

THE EFFECT OF OPAQUE MATERIALS ON SPECTRAL REFLECTANCE OF THE CHEROKEE SPRINGS LL CHONDRITE: IMPLICATIONS FOR ASTEROID ITOKAWA. E. A. Cloutis¹, D. Trang², and P.G. Lucey², ¹Department of Geography, University of Winnipeg, Winnipeg, MB, Canada R3B 2E9; e.cloutis@uwinnipeg.ca. ²HIGP, SOEST, University of Hawaii, Honolulu, HI, USA 96820.

Introduction: The JAXA Hayabusa mission provided the first returned samples from an asteroid (Itokawa), allowing us to confidently identify it as an LL ordinary chondrite (OC) body [1]. More importantly, analysis of the returned samples has enabled investigation of how space weathering can affect the spectral reflectance properties of OC asteroids [e.g., 2, 3].

The spectrum-modifying effects of exposure of asteroidal materials to the space environment has long been suspected [4], including for asteroid Itokawa [5]. Analysis of the Itokawa returned samples has found that their surfaces have been modified by a number of processes, some of which likely affect their spectral reflectance properties [6]. Modification processes include production of an amorphous Si-enriched upper layer containing embedded Fe and Fe-S nanoparticles [6, 7].

To better understand whether the production of nanophase iron (and amorphous Si-rich rims) on Itokawa mineral grains is responsible for the differences in spectral slopes between observational data for Itokawa and LL chondrite laboratory spectra, we undertook a laboratory spectroscopic study of a fresh LL6 ordinary chondrite (Cherokee Springs, fall: 1933), "doped" with various kinds of Fe-bearing materials.

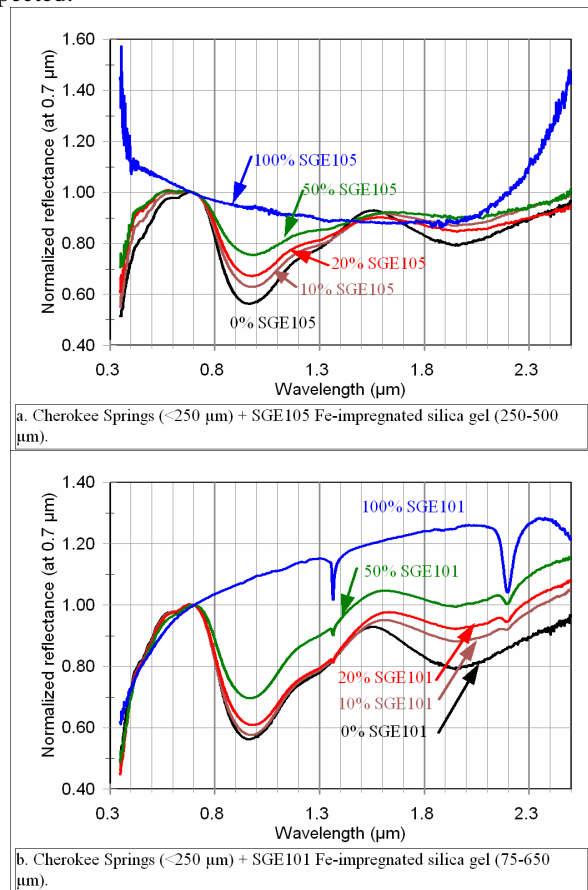
Methodology: A fresh interior multi-gram sample of the Cherokee Springs LL6 ordinary chondrite was crushed to $<250\ \mu\text{m}$; metal grains which could not be crushed to $<250\ \mu\text{m}$ were added back in to the powdered sample. Splits of the sample were intimately mixed with varying proportions of two types of Fe-impregnated silica gel, prepared as per [8], and two different sizes of nanophase iron (**Table 1**).

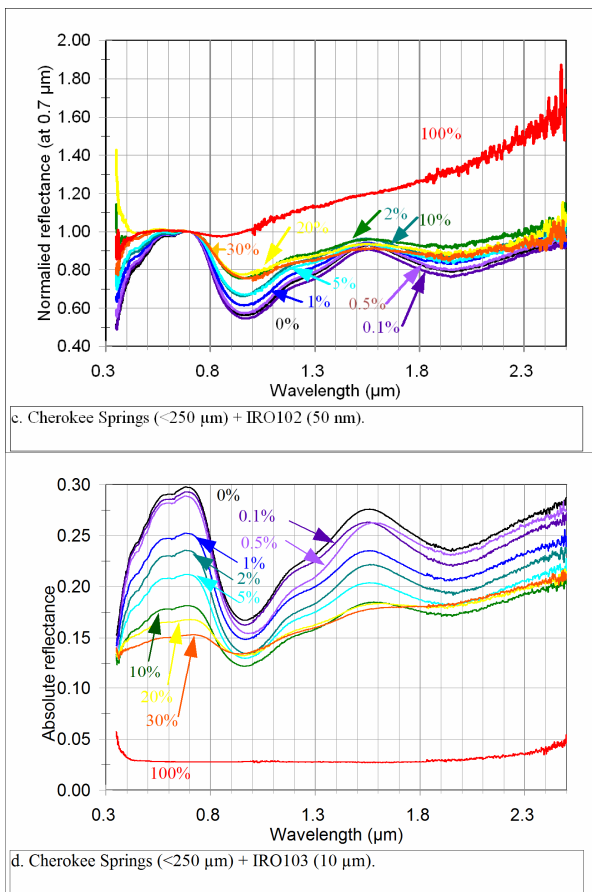
Mixture preparation and spectral reflectance measurements were all performed in a nitrogen-purged glove box to prevent oxidation. Reflectance spectra were acquired with an ASD FieldSpec Pro HR spectrometer from 0.35-2.5 μm and 2-7 nm resolution. Spectra were measured at $i=30^\circ$ and $e=0^\circ$ relative to a Spectralon standard and corrected for dark current, and occasional small detector offsets, at 1.00 and 1.83 μm , as well as for Spectralon reflectance irregularities at $>2\ \mu\text{m}$. Sample illumination was provided by an in-house 100 W stabilized quartz-tungsten-halogen light source, and 200 spectra of standard, sample and dark current were acquired to improve signal-to-noise.

