EXPLAINING THE SULFUR DEPLETION ON EROS AND THE DIFFERENT SPACE WEATHERING OF S-TYPE AND V-TYPE ASTEROIDS. J. J. Gillis-Davis[1] and E. R. D. Scott[1]. [1]University of Hawaii – Manoa, Hawaii Institute of Geophysics & Planetology, 1680 East-West Road, Honolulu, HI 96822, USA (gillis@higp.hawaii.edu)

Introduction: This abstract proposes a hypothesis to explain two questions about space weathering of asteroids; 1) What caused sulfur depletion on the surface of Eros? 2) Why do S-type asteroids appear much more weathered than the surface of Vesta?

Spectra of Eros, like those of other S-type asteroids, are dissimilar to ordinary chondrites (OC) in terms of spectral slope, albedo, and contrast of their absorption bands. S-type asteroids are redder, darker and exhibit lower spectral contrast compared with spectra of OC. The differences in spectral properties between S-type asteroids and OC are attributed to the alteration of the optical surface by exposure to processes collectively called "space weathering" (e.g., 1-3). The main components of space weathering are radiation (e.g., solar wind and photon) and meteoroid/micrometeorite bombardment. The archetype example is the Moon, where exposure to space causes the regolith to darken, redden, and lose spectral contrast. These optical effects are attributed to a combination of the generation of nanophase iron metal <50μm (reddening), solar wind irradiation (darkening), increase of agglutinate glass (darkening), and reduction of grain size distribution (brightening).

Space weathering alters not only the observable spectral properties of surfaces of atmosphere-free bodies but also the chemistry. Chemical analyses of planetary surfaces using X-ray (XRS) and neutron spectrometers are affected by the removal of volatiles. For instance, XRS data for a portion of Eros' northern hemisphere exhibit ratios among Al, Mg, Si, and Fe that are similar to those found in L and LL chondrite meteorites [4,5]. However, the X-ray data also reveal substantial depletion of elemental sulfur (~2x) [4,5], compared with typical values for L and LL [6]. This depletion does not reflect loss of FeS by partial meting as the surface has chondritic Cr/Fe, Mn/Fe and Ni/Fe ratios [5]. Eros's composition is also inconsistent with a subset of primitive achondrite meteorites (e.g., aubrites) as spectral properties of some primitive achondrite powders show that they have band area and band ratio values inconsistent with those derived from the NEAR spacecraft [7]. Hence the important question is, if Eros is similar to an L or LL OC, how was S depleted in its surface.

Since Eros is well matched chemically and spectrally by L and LL chondrites, the S depletion is probably due to space weathering [4, 5]. We propose that this depletion is closely linked to the spectral differences with ordinary chondrites. To help elucidate why Eros is depleted in S and how mobilization of FeS may be responsible for the optical weathering effects on S-type asteroids, we present experimental data and observations of OC in thin sections where troilite (FeS) has been mobilized by impact shock and heating. Previous workers [8,9] have argued that mobilization of FeS is an important spectral weathering process on OC asteroids and our studies support and extend their conclusion. We extend the current state of knowledge by comparing spectra and compositions of S-type and V-type asteroids to support the importance of FeS in space weathering.

Data: A 17.2 g sample of Holbrook (L6) OC and 9.8 g sample of a troilite inclusion were used in simulated micrometeorite impact experiments. Impact heating by high-velocity dust particles was replicated using Continuum Surelite I-20, Nd:YAG (1064 nm), pulsed (20-Hz) laser. The pulse duration is 5-7 ns, which is comparable to the timescale of micrometeorite impacts. Each sample was irradiated with 30mJ laser pulses. Irradiations were done in 1-minute increments using a rastered beam, for a total of 10 minutes. A vacuum of $1–2\times10^{-6}$ torr was achieved using Pfeiffer Hi-cube turbo and roughing pump combination. The presence and partial pressure of H_2S and SO_2 along with H, H_2O, NO, N, CO and CO_2 were measured inline with a Stanford Research Systems 100 amu residual gas analyzer (RGA), which is a mass spectrometer consisting of a quadrupole probe. The RGA measured the partial pressure of the gases with time throughout the duration of the experiment.

Two OCs were studied in thin sections: McKinney (L4) and a Forest City (H5) sample with an atmospherically heated surface. They are listed as S4-S6 and S2 respectively [10].

Discussion: *Experimental data* – RGA partial pressure measurements of volatiles during laser irradiation experiments of Holbrook indicated that volatile elements are mobilized by pulse heating (Fig. 1). The partial pressure of gases such as H, H_2O, and CO_2 increased the most, by about 2 orders of magnitude, while gases such as H_2S and N increased the least, by an order of magnitude or less. When irradiation was stopped the abundance of all gases immediately decreased by 95%. Ten minutes was allowed to elapse for gases to approach their pre-irradiation background levels. Measurements made while the laser was off are labeled background in Fig 1.

