SPACE WEATHERING EFFECTS FROM UV TO RADAR WAVELENGTHS.

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Introduction: Optical remote sensing of airless bodies in the solar system is strongly affected by space weathering. Spectral reddening in Visible/Near-Infrared (VIS/NIR) observations of mature lunar regolith compared to spectra of pristine lunar rocks has been extensively studied, and is largely attributed to the accumulation of nanophase metallic iron ($npFe^0$) rims on regolith particles and larger metallic iron grains; more generally collectively referred to as submicroscopic metallic iron (SMFe) [1, 2]. Space weathering effects at ultra-violet (UV) wavelengths have been identified as a bluing of spectra of lunar regolith and S-type asteroids [3,4]. The small penetration depths of VIS/NIR and UV radiation make these wavelengths sensitive to the subtle modification of regolith grains by space weathering. In contrast, microwaves used in planetary radar astronomy have penetration depths several orders of magnitude greater, and are not considered to be as strongly affected by the buildup of nano- and micrometer-scale metallic iron particles.

In this study, we explore how the techniques applied to model optical space weathering can be extended to UV and microwave wavelengths. For microwave wavelengths, we aim to identify if there is the potential for SMFe to impact planetary radar observations, and to try to constrain the magnitude and nature of any such impact. Because the UV reflectance is possibly a sensitive indicator of space weathering, we are interested in comparing radar observables, such as a target's albedo and circular polarization ratio (CPR), with observed alterations of the VIS/NIR and UV spectra to assess the extent of space weathering of an object.

UV Space Weathering: In [1], a light-scattering model is developed to explain spectral reddening of silicate powders by the addition of small quantities of SMFe. The decreased reflectance at short wavelengths is modeled by the increase in the absorption coefficient, α, of the powder with the addition of SMFe. The absorption coefficient is related to the imaginary part of the complex index of refraction, k, of the powder and the observing wavelength, λ, through the dispersion relation:

$$\alpha = \frac{4\pi k}{\lambda}.$$

Both the real and imaginary parts of the complex index of refraction of metallic iron are significantly higher than that of silicate minerals, so that even small amounts of metallic iron can change the index of refraction of the bulk powder. The indices of refraction of the SMFe and silicate components are used with an effective medium model, specifically the Maxwell Garnett equation, to calculate the effective index of refraction of the bulk powder, which represents a form of volumetric average of each component. In our treatment of this model, we apply the same Maxwell Garnett equation, but rather than use the dielectric constants of the powder components, as in [1], we use the complex indices of refractions. We follow the remaining steps of the original model in [1] to calculate the hemispherical reflectance of a theoretical silicate powder with the addition of SMFe, making use of newer laboratory measurements of the index of refraction of metallic iron as a function of wavelength from [5]. The results following the original model in [1], and our new treatment (both using the same index of refraction measurements from [5]), are presented in Figure 1. Here we can see that with our

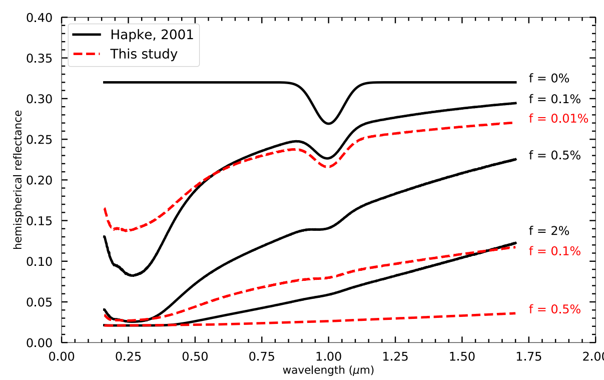

Figure 1: Modeled spectral reddening following [1] (black lines) and with our treatment of this model (red lines). f is the mass fraction of SMFe.

application of the Maxwell Garnett theory, a similar degree of spectral reddening in VIS/NIR (> 0.5 μm) wavelengths can be obtained for an order of magnitude less mass fraction of SMFe. The spectral reversal visible around 0.25 μm is consistent with the UV blue spectral slope identified in [3]. Interestingly, in both treatments of the light-scattering model, the blue slope of the UV portion of the spectra are more prominent with relatively smaller mass fractions of SMFe.

