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Incremental laser space weathering of Allende reveals non-lunar like space weathering effects

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ABSTRACT

We report findings from a series of laser-simulated space weathering experiments on Allende, a CV3 carbonaceous chondrite. The purpose of these experiments is to understand how spectra of anhydrous C-complex asteroids might vary as a function of micrometeorite bombardment. Four 0.5-gram aliquots of powdered, unpacked Allende meteorite were incrementally laser weathered with 30 mJ pulses while under vacuum. Radiative transfer modeling of the spectra and Scanning Transmission Electron Microscope (STEM) analyses of the samples show lunar-like similarities and differences in response to laser-simulated space weathering. For instance, laser weathered Allende exhibited lunar-like spectral changes. The overall spectra from visible to near infrared (Vis-NIR) redden and darken, and characteristic absorption bands weaken as a function of laser exposure. Unlike lunar weathering, however, the continuum slope between 450–550 nm does not vary monotonically with laser irradiation. Initially, spectra in this region redden with laser irradiation; then, the visible continua become less red and eventually spectrally bluer. STEM analyses of less mature samples confirm submicroscopic iron metal (SMFe) and micron sized sulfides. More mature samples reveal increased dispersal of Fe-Ni sulfides by the laser, which we infer to be the cause for the non-lunar-like changes in spectral behavior. Spectra of laser weathered Allende are a reasonable match to T- or possibly K-type asteroids; though the spectral match with a parent body is not exact. The key take away is, laser weathered Allende looks spectrally different (i.e., darker, and redder or bluer depending on the wavelength region) than its unweathered spectrum. Consequently, connecting meteorites to asteroids using unweathered spectra of meteorites would result in a different parent body than one matched on the basis of weathered spectra. Further, spectra for these laser weathering experiments may provide an explanation for inconsistencies observed in both laboratory (e.g., Hiroi et al., 2003, 2001; Lazzarin et al., 2006; Moroz et al., 2004, 1996; Shingareva et al., 2004) and telescopic data (Lazzarin et al., 2006; Marchi et al., 2006; Nesvorný et al., 2005).

1. Introduction

Space weathering encompasses several processes that affect rocks and regoliths on airless bodies. The two principal processes are solar-wind irradiation and micrometeorite impacts. Knowledge of the effects of these processes primarily comes from analyzing and comparing lunar samples and spectra. This body of research yields a lunar-based space-weathering model, whereby physical features such as nanophase iron bearing rims on silicate minerals (Keller and McKay, 1993; Keller and McKay, 1997; Noble et al., 2005) and agglutinates (Duke et al., 1970) increase as a function of surface exposure (i.e., maturity). The accumulation of these products cause increased reddening, darkening, and reduced spectral contrast (Domingue et al., 2014; Fischer and Pieters, 1996; Hapke, 2001; Hapke et al., 1975; Noble et al., 2001; Pieters et al., 1993; Pieters et al., 2000). Inherent in this model are lunar specific elements of target composition (e.g., plagioclase, pyroxene, and olivine (e.g., Taylor et al., 1991)), surface environment (acceleration due to gravity is 1.62 m/s^2, H$^+$ flux of $\sim 1 \times 10^8$ ions/cm^2/s (Pillinger, 1979), gardening rates, and micrometeorite velocity distribution and flux (Cintala and Hörz, 1987; Grün et al., 2001)). As all of these factors are different between asteroids and the Moon, and even among asteroids themselves, a single model for how spectra should change and the space-weathering products formed is not possible. Hence, these lunar specific space weathering components must be taken with certain caveats when applied to other airless bodies.

