

SPACE WEATHERING: A PROPOSED LABORATORY APPROACH TO EXPLAINING THE SULFUR DEPLETION ON EROS. M. A. Franzen^{1,2}, A. Kracher^{1,2,3}, D. W. G. Sears^{1,2}, W. Cassidy⁴, and B. Hapke⁴. ¹W. M. Keck Laboratory for Space Simulation, Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, Arkansas, 72701, ²Department of Chemistry and Biochemistry, Fayetteville, Arkansas 72701, ³Ames Laboratory, 227 Wilhelm Hall, Iowa State University, Ames, IA 50011-3020, ⁴Department of Geology and Planetary Science, 200 Space Research Coordination Center, University of Pittsburgh, Pittsburgh, PA 15260. mfrazen@uark.edu.

Introduction: Space weathering is the cumulative effect of physical and chemical changes that occur to substances exposed on the exterior of body void of an atmosphere [1], in this case the regolith on asteroid Eros. It is only recently that the scientific community has accepted the theory first developed in the mid-1970s by Hapke and his colleagues of how space weathering occurs. The theory [1] asserts that optical and magnetic effects, first studied on moon rocks and lunar regolith, are caused by submicroscopic metallic iron (SMFe), smaller than the wavelength of light in vapor deposit coatings, on regolith grains, and in agglutinates. This vapor is generated by solar wind and micrometeorite impacts and does not require additional heating, melting, or a reducing environment to produce space weathering. One of the major finds of the first detailed reconnaissance of an asteroid by the NEAR Shoemaker mission was that the surface of Eros was essentially chondritic yet showed major depletions in sulfur [2, 3]. Here we propose space weathering sputtering experiments that may contribute to the explanation of sulfur depletion on asteroid Eros.

Depletion of Sulfur on Eros. The measurement of S/Si ratio by NEAR Shoemaker was only possible during solar flares. From these data, an upper limit for the S/Si ratio of 0.05 by weight was derived by Nittler et al. [2], while McCoy et al. [3] estimated an S/Si ratio of 0.014 ± 0.017 . In contrast, the S/Si ratio of CI chondrites is 0.528 [4]. It is typical that deviations from the CI chondrite values in major element to Si ratios are very modest (eg., unweathered chondrites have S/Si ratios at most 4x lower than CI) [5]. However, S/Si ratios for Eros of Nittler et al. [2] and McCoy et al. [3] are 11x and 38x lower than the CI ratio, respectively. This clearly shows a loss of sulfur from at least the surface regolith of Eros [5].

Troilite. The most common sulfur-bearing mineral in almost all anhydrous meteorites is troilite (FeS), and this is true of all meteorite classes that potentially have an S(IV)-type asteroid like Eros as a parent body [5,6]. Thus, Eros likely contains most of its sulfur in the form of FeS. The melting point of FeS is 1468 K [5]. It forms a eutectic with metallic nickel-iron. The eutectic system has a melting point of 1261 K in a pure Fe-FeS system and the temperature decreases with the addition

of Ni [5]. Out of all the major components of a chondritic mineralogy, the sulfide eutectic has the lowest melting point; therefore, partial melting must be considered for depleting sulfur on Eros [5]. However, partially differentiated bodies may be indistinguishable from chondritic objects by their reflection spectra because the taxonomy of S asteroids is drawn from minerals with high melting temperatures [5].

Potential Mechanisms for Sulfur Loss: No matter what process is found to be the explanation for the sulfur loss on Eros, the removal of the sulfur will undoubtedly require energy to drive the mechanism [5]. Currently, there are two processes that will deliver sufficient energy to the surface of an asteroid for the decomposition of anhydrous minerals, which are solar wind and high-velocity impacts. Three potential mechanisms will be discussed.

Physical Separation. Physical separation can be accomplished through outgassing of volatiles within the interior of the asteroid. In this scenario, the bulk mineral abundance may be different from the surface abundance due to volatiles sorting the regolith through fluidization, (ie., metal/silicate fractionation) [7,8]. These volatiles are thought to be generated through impact, therefore, this process can be linked to the impact section below. Other physical sorting processes include size-dependent sorting and seismic shaking [2]. One difficulty with physical separation, is whether or not it can cause mineral separation over the entire asteroid surface to the degree denoted by the low S/Si ratio on Eros [5].