Table 1. Mixtures and description of opaques

Opaque phase	Wt. % mixed with Cherokee Springs
npFe-impregnated silica gel (SGE101A: 2.2 nm pores, high-Fe)	0, 10, 20, 50
npFe-impregnated silica gel (SGE105A: 15 nm pores; high-Fe)	0, 10, 20, 50
IRO102: iron powder, 50 nm average grain size	0.1, 0.5, 1, 2, 5, 10, 20, 30
IRO103: iron powder, 10 μm average grain size	0.1, 0.5, 1, 2, 5, 10, 20, 30

Results: Normalized reflectance spectra of the four mixture series are shown in Figure 1. In terms of absolute reflectance (not shown), increasing Fe content leads to progressively lower overall reflectance, as expected.





The normalized reflectance spectra show variable behavior. The pure SGE105 spectrum has a concave-up shape and is dark (**Fig. 1a**). Increasing the SGE105 abundance in the mixture causes a flattening of the visible region slope, slight reddening beyond 0.7 μm, and decreases in 1 and 2 μm region silicate absorption band depths. The pure SGE101 spectrum (**Figure 1b**) is brighter and red-sloped, and shows evidence of Si-OH absorption features near 1.38 and 2.20 μm, consistent with previous spectra [8]. Increasing abundance of this opaque causes no change in visible region slope (because pure SGE101 and Cherokee Springs have similar spectral slopes in this region), noticeable reddening beyond 0.7 μm and decreases in absorption band depths (**Fig. 1b**).

The pure IRO102 spectrum is dark and red-sloped, and increasing abundance of this phase causes the expected darkening and flattening of the spectrum in the visible region (**Fig. 1c**). Band depths again decrease, and reddening beyond 0.7 μm is modest, in spite of IRO102's strong red slope. Finally, the IRO103 spectrum (larger grain size than IRO102: 10 μm versus 50 nm) also has an overall red slope beyond 0.4 μm, and increasing abundances of this phase results in a flattening in the visible region, and a stronger red slope than for IRO102 (**Fig. 1d**). Table 1 summarizes the spectral

changes observed for the various opaques. From these results it can be seen that the spectral properties of the opaque phase relative to the meteorite control the observed spectral changes. For instance, SGE101 has a similar visible region slope as Cherokee Springs, and even though it is much darker, it causes no change in spectral shape in this region. Conversely, SGE105 and IRO102 are both red-sloped beyond 0.7 μm, but neither causes an appreciable and systematic reddening. The other two opaques are also red-sloped beyond 0.7 μm, and cause appreciable and systematic reddening.

Table 1. Change in selected spectral parameters with increasing opaque abundance.

Opaque phase	Visible region slope (0.6/0.4 μm ratio)	Infrared region slope (2.45-2.50/0.7 μm ratio)
SGE101	no change	redder
SGE105	flatter	no systematic change
IRO102	flatter	slight reddening
IRO103	flatter	redder

Summary: The spectrum-altering effects of Fe are variable and differ depending on its grain size and physical state (i.e., whether the Fe is embedded in silica or not), and will also depend on nanoparticle composition and abundance [8]. This spectral variability may be useful for constraining the nature of fine-grained opaques that cause spectral reddening on asteroids. Asteroid Itokawa provides valuable ground truth on how a particular type of nanophase Fe (and FeS) [1] affects reflectance spectra of OCs. None of the Fe phases examined here show the overall spectral reddening exhibited by Itokawa compared to LL chondrites [5], suggesting that the FeS detected in Itokawa grains [1] may also be playing a role in its reddening.

References: [1] Nakamura T. et al. (2011) *Science*, 333, 1113-1116. [2] Bonal et al. (2015) *MaPS*, 50, 1562-1576. [3] Abe M. et al. (2006) *Science*, 312, 1334-1338. [4] Chapman C.R. and Salisbury J.W. (1973) *Icarus*, 19, 507-522. [5] Binzel R.P. et al. (2001) *MaPS*, 36, 1167-1172. [6] Noguchi T. et al. (2011) *Science*, 333, 1121-1125. [7] Nagao K. et al. (2011) *Science*, 333, 1128-1131. [8] Noble S.K. et al. (2007) *Icarus*, 192, 629-642.

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