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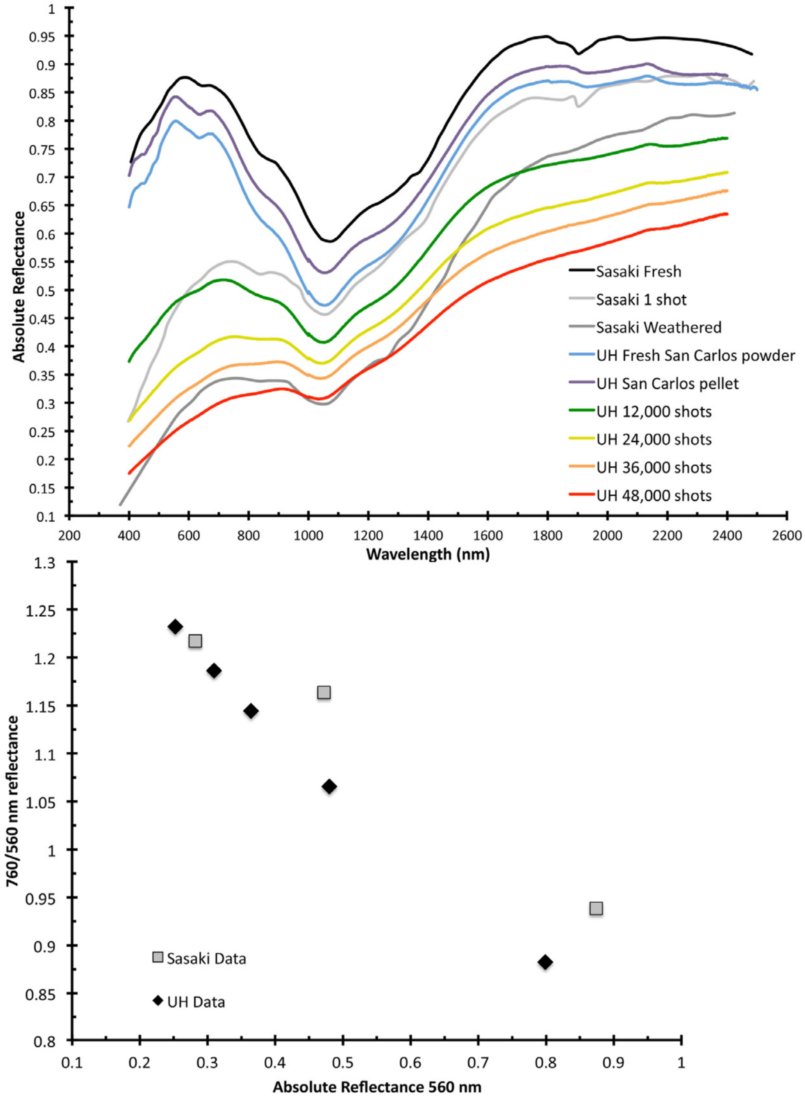

Fig. 1. (A) a comparison of spectra of altered San Carlos olivine of similar grain size (< 75 µm) between laser irradiation experiments done previously (Sasaki et al., 2001) and those done at our laser space weathering facility. (B) Comparison of spectral ratios similar to Figs. 3 and 10. On the basis of these data we find that it takes between 36,000 and 48,000 laser shots in 0.5 g of material to reproduce the spectral change observed in 5 laser shots into the pressed pellet (Sasaki et al., 2001). We include an un-irradiated pressed pellet spectrum to show the reproducibility of our spectrometer and sample with the experimental setup of Sasaki et al. (2001).

For instance, S- and V-type asteroids in general follow lunar spectral trends, but in detail these asteroids seem to weather differently (Chapman, 2004; Clark et al., 2002; Pieters et al., 2012) despite being approximately lunar in composition. The optical properties of carbonaceous chondrites are dominated by fine-grained opaque phases such as sulfides and organics. The response of sulfides and organics to space weathering could be significantly different from that of silicates (Moroz et al., 2004). On this basis, the vastly different composition and environment of C-type asteroids would suggest that a lunar space-weathering model, which was developed to predict the spectral response and space weathering effects of lunar materials under lunar conditions, is not likely an accurate model for C-type asteroids.

The possibility of a non-lunar type of space weathering motivates our experimental approach. The premise of our experiments is further formed by three other factors. First, associations between asteroid types (analyzed remotely in space) and meteorite classes (analyzed in laboratories) are made on the basis of spectral similarities. There are multiple factors that must be considered when comparing spectra of the two (e.g., phase angle, grain size, type and amount of space weathering). Laboratory analyses allow systematic examination of a single parameter or multiple parameters at a time. The aim of this research is to provide insight as to how the surfaces of anhydrous C-complex asteroids evolve in response to space weathering – future work will investigate the spectral response of aqueously altered meteorites (e.g., CI1, CM1-2 and CR1-2) or aqueously altered meteorite components (Kaluna et al. 2016). Hence we limit our experimental set up to laser space weathering while holding other factors constant. Second, asteroid reflectance spectra only “scratch the surface” of what can be known about them, while information about asteroid interiors (e.g., chemistry, mineralogy and thermal history) can be provided by meteorites. Our results are intended to facilitate connections between meteorites and asteroid parent bodies in order to better understand the interiors of anhydrous C-complex asteroids, one of the largest asteroid groups (Bus and Binzel, 2002; DeMeo and Carry, 2014; Gradie et al., 1989). And lastly, spectra of carbonaceous materials subjected to step-wise laser-weathering are vital for spectral interpretation and sample site selection for missions investigating C-complex asteroids (e.g., OSIRIS-Rex (Lauretta et al., 2015), Dawn at Ceres (e.g., Bland et al., 2016; Nathues et al., 2015), and Hayabusa-2 (Tachibana et al., 2014)). These experimental data may