Eros regolith.

Metal might of course be present in the form of much larger grains which would have less effect on the optical spectrum than surface-correlated SMFe. This presents a different problem, however. The evidence from macroscopic lunar metal and sulfide indicates that sulfur is not readily lost from millimeter-sized particles. Blau and Goldstein (1975) studied metal grains from the lunar soil between 50 μm and 5 mm in diameter, and prepared laboratory analogs. They found that many of the lunar particles contained, and some were mantled by, Fe–FeS eutectic. The source of the sulfide was presumably an impacting meteorite. The average sulfur content of their metal particles of 2.74% by weight is similar to bulk sulfur abundances in ordinary chondrites and typical iron meteorites. Although it is impossible to quantify impact-induced chemical changes from the very rare metal particles in the lunar soil, these results indicate that sulfur loss from macroscopic metal-sulfide particles may be inefficient under conditions of the lunar surface.

8. Physical separation

Remote sensing of asteroid surfaces has to contend with the question of how surfaces relate to bulk properties (Nittler et al., 2001), or by the definition given by Clark et al. (2002) how they are affected by space weathering. However, not all processes that change the surface composition are due to "weathering" in the commonly understood sense, i.e., changes in the properties of individual regolith particles induced by energetic processes. Particle properties may be unchanged, but the relative abundance of minerals may be different on the surface from the bulk abundance. Since this is a fundamentally different process from the changes induced by impact vaporization and solar wind sputtering, it should perhaps not be included in the category of "space weathering" processes, even though it does change the remotely sensed surface composition relative to the bulk asteroid.

Huang et al. (1996) and Akridge and Sears (1999) have considered the role of aerodynamic effects due to volatiles in the accretion and evolution of asteroids. Volatiles escaping from the interior of a chondritic body can produce sorting of the regolith, particularly metal/silicate fractionation, by a process known as fluidization (Kunii and Levenspiel, 1991).

Whether the surface becomes enriched or depleted in metal depends on the size ratio of metal and silicate particles.

Fluidization is not the only process that can lead to mineral sorting. Nittler et al. (2001) and Asphaugh et al. (2001) consider size-dependent sorting, known as brazil nut effect and reverse brazil nut effect, and seismic shaking. Benoit et al. (2003) carried out experiments showing that the effect of shaking can be opposite to that of fluidization.

What these processes have in common is that they can change the apparent composition of an asteroid as determined by remote sensing without requiring energy levels that actually break chemical bonds. The net energy change of the system is merely the difference in potential energy between two different arrangements of particles, and since the gravity on asteroids is low, potential energy differences are quite small. In fact when metal segregates to the bottom of the regolith the system attains a lower energy state. Therefore physical segregation is not subject to the time scale constraints that apply to processes like solar wind irradiation, which require a sufficient time-integrated energy flux to induce the chemical changes ascribed to them. It remains to be seen, however, whether mineral separation can occur over the entire asteroid surface to the extent indicated by the low S/Si ratio on Eros.

9. The need for laboratory simulations

A range of surface modifications of planetary bodies has been studied by simulation experiments. Impact studies include experiments with hypervelocity guns, and micrometeorite impact simulations have been conducted by laser irradiation. Solar wind sputtering has been studied by irradiating samples with ion beams. Impact experiments into porous targets (e.g., Stöffler et al., 1975; Schaal and Hörz, 1977; Hörz and Schaal, 1981) show that melting occurs at progressively lower shock pressures as porosity increases. At impact velocities typical of asteroids non-porous targets are not shock-melted. Moderate melting may still occur in porous, regolith-like targets at impact velocities around 5 $\mathrm{km\,s^{-1}}$, typical of the main belt (Hörz and Schaal, 1981), and more extensive melting at the higher kinetic energy in near-Earth orbit.

Micrometeorite impacts have been simulated by laser irradiation experiments of Mukhin et al. (1989), Moroz et al. (1996), Yamada et al. (1999), and Sasaki et al. (2001, 2002). The more recent of these papers stress the importance of adjusting the conditions so that absorption depth and pulse duration matches the size and time scale of energy dissipation in micrometeorite impacts. Even so laser experiments cannot be entirely realistic in chondritic material that contains a mixture of opaque and transparent minerals. Sugita et al. (2003) have pointed out that laser irradiation produces vapor that differs considerably in temperature and entropy from impact-generated vapor. The closest analogy to laser irradiation is collision with cometary debris at very high velocity rather than impact in the typical main belt regime.

