Studying the Spectral Effects of Space Weathering on Carbonaceous Chondrites via Simulation Experiments

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Space Weathering of C Chondrites

Space weathering, a term that encompasses the physical and chemical processes caused by exposure of cosmic bodies to the harsh cosmic environment, can significantly alter the surfaces of airless bodies (e.g. asteroids, moons, comets, planets without atmospheres). Due to its dramatic effects on the composition, morphology, and, subsequently, optical properties, studying the mechanisms and effects of space weathering is vital to the complete characterization of these bodies.

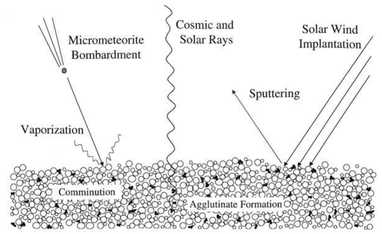

Fig. 1 Space weathering is divided into two categories: 1) irradiation via small, energetic particles like photons, electrons, solar wind ions, and galactic cosmic rays, and 2) physical impact with other bodies like meteoroids.
Credit: Wikipedia

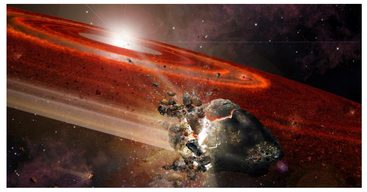

Fig. 2 Artist's rendition of asteroid formation in a primitive solar nebula, the stage at which carbonaceous chondrites formed.
Credit: Harvard CFA

Carbonaceous (C-type) asteroids and their daughter meteorites are of great interest since they are close in composition to the primitive solar nebula (Metzler et al. 1992), so understanding their evolution would improve understanding of the evolution of the Solar System.

Although most meteorites are believed to have originated in the asteroid belt, the spectra of asteroids do not exactly match the spectra of their hypothetical daughter meteorites (Clark et al. 2002). It was initially hypothesized that these spectral differences could be explained by surficial alteration of asteroids caused by space weathering, but laboratory experiments have only challenged this hypothesis.

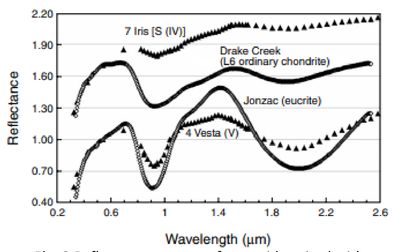

Fig. 3 Reflectance spectra of asteroids paired with their meteorite analogs. The asteroid spectra are redder and have reduced band depth, thought to be caused by space weathering.
Credit: Clark et al., 2002.

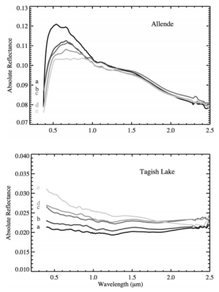

Fig. 4 Conflicting spectral trends in space weathering of meteorites Allende (CV) and Tagish Lake (C2) after irradiation with 5e15 (b), 1e16 (c), 3e16 (d), and 6e16 (e) He^+/cm^2
Credit: Lantz et al., 2013.

Meteorite	Spectrum	Albedo	Slope	Bands	Reference
Murchison (CM2)	UV	Brighter	Bluer	Depth ↓	Matsuoka et al. 2015
	Vis-NIR	Darker Darker Brighter	Bluer Redder Redder	Depth ↓ None None	Matsuoka et al. 2015 Thompson et al. 2019 Lantz et al. 2015
	NIR	Darker	Redder	Depth ↓	Keller et al. 2015
	NIR-MIR	Darker Brighter	None None	Redshift Redshift	Brunetto et al. 2018 Lantz et al. 2015
Allende (CV3)	UV-Vis-NIR	Darker	Redder, then Bluer	Depth ↓	Gillis-Davis et al. 2017
	NIR-MIR	Darker	None	Redshift	Brunetto et al. 2018
	Vis-NIR	Darker	Redder	Depth ↓	Lantz et al. 2017
	MIR	None	None	Redshift	Lantz et al. 2017
Tagish Lake (C2)	Vis-NIR	Brighter Brighter	Bluer Bluer	None None	Vernazza et al. 2013 Lantz et al. 2017
	MIR	Brighter Brighter	None None	Redshift Redshift	Vernazza et al. 2013 Lantz et al. 2017
Lance (CO3)	Vis-NIR	Brighter	Bluer	Depth ↓	Lantz et al. 2017
	MIR	Brighter	None	Redshift	Lantz et al. 2017

UHV Chamber Design

A UHV chamber (currently under construction) will enable the simulation of space weathering via both irradiative mechanisms (like UV, electron, and solar ion irradiation) via a UV lamp, an electron gun, and an ion gun, as well as via physical mechanisms (like micrometeoroid impacts) via laser-induced impact shock melting.

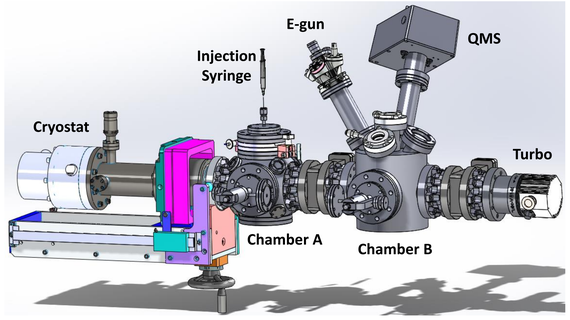

Fig. 5 Chamber design. A cryostat will cool a sample holder that will be moved between two chambers (one for sample preparation, A, and one for simulating space weathering and IR and MS data collection, B) via a linear transfer mechanism. An e-gun is shown in this picture, but other radiation sources (e.g. UV lamp, ion gun) can be attached to this port for a variety of space weathering simulations.