The successive decrease in the abundance of volatile gases was observed to occur with each successive irradiation. After six (H_2S) to nine (H_2O) irradiations the partial pressure of the two gases did not increase

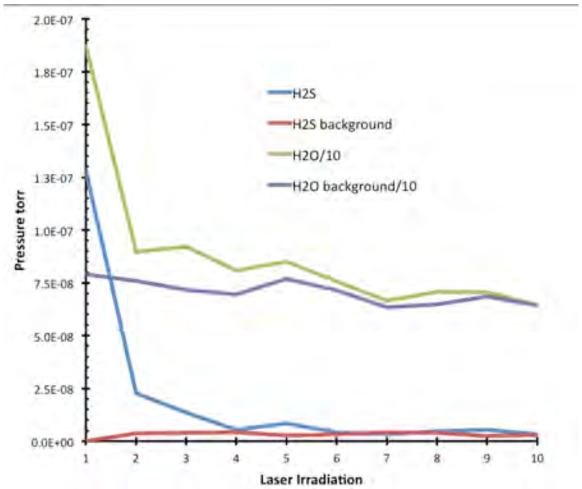

Fig 1. Pressure of H_2O (divided by 10) and H_2S that were released when the Holbrook L4 chondrite was irradiated ten individual times for one minute versus the background for that gas between laser irradiation.

significantly above background during lasing. These data suggest that the surfaces of the materials have become progressively depleted in these two volatile species. We infer that laser heating vaporizes adsorbed water But vaporizes and disassociates FeS. Most of S combines with hydrogen (H_2S) or oxygen (SO_2), while Fe-metal condenses on the sample as large (>50µm) nanophase iron. The result is that the surfaces of both samples become dark and flat.

Ordinary chondrite studies – In transmitted light, a thin section of McKinney is nearly opaque. Areas where light is transmitted exhibit undulatory extinction and mosaicism. Planar fracturing of chondrules and olivine, along with pockets of impact melt were most obvious in reflected light (Fig. 2). Examination of the samples in reflected light reveals FeS and Fe-Ni metal filling fractures and veins. FeS is more readily mobilized by shock and heating than any other common mineral. Metal-troilite and silicate-FeS interfaces are where shock melting begins in OCs. Shock stages S1-S3 in OC may contain shock-melted troilite even though the silicates are barely deformed and heated as seen in samples of Forest City. Spherical melt droplets were observed at every resolution between 50× and 500×. Beneath the fusion crust of Forest City there is an opaque zone where troilite has melted and migrated up micrometer-wide silicate fractures as in McKinney.

Note that in very reduced systems, 1-3 wt.% S can dissolve in the silicate melt [11]. Since S is relatively insoluble in silicate, crystallization of S-bearing silicate melts can cause microprecipitates (>50 µm) of FeS to form in interstitial silicate melt. Such particles darken their host material but do not redden its spectrum.

Comparison of S- and V- Types: Albedo and near-IR slope are often used as proxies for degree of space weathering [1-3]. On this basis, space-weathering effects of S-type asteroids seem greater compared to those observed for Vesta, which is well matched spectrally by howardites [12, 13]. In both cases, there is ample FeO in silicates available for formation of nanophase metal. Hence, one might infer from spectral data alone that Vesta/Vestoids have spectrally immature surfaces. However, as noted by [8] the abundance of Fe-Ni-S phases in OCs and HEDs is considerably different and this may account for the different space weathering of V and S types. Troilite abundances are >10x higher in OC than in HEDs (2 wt.% S vs. 0.1-0.2 wt.% S in HEDs [6]). This effect of spectral darkening as a function of S composition is greatest for Mercury [14]. XRS measurements of S are as high as 4 wt.% while Fe 2.5 wt.% [15] but the average reflectance of its crust is only 5.5% at 550 nm [14].

Conclusions: Our experiments and observations suggest that spectra of surfaces with FeS are modified by space weathering by a greater degree than surfaces which lack FeS. Troilite is easily mobilized by shock and impact heating. Impact energy volatilizes S at the surface as well as mobilizing FeS into fractures and melt droplets. Both processes enhance darkening. Hence objects with greater S composition should exhibit more darkening than bodies with less S yet similar Fe compositions (e.g., OC v. Vesta; and lunar highlands v. average Mercury crust).

References: [1] Chapman C. R. (2004) *Annu. Rev. Earth Planet. Sci. 32*, 539. [2] Hapke B. (2001) *JGR 106*, 10039. [3] Binzel R. P. et al. Ast III. P. 379. [4] Foley C. N. et al. (2006) Icarus 184, 338. [5] Lim L. F. & Nittler L. R. (2009) Icarus 200, 129. [6] Jarosewich E. (1990) *MAPS 25*, 323. [7] Burbine T., et al. (2001) *LPS 32,* #1860. [8] Hörz F. *et al.* (2005) *MAPS 40*, 1329. [9] Keller et al., 2013, *LPSC 44*, #2404. [10] Stöffler D., et al. (1991) *GCA 55*, 3845. [11] McCoy T. J. et al. (1999) MAPS 34, 735. [12] McCord T. B. et al., (1970) *Science*, *168*, 1445. [13] Pieters et al. 2005, *Proc. IAU Symposium 229*, 273. [14] Gillis-Davis J.J. et al. (2013) AGU, PA11-07. [15] Nittler R. et al. (2011) *Science 333*, 1847.

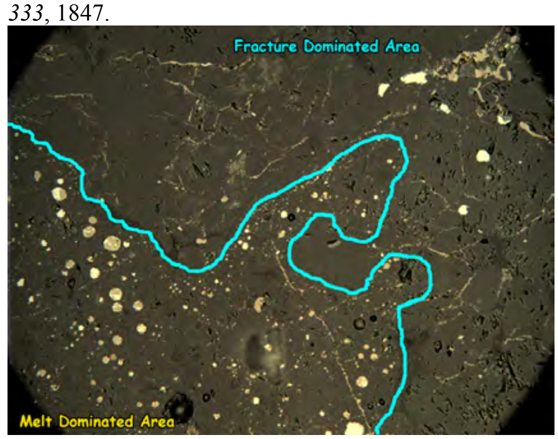

Fig. 2. Reflected light image of McKinney (L4) showing troilite in fractures and Fe-Ni-S spherules due to shock and impact heating.