Impacts. Hypervelocity impacts have been studied extensively on the moon; however, there is a problem comparing impacts on the moon with those that occur on Eros [1]. Impact velocities are much lower on Eros. Thus, the nature of the impact event is different [5]. Typical energies in the main belt are marginally sufficient to produce melting [9]. However, Killen [10] calculated the impact volatilization of sulfide for Eros and concluded that impacts were able to remove sulfur more efficiently than other elements. Calculated erosion rates are similar to removing sulfide from the top 10-100 μ m of regolith in 10⁶ years which is comparable to the erosion rate for sputtering but assuming that sulfide is eroded 9x faster than typical

regolith. [5, 10]. This would likely be an upward bound considering energetic considerations discussed in the next section. Another aspect of impacts to consider is the “gardening” of the regolith. Impacts often cause top layers to overturn bringing fresh regolith to the surface. This process is observed in analyses of asteroids. It is also questionable as to how much surface alteration happened in Eros’ current location. Some scientists think that different rates of surface maturation and impact cratering happen depending on whether the asteroid is in the Main Belt or a near-Earth orbit [11].

Sputtering. Solar wind is essentially a stream of protons (96%) and He⁺² ions (3.8%) [12]. The average kinetic energy of a proton is 0.8 keV while the flux at Eros is $\sim 1 \times 10^8$ ions/s/cm² (i.e., particle density ~ 5 cm⁻³). Alpha particles are considerably more effective for space weathering, having an energy of 3.2 keV although the flux is only $\sim 4 \times 10^6$ ions/s/cm² [5]. Kracher and Sears [5] estimated the energetic surface processes by adding up the enthalpy of formation from the standard states of the constituent elements plus the dissociation enthalpy, assuming that the main product of the process is the formation of a monatomic vapor in Table 1 below.

Mineral	Volume Normalized Dissociation Enthalpy (kJ/cm ³)
Mg ₂ SiO ₄	89.32
Fe ₂ SiO ₄	81.38
MgSiO ₃	91.91
MgCaSi ₂ O ₆	89.74
NaAlSi ₃ O ₈	77.09
CaAl ₂ Si ₂ O ₈	79.12
Fe	58.58
FeS	42.79

The energy required to vaporize FeS is half as much compared to that required to vaporize the silicate minerals and significantly lower than that required to vaporize Fe metal. Therefore, the surface of Eros would lose FeS much faster than other minerals on the surface and subsequently result in sulfur depletion. Assuming an erosion rate of lunar materials is 0.5×10^{-4} μ m per year [13], and erosion rate on Eros would be approximately half of the lunar case, sulfur would be lost from the top 25 μ m of regolith in 10^6 years [5]. The erosion rate for sputtering and impact are approximately the same [5].

Proposed Experiments: One of the problems that potentially stands in the way of explaining sulfur loss on Eros is that most of the ideas about space weathering

come from experiments done on lunar-like materials. However, lunar materials are not very chondritic in nature. A better representative of Eros are chondritic meteorites.

The experiments proposed here use chondrite meteorites to represent the surface of Eros. The experiments will follow work performed by Hapke as closely as our instrument allows [14]. The instrument used in these experiments to simulate solar wind sputtering will be a Hummer II sputtering unit made by Technics which includes a self contained vacuum pump. Chondritic meteorite analogues will be ground to finer than 37 μ m with a mortar and pestle and placed on a glass slide which is placed on the substrate holder (anode) at the bottom of the bell jar. One side of the sample will be covered and not irradiated. This will serve as a control, allowing for the determination of sulfur content in a non-irradiated specimen. The cathode is located at the top of the bell jar. The sputtering ions will be produced from argon ions produced at the cathode and accelerated toward the anode due to a potential of ~ 1.2 kV applied across the system. The Ar ions will hit the target samples and cause sputtering. The pressure of the system will be ~ 50 mtorr during each experiment. The sample will be irradiated until it has received a dose of 30 C cm⁻². Hydrogen and helium can be used separately or as a mixture as an alternative to argon and current neutralization will prevent charge build-up on the samples. The irradiated samples will be analyzed for sulfur loss using a defocused electron microprobe.

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