This chamber will be set up to collect bidirectional diffuse reflectance spectra with a similar geometry to the NASA RELAB facility (i = 30°, e = 0°). Our FTIR can collect spectra from the visible to the mid-IR range, allowing us to characterize changes in visible slope and albedo in the Vis-NIR ranges and chemical changes in the MIR range. In addition, a QMS will be used to detect volatiles formed during radiation (most likely primarily H_2) by heating samples, inducing desorption of species on the samples' surfaces, and monitoring masses detect in a range of temperatures via TPD.

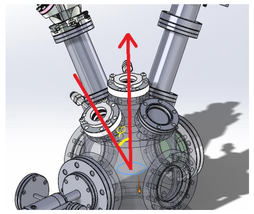

Fig. 6 A φ of 30° will be used to collect bidirectional diffuse reflectance spectra of samples, which will be directly in the middle of Chamber B.

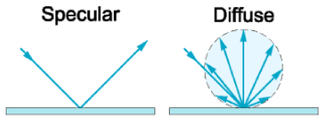

Fig. 7 Reflections off a perfectly specular surface (left) and a perfectly Lambertian surface (right).
Credit: OpenGATE

Fig. 8 Lunar Highlands Simulant (LHS) and CI Meteorite Simulant (CI) powders from Exolith Lab. CI contains carbon in the form of bituminous coal.
Credit: Exolith Lab UCF

For the spectral data collected in this chamber to be comparable to observational spectra of airless bodies, which are typically diffuse reflectance spectra, diffuse reflectance spectra of the samples before and after space weathering need to be collected. Thus, a bidirectional diffuse reflectance set-up was designed to collect spectra of both meteorites and meteorite simulants in powder form.

Preliminary Experiments

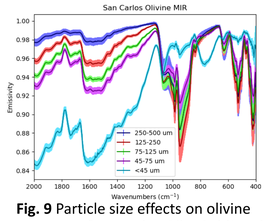

Fig. 9 Particle size effects on olivine spectra (referenced to Pike Gold) and its repacking errors. As particle size decreases, spectral dominance increases and packing error decreases.

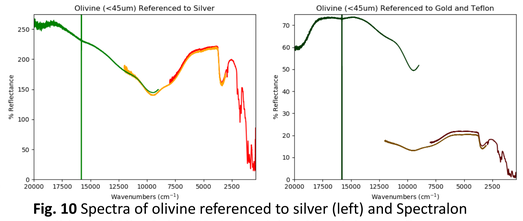

Fig. 10 Spectra of olivine referenced to silver (left) and Spectralon (visible) and Pike Gold (NIR, MIR) (right). Silver's large reflectance range allows for the collection of a continuous spectrum from the MIR to the visible; however, a decrease in its reflectance warps its slope past 17500 cm^{-1}.

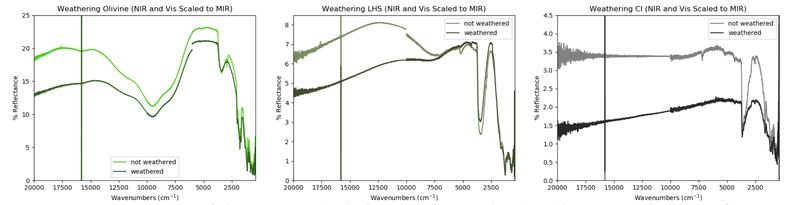

Fig. 11 Continuous spectra of olivine, LHS, and CI before and after simulated weathering in a tube furnace (150°C under Ar for 60 min, then 450°C under H_2 for 60 min). These conditions were meant to simulate micrometeoroid impacts, during which iron present in the regolith is reduced to form sub-microscopic metallic iron. All weathered spectra had a darker albedo, and band depth was reduced, as predicted by Lunar space weathering trends.

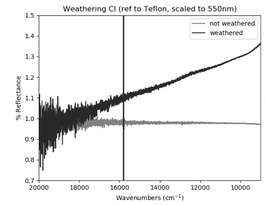

Fig. 12 When scaled to 550nm, the weathered CI shows a clear reddening in the visible slope, which is highly consistent with Lunar space weathering and some space weathering experiments of meteorites.

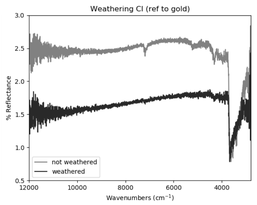

Fig. 13 NIR region of weathered CI shows a lowered albedo and decreased band depth. The disappearing peaks in the not weathered sample may just be atmospheric noise (water combination bands.

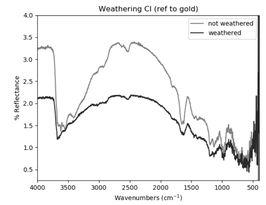

Fig. 14 MIR region of weathered CI shows a lowered albedo, decreased band depth, and a slight change in the OH-stretching region.

Future Directions

- Rhodium will be investigated as a potential reference material and alternative to silver for creating continuous spectra from the visible to the mid-IR.
- Preliminary experiments will be conducted on actual meteorite samples and be compared to the meteorite simulant spectra to assess validity of using simulants in space weathering experiments.
- Following assembly of the chamber, irradiation experiments on the simulants and meteorites will be performed, and the resultant spectral effects will be compared to those from the heating experiments.
- New meteorite simulants will be created without bituminous coal and be spiked with organics present in meteorites to see effects of various carbon-bearing species on spectral changes during space weathering.
- Experiments utilizing multiple simulated space weathering techniques (e.g. heating and irradiation) will be performed to analyze synergistic effects.

References

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Acknowledgements

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