Fortunately the predominant source of space weathering on asteroids is likely to be solar wind sputtering rather than impact vaporization. Except for occasional collisions with retrograde cometary debris it is unlikely that impacts on asteroids can efficiently produce lunar-style vapor deposits on regolith grains (Hörz and Cintala, 1997). Among the numerous studies pertaining to sputtering by energetic atoms and ions, the experiments summarized by Hapke (2001) are the ones specifically designed to simulate solar wind. However, space weathering simulations must take additional processes into account. Since the balance between resurfacing and surface alteration seems very sensitive, as indicated by the difference between Ida and Eros (Clark et al., 2002), some means of artificially resurfacing the simulant also needs to be developed. The third possible class of processes, mechanical grain sorting by shaking (Benoit et al., 2003), fluidization (Akridge and Sears, 1999), or similar phenomena, should likewise be taken into account in realistic simulations.

This requires a fairly large environmental chamber that will need to be evacuated to sufficiently low pressures to carry out the sputtering experiments. The challenges posed by these experimental requirements can be illustrated by the following consideration. Irradiating a target area large enough to carry out simultaneous resurfacing is likely to require a distance of ~ 50 cm to the plasma source. As realistic limit for the vacuum system of such a large chamber we assume a pressure of 3×10^{-5} torr (4×10^{-8} times atmospheric pressure). Under these conditions about 22% of protons are deflected by collisions with residual gas molecules.

Sputtering with plasma sources also has certain limitations, because there is currently no simple way to carry out laboratory experiments on regolith simulants with the highly charged heavy ions that are part of the solar wind. Their contribution to the overall sputtering process will have to come from theoretical assumptions until suitable experimental setups are designed.

10. Conclusions

Whatever the cause of the low sulfur abundance on Eros, the low specific dissociation energy of FeS raises the possibility that space weathering has preferentially removed this mineral from the top layer of the regolith. Unlike the case for oxygen, it is likely that the portion of sulfur missing from the surface layer has migrated downward into the regolith rather than having been lost into space. At present it is impossible to say whether this component is present as sulfide or in some other chemical form.

Although both impacts and solar wind sputtering may contribute to the sulfur deficiency of the top regolith layer, we consider sputtering the dominant process. Micrometeorite impacts probably play only a minor role. Note, however, that this assessment is strictly limited to the causes of sulfur loss, and does not imply that a similar relationship obtains between impacts and sputtering as a cause for changes in optical properties of the regolith.

However, problems with this hypothesis remain. Alternative explanations, such as partial melting or a primary depletion should also be pursued. We will address the issue of primary depletion and the validity of meteorite comparisons in a separate paper. With regard to space weathering, micrometeorite impacts can be approximately simulated by laser evaporation studies, and their effects inferred from extrapolation of hypervelocity impact experiments. Solar wind sputtering by hydrogen and helium can probably be successfully simulated in the laboratory, but the effect of heavier ions has to be modeled theoretically.

Acknowledgments

The calculations of X-ray attenuation were carried out with the help of the web site at Lawrence Berkeley Laboratory maintained by Eric Gullikson. Thorough reviews by Clark Chapman and Bruce Hapke are greatly appreciated. This work was supported by funds from the National Science Foundation and the State of Arkansas.

References

Akridge, D.G., Sears, D.W.G., 1999. The gravitational and aerodynamic sorting of meteoritic chondrules and metal: experimental results with implications for chondritic meteorites. J. Geophys. Res. E 104, 11853–11864.

Anders, E., Grevesse, N., 1989. Abundances of the elements: meteoritic and solar. Geochim. Cosmochim. Acta 53, 197–214.