Microwave Space Weathering: Effective medium models are widely used in the analysis of planetary radar observations. The large wavelengths compared to fine-grained regolith is conducive to this type of reasoning, which is often applied in estimating the bulk density in the near-surface of radar observed airless bodies, such as asteroids and the Moon. If effective medium theory is able to replicate the significant decrease in reflectance caused by SMFe at optical wavelengths, it stands to reason that similar effects should manifest at longer wavelengths, such as microwaves.

Laboratory measurements of the complex permittivity and permeability of carbonyl iron powder (CIP) at microwave wavelengths show significant absorptive properties [6]. CIP is highly pure iron synthesized from iron pentacarbonyl, and is commonly used in radar absorbing materials [6]. In [6], the complex permittivity and permeability is measured for mixtures of CIP particles <10 μm in size in an insulating rubber material at various volume fractions. We fit the Bruggeman-Hanai-Sen effective medium equation to these measurements at 2.6 GHz to determine the complex index of refraction, $m = n + ik$, of the CIP particles. The best fit results in $n = 38.95$ and $k = 21.47$, indicating significant absorptive properties at S-band radar frequencies.

We approximate the complex index of refraction of SMFe at microwave wavelengths by that derived for CIP above due to a lack of laboratory experiments on the electromagnetic properties of SMFe at these wavelengths. We calculate the reflectivity, $|\rho|$, at normal incidence of a two-layer model at 2.38 GHz according to the propagation matrix method in [7], with the upper layer consisting of a mixture of silicate particles and SMFe at a porosity of 50%, and the lower layer consisting of only silicate particles at a porosity of 50%. The results for a range of volume fractions of SMFe and depths of the upper layer are shown in Figure 2. The sinusoidal variation in the reflectivity of the two-layer

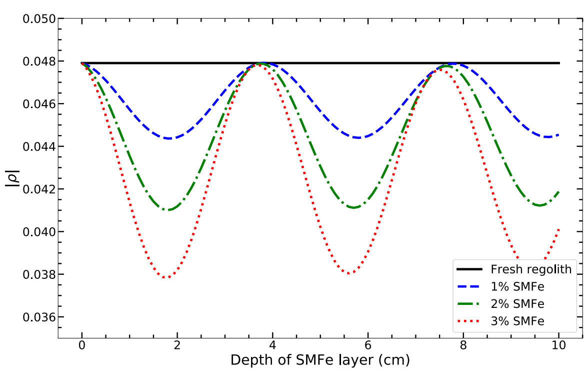

Figure 2: Reflectivity of the two-layer model with varying SMFe volume fraction and depth of the upper weathered layer.

model is caused by the constructive and destructive interference of multiple reflections occurring in the upper layer as a function of the depth of the layer. Figure 2 shows that with the addition of SMFe the reflectivity decreases, reaching roughly 20% decrease with 3% SMFe and a depth of ~2 cm in the upper layer.

Conclusions: The build-up of SMFe in the regolith of airless bodies in the solar system is a well-known by-product of space weathering. This SMFe has been shown to be a plausible explanation for the spectral reddening observed at VIS/NIR wavelengths. We have applied a slightly revised version of the light-scattering model in [1] to explore possible effects at UV wavelengths, making use of more recent measurements of the index of refraction of metallic iron. Our preliminary results confirm that very small amounts of SMFe can result in spectral reddening at VIS/NIR wavelengths, and may also contribute to the spectral reversal at roughly 0.25 μm and blue spectral slope at shorter wavelengths. We use laboratory measurements of the complex index of refraction of CIP to model the changes in reflectivity of planetary regoliths at microwave wavelengths that can result from build-up of SMFe. Our results suggest that the reflectivity can be reduced by up to 20% for as little as 3% SMFE.

A reduction of radar albedo by space weathering further complicates the interpretation of radar observations of planetary bodies. Higher radar reflectivity increases the power of multiple reflections, and therefore can also increase the CPR. The interpretation that fresher material has a higher radar albedo and CPR is consistent with near-Earth asteroids having a higher CPR than main belt asteroids, the high albedos and CPR of E-type asteroids, and the high CPR for asteroid 4 Vesta. By this reasoning, fresh material exposed by cratering enhances the CPR of impact ejecta on the Moon. These compositional effects on CPR are likely not as dominant as surface roughness; however, their impact should not be disregarded completely.

Further laboratory experimentation is necessary to explore the relationship between SMFe and microwave radiation. In [8] it is suggested that nanophase iron does not contribute to absorption of microwave radiation. The lack of focused study in this area leaves this an open question that deems future interest.

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