

**UNDERSTANDING THE NATURE OF METAL SEGREGATION IN ASTEROID REGOLITH** P.E. Clark<sup>1</sup> and R. Killen<sup>2</sup>, <sup>1</sup>EER Systems, Inc., 3750 Centerview Drive, Chantilly, VA 20151 (Pamela.Clark@gssc.nasa.gov), <sup>2</sup>Astronomy Department, University of Maryland, College Park, MD 20700 (rkillen@astro.umd.edu)

**Metal/Silicate Fractionation:** The process of regolith formation on an asteroid normally results in the sorting of the asteroid's regolith, a process that would involve segregation of the denser, less brittle metallic from silicate particles. It has been proposed that, as a result of mobilization of volatiles, the position of this particle layer in the regolith would depend on initial size and abundance of metal particles, as well as availability of volatiles for fluidization [1]. According to this model, less abundant, smaller diameter metal particles, present in L and LL Chondrites, would tend to rise to the surface, whereas more abundant, larger diameter particles, present in H Chondrites, would tend to sink. We discuss here how segregating a metallic component in this way would modify the apparent element and mineral abundance ratios relative to the parent material. We also discuss the impact such a process would have on X-ray and other remote spectral measurements, as well as on the availability of Fe or volatiles such as S for 'space weathering' processes.

**Impact on XRS measurements:** Heavier elements, the most prevalent of which is iron, have a higher absorption cross-section for solar X-rays. The presence of metallic iron particles will induce 'matrix effects' on X-ray fluorescent lines. Matrix effects, which create non-linearity in the relationship between fluorescent line intensity and elemental abundance, are caused by macroscopic and microscopic physical heterogeneities in the medium being measured which result in variation in the degree to which the medium absorbs X-rays. In a light, fine-grained matrix with metallic particles, less effective absorption by the lighter matrix causes relatively lower intensity for light element lines, and relatively greater intensity for Fe lines than linear relationships with abundance would predict, an effect which becomes more pronounced as the metallic particle size decreases [2,3]. For chondritic compositions, Si, Al and Ca are anti-correlated with Fe, and their anti-correlation, particularly in the case of the low abundance components Al and Ca, would tend to be exaggerated downward in areas of greater metallic Fe abundance. The downward effect on Mg, which is generally correlated with metallic Fe, would be less pronounced. Because "a fluorescent element has a sensitivity which varies with the nature of the matrix it is in" [4], the relationship between intensity and abundance depends critically on particle size, composition, and distribution for each element.

In an asteroid regolith, the depth of penetration for X-rays is on the order of tens of microns, approximating anticipated grain sizes in the regolith, thus matrix effects would be observable only if the iron layer forms on the surface. Such a surface iron layer would systematically lower the intensity for lighter element lines as a function of anticipated abundance, while maintaining the intensity for iron. In that case, the asteroid would look like a more iron rich chondrite from the standpoint of iron. The apparent Fe/Si ratio would be higher than the actual ratio in the parent material. On the other hand, the lack of metallic component at the surface would not affect X-ray absorption by the lighter elements, but the apparent lower abundance of iron would indicate an iron poor chondrite. The apparent Fe/Si ratio would be lower than the actual ratio in the parent material. In the case of NEAR XRS measurements for Eros [5], the Fe/Si ratios appear to be somewhat higher than for the L/LL Chondrite composition indicated by other measurements, which is consistent with a metallic component on the surface indicative of L/LL chondrite compositions [1].

We are currently attempting to model and hoping to further investigate in the laboratory the relationship between the abundance and distribution of a metallic component, lighter element fluorescent intensity ratios, and fluorescent/scattered X-ray intensities. Laboratory studies have already shown that scattered radiation behaves somewhat differently from fluorescent radiation [3,6,7], and that scatter alone or the scatter/intensity ratio is a good measure of the absorbing properties of the matrix, particularly in regard to iron content.

**Impact on other measurements:** The universally recognized features in near infrared spectra result from energy transitions associated with iron in the iron-bearing minerals, pyroxene and olivine, and, to a lesser extent, ilmenite. Iron in the form of metallic iron cannot be directly measured, although overall 'reddening' (changing the shape of the continuum as a function of wavelength) is considered likely, but not quantifiable. Band intensities and ratios in the NEAR NIS data indicate pyroxene/olivine and cation ratios most consistent with L/LL chondrite [8].