Arnau, A., Aumayr, F., Echenique, P.M., Grether, M., Heiland, W., Limburg, J., Morgenstern, R., Roncin, P., Schippers, S., Schuch, R., Stolterfoht, N., Varga, P., Zouros, T.J.M., Winter, H.P., 1997. Interaction of slow multicharged ions with solid surfaces. Surf. Sci. Rep. 27, 113–239.

Asphaugh, E., King, P.J., Swift, M.R., Merrifield, M.R., 2001. Brazil nuts on Eros: size-sorting of asteroid regolith. In: Proc. Lunar Planet. Sci. Conf. 32nd. Abstract #1708 [CD-ROM].

Bell, J.F., Davis, D.R., Hartmann, W.K., Gaffey, M.J., 1989. Asteroids: the big picture. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. Univ. of Arizona Press, Tucson, pp. 921–945.

Benedix, G.K., McCoy, T.J., Keil, K., Bogard, D.D., Garrison, D.H., 1998. A petrologic and isotopic study of winonaites: evidence for early partial melting, brecciation, and metamorphism. Geochim. Cosmochim. Acta 62, 2535–2553.

Benedix, G.K., McCoy, T.J., Keil, K., Love, S.G., 2000. A petrologic study of the IAB iron meteorites: constraints on the formation of the IAB-Winonaite parent body. Meteorit. Planet. Sci. 35, 1127–1141.

Benoit, P.H., Hagedorn, N.L., Kracher, A., Sears, D.W.G., White, J., 2003. Grain size and density separation on asteroids: comparison of seismic shaking and fluidization. In: Proc. Lunar Planet. Sci. Conf. 34th. Abstract #1033 [CD-ROM].

Betz, G., Wehner, G.K., 1983. Sputtering of multicomponent materials. In: Behrisch, R. (Ed.), Sputtering by Particle Bombardment II. Springer-Verlag, Berlin, pp. 11–90.

Bibring, J.P., Langevin, Y., Maurette, M., Meunier, R., Jouffrey, B., Jouret, C., 1974. Ion implantation effects in "cosmic" dust grains. Earth Planet. Sci. Lett. 22, 205–214.

Blau, P.J., Goldstein, J.I., 1975. Investigation and simulation of metallic spherules from lunar soils. Geochim. Cosmochim. Acta 39, 305–324.

Bochsler, P., 2000. Abundances and charge states of particles in the solar wind. Rev. Geophys. 38, 247–266.

Burbine, T.H., McCoy, T.J., Nittler, L.R., Bell III, J.F., 2001. Could 433 Eros have a primitive achondritic composition? In: Proc. Lunar Planet. Sci. Conf. 32nd. Abstract #1860 [CD-ROM].

Chapman, C.R., 1995. Near Earth asteroid rendezvous: Eros as the key to the S-type conundrum. In: Proc. Lunar Planet. Sci. Conf. 26th, pp. 229–230.

Chapman, C.R., 1996. S-type asteroids, ordinary chondrites, and space weathering: the evidence from *Galileo's* fly-bys of Gaspra and Ida. Meteorit. Planet. Sci. 31, 699–725.

Chapman, C.R., Salisbury, J.W., 1973. Comparison of meteorite and asteroidal spectral reflectivities. Icarus 19, 507–522.

Clark, B.E., Fanale, F., Salisbury, J., 1992. Meteorite–asteroid spectral comparison: the effects of comminution, melting and recrystallization. Icarus 97, 288–297.

Clark, B.E., Lucey, P., Helfenstein, P., Bell III, J.F., Peterson, C., Veverka, J., McConnochie, T., Robinson, M.S., Bussey, B., Murchie, S.L., Izenberg, N.I., Chapman, C.R., 2001. Space weathering on Eros: constraints from albedo and spectral measurements of Psyche crater. Meteorit. Planet. Sci. 36, 1617–1637.

Clark, B.E., Hapke, B., Pieters, C., Britt, D., 2002. Asteroid space weathering and regolith evolution. In: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. Univ. of Arizona Press, Tucson, pp. 585–599.

Dreibus, G., Palme, H., Spettel, B., Zipfel, J., Wänke, H., 1995. Sulfur and selenium in chondritic meteorites. Meteoritics 30, 439–445.

