

DETERMINATION OF IRON METAL OPTICAL CONSTANTS: IMPLICATIONS FOR LUNAR REMOTE SENSING. Joshua T.S. Cahill¹, David T. Blewett¹, Nhan Van Nguyen², K. Xu², Samuel J. Lawrence³, Brett W. Denevi¹, and Ecaterina I. Coman¹. ¹JHU-APL, Laurel, MD; ²NIST, Gaithersburg, MD; ³ASU, Tempe, AZ. (joshua.cahill@jhuapl.edu)

Introduction: Accurate interpretation of reflectance spectra for airless bodies such as the Moon, Mercury, and asteroids requires proper accounting for the effects of opaque metals. Opaque metal and its various alloys are often found as native igneous phases in meteorites and on planetary surfaces in the form of grains significantly larger than the wavelength of the incident light. However, nanophase iron metal grains are also a key by-product of space weathering and introduce confounding effects on ultraviolet (UV) to mid-infrared (MIR) spectra as seen in the laboratory and orbital data sets (e.g., M³, LROC, and Diviner). Sufficient knowledge of the optical properties of these metals is necessary for effective spectral characterization and theoretical modeling analysis of mixtures containing these constituents. Measured optical constants of iron are presently available in the literature [1-4], however these data sets have various drawbacks with respect to use in planetary reflectance modeling. For example, spectral resolution and range of wavelength coverage are less than ideal, and the extent to which the metals were exposed to the atmosphere are poorly documented. Here we report new measurements of the optical constants of iron metal for the UV, visible (VIS), and near-infrared (NIR), with hyperspectral sampling. The data should enable substantially improved modeling of space weathering and compositional mapping for a variety of airless Solar System bodies.

Background: Various approaches have been taken in order to translate reflectance theory into a practical algorithm for analysis of spectral data obtained by spacecraft or telescopes. In all of these approaches assumptions have been made to enable a realistic and successful application. However, theoretical advances and improved processor capability are gradually enabling the application of more computationally intensive radiative transfer mixing models to invert composition from spectral data with fewer assumptions [5-7].

Opaque metals are a component of these models for which assumptions have been made in the past, but in the context of airless bodies are a critical for accurate spectral analysis. These metals are potentially present in planetary regoliths in three physical forms, categorized by grain size: macroscopic, microphase (Britt-Pieters particles), and nanophase [6, 8-15]. Iron metal in particular is relevant for unraveling space weathering effects which are dramatically apparent in laboratory spectra of returned lunar samples. For example, compared with the reflectance spectrum of a freshly powdered lunar rock, a mature lunar soil has a "red" continuum slope, reduced overall reflectance, and greatly muted absorption bands all of which are

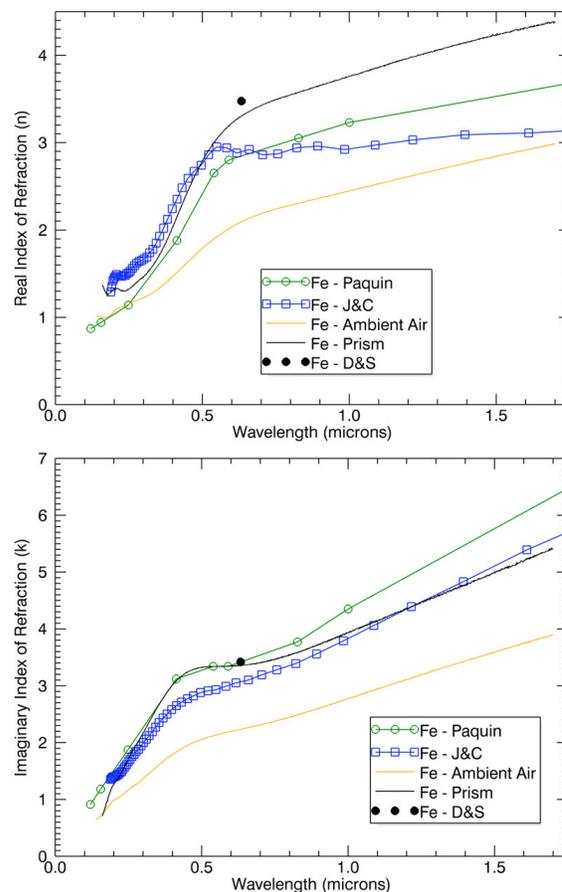


Figure 1: The real, n (top), and imaginary, k (bottom), parts of the index of refraction of Fe [1-3, and this work].

dominantly due the presence of nanophase metallic iron in the soil [6, 16].

Modeling Theory: In Hapke's formulation, the reflectance spectrum of a mixture is computed from the single-scattering albedos of the mineral endmembers included in the mixture [5, 6, 17]. Single-scattering albedo (w), the probability a photon incident on a regolith particle will be absorbed or scattered out of the beam, is independent of illumination or viewing geometry and is a function of a grain's scattering behavior (e.g., degree of internal scattering) and absorption coefficient. The absorption coefficient is in turn governed by the material's complex index of refraction which is a function of the optical constants. These are components of the complex index of refraction, $n_c = n + ik$ where n and k are the real and imaginary components, respectively, and i is $\sqrt{-1}$ [18, 19]. Thus, optical constants are wavelength-dependent quantities that are unique to each particle type in a regolith and reflect the inherent physical and chemical properties of each ma-

terial [19]. They are critical for radiative transfer intimate mixing models.