Matrix effects also play a role in Gamma-ray measurements, due to differential cross-sections for the neutrons induced by cosmic rays. Iron is relatively abundant and has a high cross-section, thus great variations in metallic iron content could affect the line

intensity versus abundance relationships for other elements and the effect would resemble the matrix effect for XRS measurements. In the case of the NEAR GRS measurements [7], which were made in situ, relatively low Fe abundance was found, but other elemental abundance ratios were indicative of chondritic composition, which could point to the absence of a metallic component. This observation is not consistent with the other observations, which support the prediction of a near-surface metallic component for L/LL chondrites [1]. Significantly, the depth of penetration for Gamma-rays is much greater, on the order of tens of centimeters, and thus an iron layer should be observable in this relatively thin regolith. Where is the iron? Perhaps local horizontal as well as vertical segregation mechanisms are segregating metallic iron particles.

**Impact on other loss processes:** Sulfur is apparently depleted by an order of magnitude relative to ordinary chondrite S abundances (~1.5-3 wt.% [9]). The detection limit for S should be approaching a couple of tenths of a percent for chondritic compositions during a solar flare [10]. Thus, S is at or below the detection limit. What processes would deplete S by an order of magnitude or more? Trombka and coworkers [5] suggested that S could be depleted by either partial melting, since the first partial melt of an ordinary chondrite is rich in S, or impact volatilization of troilite (FeS) and loss of S in the regolith. In this abstract, we explore the possibility that impact volatilization in the regolith produced the S depletion and examine the efficiency of this process. Because we are looking at extremely surficial regolith, a process involving volatilization may be reasonable to explain the observed depletion. How efficient is, for example, impact volatilization, and how is it affected by segregation of the metallic component with which troilite would be associated? Three processes are likely to be efficient at play a role in removing sulfur from the surface of Eros (1): impact vaporization by micrometeorites, (2) solar wind ion sputtering and (3) photo-stimulated desorption.

Although the boiling point of sulfur is only 717.8 K, compared with 1156.0 for Na based on the results of Wiens and coworkers [11], we have used a photo-sputter yield of S that is an order of magnitude less than that for Na. We use a photo-sputter yield of  $1 \times 10^{-22}$  per UV photon. In considering impact vaporization by micrometeorites, the impact velocity of micrometeorites is much less at Eros than at the surface of the Earth due to the larger orbital distance for Eros at the time of encounter and the lesser gravitational acceleration at Eros. Thus impact vaporization will be about 20% as efficient as photon-stimulated desorption. Using the values for impact of Al onto enstatite, we find

that the vaporization rate for troilite, the main repository of sulfur, is 9 times faster than that for the bulk of the regolith. Sulfur can be depleted from a surface by sputtering from solar wind plasma. Ion sputter is effective at selective depletion of volatiles, especially on bodies that are constantly exposed to the solar wind. If the yield of sulfur is similar to that of sodium, then we can expect a yield of about 0.08 per incident proton in the energy range of 500 eV to up to 2 keV [12]. If the solar wind density is  $100 \text{ cm}^{-3}$ , the velocity is  $400 \text{ km s}^{-1}$  and the sulfur fraction in the regolith is 1%, the yield of sulfur will be approximately  $3 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ . This yield is comparable to the yield from impact vaporization at a density of  $1800 \text{ Kg m}^{-3}$  and porosity 0.3. We assume that only the heavy ions in the solar wind are capable of sputtering sulfur; therefore we use an ion sputter yield of 0.01 per solar wind ion. The impact vaporization rate is calculated using a volatilized volume as a function of impact velocity based on the planar impact approximation [13,14]. We assume that all of the sputtered or vaporized atoms are lost. Based on these calculations, which assume a uniform distribution of troilite to that depth, we conclude that sulfur will be depleted in the upper 3 mm of Eros' regolith in  $10^7$  years. As long as the metallic component is near the surface, as it is predicted to be in an L/LL Chondrite [1], this model accurately predicts S loss. If the metallic component is buried, then S would require orders of magnitude longer time frames to undergo depletion.

**References:** References: [1] Huang et al, 1996, JGR, 101, 29373; [2] Gunn, 1961, Advances in X-ray Analysis, 4, 382-400; [3] Mitchell and Kellam, 1968 Applied Spectroscopy, 22, 363; [4] Claisse and Samson, 1962, Advances in X-ray Analysis, 5, 335-354; [5] J. Trombka et al, Science, 289, 2101-2105, 2000; [6] Garcia-Gonzalez, 1992, The Analyst, 117, 1169-1172; [7] Lubecki et al, 1967, Spectrochim Acta A 23, 831-837; [8] J. Veverka et al, Science, 289, 2088-2093; [9] Jarosewich, 1990, Meteoritics, 25 (4): 323-337; [10] Clark et al, 2001, LPS 34<sup>th</sup> Abstracts, CD-ROM; [11] R. Wiens et al., 1997, Icarus, 128, 386-397; [12] (Lammer *et al.*, 2002); [13] H. J. Melosh, 1989, Impact Cratering: A Geologic Process; [14] R. Killen, Meteoritics and Planet. Sci., In press.