Dukes, C.A., Baragiola, R.A., McFadden, L.A., 1999. Surface modification of olivine by H^+ and He^+ bombardment. J. Geophys. Res. E 104, 1865–1872.

Evans, L.G., Starr, R.D., Brückner, J., Reedy, R.C., Boynton, W.V., Trombka, J.I., Goldsten, J.O., Masarik, J., Nittler, L.R., McCoy, T.J., 2001. Elemental composition from gamma-ray spectroscopy of the NEAR-Shoemaker landing site on 433 Eros. Meteorit. Planet. Sci. 36, 1639–1660.

Gaffey, M.J., 1976. Spectral reflectance characteristics of the meteorite classes. J. Geophys. Res. 81, 905–920.

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

Gaffey, M.J., Burbine, T.H., Binzel, R.P., 1993b. Asteroid spectroscopy: progress and perspectives. Meteoritics 28, 161–187.

Hapke, B., 2001. Space weathering from Mercury to the asteroid belt. J. Geophys. Res. E 106, 10039–10073.

Hapke, B., Cassidy, W., Wells, E., 1975. Effects of vapor-phase deposition processes on the optical, chemical, and magnetic properties of the lunar regolith. The Moon 13, 339–353.

Henke, B.L., Gullikson, E.M., Davis, J.C., 1993. X-ray interactions: photoabsorption, scattering, transmission, and reflection at $E = 50$–30000 eV, $Z = 1$–92. At. Data Nucl. Data Tables 54, 181–342.

Hörz, F., Cintala, M., 1997. Impact experiments related to the evolution of planetary regoliths. Meteorit. Planet. Sci. 32, 179–209.

Hörz, F., Schaal, R.B., 1981. Asteroidal agglutinate formation and implications for asteroidal surfaces. Icarus 46, 337–353.

Huang, S., Akridge, D.G., Sears, D.W.G., 1996. Metal-silicate fractionation in the surface dust layers of accreting planetesimals: implications for the formation of ordinary chondrites and the nature of asteroid surfaces. J. Geophys. Res. E 101, 29373–29385.

Keil, K., Wilson, L., 1993. Explosive volcanism and the composition of cores of differentiated asteroids. Earth Planet. Sci. Lett. 117, 111–124.

Keller, L.P., McKay, D.S., 1993. Discovery of vapor deposits in the lunar regolith. Science 261, 1305–1307.

Keller, L.P., McKay, D.S., 1997. The nature and origin of rims on lunar soil grains. Geochim. Cosmochim. Acta 61, 2331–2341.

Killen, R.M., 2003. Depletion of sulfur on the surface of the asteroids and the Moon. Meteorit. Planet. Sci. 38, 383–388.

Kracher, A., 1985. The evolution of partially differentiated planetesimals: evidence from iron meteorite groups IAB and IIICD. In: Proc. Lunar Planet. Sci. Conf. 15th, J. Geophys. Res. 90, C689–C698.

Kracher, A., Sears, D.W.G., Benoit, P.H., Meier, A.J., 2003. Eros sulfur deficiency: a closer look at meteorite comparisons. In: Proc. Lunar Planet. Sci. Conf. 34th. Abstract #1023 [CD-ROM].

Kunii, D., Levenspiel, O., 1991. Fluidization Engineering, second ed. Butterworth-Heinemann, Woburn, MA.

Lide, D.R. (Ed.), 1996. CRC Handbook of Chemistry and Physics, seventy seventh ed. CRC Press, Boca Raton, FL.

Matson, D.L., Johnson, T.V., Veeder, G.J., 1977. Soil maturity and planetary regoliths: the Moon, Mercury, and the asteroids. In: Proc. Lunar Planet. Sci. Conf. 8th, pp. 1001–1011.

Maurette, M., Price, P., 1975. Electron microscopy of irradiation effects in space. Science 187, 121–129.

McCord, T.B., Chapman, C.R., 1975. Asteroids: spectral reflectance and color characteristics. Astrophys. J. 195, 553–562.