Available Data: In order to model intimate mixtures containing opaque metal, the optical constants of the metal must be supplied. Optical constants of metals and transparent minerals can be obtained from reflectance measurements [20]. However, samples of iron meteorites or terrestrial iron may be altered by exposure to the moist terrestrial atmosphere for even a brief period of time [21], potentially producing coatings that could interfere with determination of the spectral properties of the unaltered metal as it would exist in space. Hence, some workers have elected to use values for n and k of iron from the applied physics and materials science literature (e.g., [1, 2]). However, there are many shortcomings associated with use of published values, including wavelength range, spectral resolution, and consistency. No single dataset covers the entire wavelength range of interest to planetary reflectance and emission spectroscopy at high spectral resolution [1, 2, 4, 22, 23].

A New Method of Measurement: The National Institute of Standards and Technology (NIST) has devised a novel method for measuring optical constants of metals. First, a coating of high-purity iron is vacuum-deposited on one surface of a fused silica prism in an electron-beam evaporator. Next, careful design of the prism's angles and knowledge of the optical constants of the fused silica allow the measurement of n and k to be done within the prism, such that fused silica is the ambient medium. The light interacts only with the "inside" surface of the iron film in contact with the prism, which is not exposed to the atmosphere. Measurements were performed with a variable angle spectroscopic ellipsometer (VASE), from 160 to 1700 nm in 1-nm steps (far finer sampling in wavelength than previously available data). Additional measurements with an IR VASE will permit determination of optical constants to wavelengths as long as 40 μm .

Results and Relevance: Values for optical constant n here are considerably higher than those reported previously (black curve in Fig. 1). Since oxides typically have lower optical constants than do metals, these results suggest prior measurements were affected by surface oxidation. This interpretation is supported by the results of *Deeter and Sarid* [3], who employed a special hemispherical lens setup to measure the unexposed side of an iron film at a single wavelength (632-nm). For comparison, we show the results for a measurement on an iron film exposed to the ambient atmosphere (Fig. 1, orange curve). Values of both n and k determined for this surface are optically darker than those collected through the prism and are consistent with formation of a thin oxidation layer on the iron.

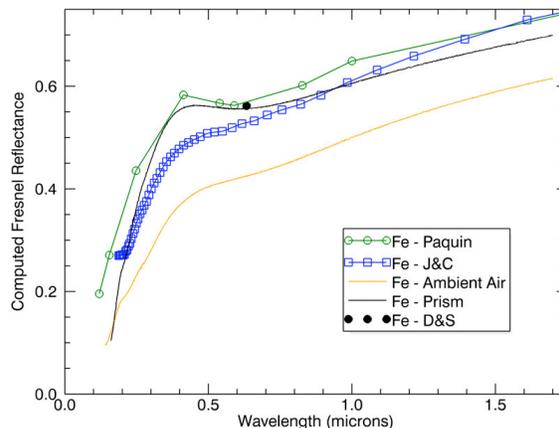


Figure 2: Fresnel reflectance of Fe, computed using optical constants from the literature [1-3] and this work.

The difference between the computed Fresnel reflectance of air-exposed and unexposed iron films at normal incidence has interesting implications for remote sensing (Fig. 2). Specifically, comparisons of laboratory and remotely collected spectra should be interpreted with caution. Although our air-exposed film has a bright, mirror-like surface when measured, its optical properties differ substantially from those of the iron film protected from the atmosphere (~50% lower reflectance near 0.4 μm ; Fig. 2). Therefore, thin, optically active oxidation layers may form rapidly on metals exposed to air, such as meteorites and lunar samples, even if their surfaces appear visually pristine.

Modeled Fresnel reflectance data also suggest steeper slopes in the UV (~0.16 to 0.4 μm) compared to previous studies (Fig. 2). This is significant as recent work suggests the UV provides a more sensitive measure of surface maturity than VIS data [24, 25]. Thus, the data reported herein will provide critical inputs for modeling the UV for maturity as well as mineral and nanophase iron abundances on the freshest surfaces.

On-Going Work: Further study of laboratory spectra and theoretical analysis will explore the impact of these new data on the interpretation of reflectance spectra. Data is also being collected for Fe, Ni, and FeNi in the UV to MIR.

References: [1] Paquin, Ed., (1995); [2] Johnson and Christy, *PR*, (1974); [3] Deeter and Sarid, *AO*, (1989); [4] Ordal, *AO*, (1985); [5] Hapke, (1993); [6] Hapke, *JGR* 106, (2001); [7] Shkuratov, *Icarus* 137, (1999); [8] Hapke et al., *JGR* 80, (1975); [9] Pieters et al., *MaPS* 35, (2000); [10] Noble et al., *JGR* 111, (2006); [11] Lucey and Noble, *Icarus* 197, (2008); [12] Lucey and Riner, *Icarus*, (2010); [13] Britt and Pieters, *Meteor.* 24, (1989); [14] Pieters et al., *MaPS* 35, (2000); [15] Noble and Pieters, *SSR* 37, (2003); [16] Fischer and Pieters, *Icarus* 111, (1994); [17] Hapke and Wells, *JGR* 86, (1981); [18] Hecht and Zajac, *Optics*, (1974); [19] Palik, (1991); [20] Lucey, *JGR* 103, (1998); [21] Gaffey, *Icarus* 66, (1986); [22] Lynch and Hunter, (1991); [23] Moravec et al., *PR B* 13, (1976); [24] Hendrix and Vilas, *AJ* 132, (2006); [25] Denevi, *AGU*, (2011);