McCoy, T.J., Keil, K., Clayton, R.N., Mayeda, T.K., Bogard, D.D., Garrison, D.H., Huss, G.R., Hutcheon, I.D., Wieler, R., 1996. A petrologic, chemical, and isotopic study of Monument Draw and comparison with other acapulcoites: evidence for formation by incipient melting. Geochim. Cosmochim. Acta 60, 2681–2708.

McCoy, T.J., Keil, K., Muenow, D.W., Wilson, L., 1997. Partial melting and melt migration in the acapulcoite–lodranite parent body. Geochim. Cosmochim. Acta 61, 639–650.

McCoy, T.J., Burbine, T.H., McFadden, L.A., Starr, R.D., Gaffey, M.J., Nittler, L.R., Evans, L.G., Izenberg, N., Lucey, P.G., Trombka, J.I., Bell III, J.F., Clark, B.E., Clark, P.E., Squyres, S.W., Chapman, C.R., Boynton, W.V., Veverka, J., 2001. The composition of 433 Eros: a mineralogical-chemical synthesis. Meteorit. Planet. Sci. 36, 1661–1672.

McKay, D.S., Swindle, T.D., Greenberg, R., 1989. Asteroidal regoliths: what we do not know. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. Univ. of Arizona Press, Tucson, pp. 617–642.

Meibom, A., Clark, B.E., 1999. Evidence for the insignificance of ordinary chondritic material in the asteroid belt. Meteorit. Planet. Sci. 34, 7–24.

Miller, J.K., Konopliv, A.S., Antresian, P.G., Bordi, J.J., Chesley, S., Helfrich, C.E., Owen, W.M., Wang, T.C., Williams, B.G., Yeomans, D.K., Scheeres, D.J., 2002. Determination of shape, gravity, and rotational state of Asteroid 433 Eros. Icarus 155, 3–17.

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 targets. Icarus 122, 366–382.

Mukhin, L.M., Gerasimov, M.V., Safonova, E.N., 1989. Origin of precursors of organic molecules during evaporation of meteorites and mafic terrestrial rocks. Nature 340, 46–48.

Murchie, S.L., Pieters, C.M., 1996. Spectral properties and rotational heterogeneity of 433 Eros. J. Geophys. Res. 101, 2201–2214.

Murchie, S.L., Robinson, M.S., Clark, B.E., Li, H., Thomas, P.C., Joseph, J., Bussey, B., Domingue, D., Veverka, J., Izenberg, N., Chapman, C.R., 2002. Color variations on Eros from NEAR multispectral imaging. Icarus 155, 145–168.

Nittler, L.R., Starr, R.D., Lim, L., McCoy, T.J., Burbine, T.H., Reedy, R.C., Trombka, J.I., Gorenstein, P., Squyres, S.W., Boynton, W.V., McClanahan, T.P., Bhangoo, J.S., Clark, P.E., Murphy, M.E., Killen, R., 2001. X-ray fluorescence measurements of the surface elemental composition of Asteroid 433 Eros. Meteorit. Planet. Sci. 36, 1673–1695.

Noble, S.K., Pieters, C.M., Taylor, L.A., Morris, R.V., Allen, C.C., McKay, D.S., Keller, L.P., 2001. The optical properties of the finest fraction of lunar soil: implications for space weathering. Meteorit. Planet. Sci. 36, 31–42.

Pieters, C.M., Taylor, L.A., Noble, S.N., Keller, L.P., Hapke, B., Morris, R.V., Allen, C.C., McKay, D.S., Wentworth, S., 2000. Space weathering on airless bodies: resolving a mystery with lunar samples. Meteorit. Planet. Sci. 35, 1101–1107.

Robie, R.A., Hemingway, B.S., Fisher, J.R., 1978. Thermodynamic properties of minerals and related substances at 298.15 K and 1 Bar (10^5 Pascals) pressure and at higher temperatures. Geological Survey Bulletin 1452. U.S. Government Printing Office, Washington, DC.

Robinson, M.S., Thomas, P.C., Veverka, J., Murchie, S.L., Wilcox, B.B., 2002. The geology of 433 Eros. Meteorit. Planet. Sci. 37, 1651–1684.

Roth, J., 1983. Chemical sputtering. In: Behrisch, R. (Ed.), Sputtering by Particle Bombardment II. Springer-Verlag, Berlin, pp. 91–146.

Russell, C.T., 2001. Solar wind and interplanetary magnetic field: a tutorial. In: Song, P., Singer, H.J., Siscoe, G.L. (Eds.), Space Weather. In: Geophysical Monograph, vol. 125. AGU, Washington, DC, pp. 73–89.

Sasaki, S., Nakamura, K., Hamabe, Y., Kurahashi, E., Hiroi, T., 2001. Production of iron nanoparticles by laser irradiation in a simulation of lunar-like space weathering. Nature 410, 555–557.

Sasaki, S., Hiroi, T., Nakamura, K., Hamabe, Y., Kurahashi, E., Yamada, M., 2002. Simulation of space weathering by nanosecond pulse laser heating: dependence on mineral composition, weathering trend of asteroids and discovery of nanophase iron particles. Adv. Space Res. 29, 783–788.

Schaal, R.B., Hörz, F., 1977. Shock metamorphism of lunar and terrestrial basalts. In: Proc. Lunar Planet. Sci. Conf. 8th, pp. 1697–1729.

Sears, D.W.G., 1998. The case for rarity of chondrules and CAI in the early Solar System and some implications for astrophysical models. Astrophys. J. 498, 773–778.

von Steiger, R., Schwadron, N.A., Fisk, L.A., Geiss, J., Gloeckler, G., Hefti, S., Wilken, B., Wimmer-Schweingruber, R.F., Zurbuchen, T.H., 2000. Composition of quasi-stationary solar wind flows from Ulysses/Solar Wind Ion Composition Spectrometer. J. Geophys. Res. A 105, 27217–27238.

Stöffler, D., Gault, D.E., Wedekind, J., Polkowski, G., 1975. Experimental hypervelocity impact into quartz sand: distribution and shock metamorphic ejecta. J. Geophys. Res. 80, 4062–4077.

Sugita, S., Kadono, T., Ohno, S., Hamano, K., Matsui, T., 2003. Does laser ablation vapor simulate impact vapor? In: Proc. Lunar Planet. Sci. Conf. 34th. Abstract #1573 [CD-ROM].

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

Thomas, P.C., Joseph, J., Carcich, B., Veverka, J., Clark, B.E., Bell III, J.F., Byrd, A.W., Chomko, R., Robinson, M.S., Murchie, S., Prockter, L., Cheng, A., Izenberg, N., Malin, M., Chapman, C.R., McFadden, L.A., Kirk, R., Gaffey, M.J., Lucey, P.G., 2002. Eros: shape, topography, and slope processes. Icarus 155, 18–37.

Tröger, W.E., 1979. Optical Determinations of Rock-Forming Minerals. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Veverka, J., Thomas, P.C., Robinson, M., Murchie, S., Chapman, C.R., Bell, M., Harch, A., Merline, W.J., Bell III, J.F., Bussey, B., Carcich, B., Chang, A., Clark, B.E., Domingue, D., Dunham, D., Farquhar, R., Gaffey, M.J., Hawkins, E., Izenberg, N., Joseph, J., Kirk, R., Li, H., Lucey, P., Malin, M., McFadden, L.A., Miller, J.K., Owen Jr., W.M., Peterson, C., Prockter, L., Warren, J., 2001. Imaging of small scale features on 433 Eros from NEAR: evidence for a deep regolith. Science 292, 484–488.

Wasson, J.T., Kallemeyn, G.W., 1988. Composition of chondrites. Philos. Trans. R. Soc. London A 325, 535–544.

Wilson, L., Keil, K., 1991. Consequences of explosive eruptions on small Solar System bodies: the case of the missing basalt on the aubrite parent body. Earth Planet. Sci. Lett. 104, 505–512.

Yamada, M., Sasaki, S., Nagahara, H., Fujiwara, A., Hasegawa, S., Yano, H., Hiroi, T., Ohashi, H., Otake, H., 1999. Simulation of space weathering of planet-forming materials: nanosecond pulse laser irradiation and proton implantation on olivine and pyroxene samples. Earth Planets Space 51, 1255–1265.