SPACE-WEATHERING SPECTRA EXPLAINED WITH LIGHT SCATTERING SIMULATIONS

**Motivation**
- Space-weathering (SW) affects the spectra of atmosphereless Solar System objects (see Fig. 1).
- Understanding SW helps to link the observed asteroid spectra with laboratory-measured (e.g., meteorite) spectra.
- Current SW light scattering is studied using Hapke model(s) and effective medium approximations, but they fail to explain effects related to host grain medium approximations, but they fail to explain effects related to host grain.

**Methodology**
- We employ a state-of-the-art multiscale numerical modeling scheme based on:
  - exact treatment for npFe⁰ scattering properties (Mie or volume-integral-equation simulation)
  - geometrical optics with diffuse scattering simulation for single regolith grain (with or without npFe⁰)
  - radiative transfer simulation for complete planar regolith layer
  - latest complex refractive index models for Fe⁰ (see Fig. 2)
- The npFe⁰ inclusions are located in a 200-nm thin surface layer of a random-shaped olivine grains.

In what follows, we will show how the different SW spectral effects are linked to light scattering, verifying the explanations with physical light scattering simulations.

**Decreasing Albedo**
- In SW, iron is separated from the mineral matrix and forms inclusions close to and over the size of the wavelength. Due to:
  - the large absorption coefficient (imaginary part k of the refractive index m = n + ik, Fig. 2), and
  - the Rayleigh-type behavior with scattering as r⁶/λ⁴ but absorption as r³/λ, (see Fig. 3), the absorption is governing the npFe⁰ behavior, the overall albedo is reduced.

**Dampening Bands**
Phenomenological explanation:
- Non-linear Beer-Lambert exp(-kλ) behavior of the absorption.
- Effective-medium modeling of effective k.

The brighter parts of the spectra for fresh olivine are due to the material having very small absorption coefficient k, while for the absorption bands k is already larger. Adding a small amount of npFe⁰ according to effective-medium models, adds more or less constant increase to the effective k.

Now, assuming Beer-Lambert absorption, a constant increase to a small initial k has a large darkening effect, while the same constant increase to an initially larger k has a smaller effect. Bright parts of the spectra will darkener more than the absorption bands in SW, smoothening the spectra. This is verified with our modeling (Fig. 4).

**Local Slope Changes**
- Due to the general dampening of the absorption bands (see above), all the local slopes, both positive and negative, are decreasing (in absolute sense).
- High-reflectance (peaks, continuum) are effected more with SW than absorption bands.

**Red spectral slope**
- The global (over UV-vis-NIR wavelengths) red slope (i.e., slope turning more positive with SW) is a direct consequence of the small size (compared to wavelength) of the npFe⁰ inclusions.
- The npFe⁰ size effect comes from the absorption efficiency of the particles, which is decreasing quickly after the UV wavelengths (see Fig. 5).

**UV Bluing**
- The UV bluing (effect opposite to reddening, so the local slope in UV-vis range is not increasing but decreasing with SW).

**References**


**Figure 1**: Absolute (left) and normalized (right) measured reflectance spectra of fresh and SW-treated olivine.

**Figure 2**: Real (left) and complex (right) parts of the refractive index model m for olivine, iron, and the relative m for iron in olivine host material.

**Figure 3**: The absorption and scattering cross-sectional efficiencies Qₐ, and Qₘ for 20-nm sized npFe⁰ in olivine host matrix.

**Figure 4**: Simulated RT results of the absolute reflectance of a planar layer of olivine grains (10 µm) with npFe⁰ inclusions. The graph shows the volume concentration of npFe⁰ in the 200-nm layer on the grains. The corresponding total mass ratios would be about 0.014% (for 0.05% layer volume concentration), 0.028% (for 0.1% case), and 0.14% (for 0.5% case).

**Figure 5**: Iron inclusion absorption efficiency in olivine matrix from Mie modeling.

The slope is often still ‘red’ (i.e., positive), but should be less red than with fresh material. In SW, iron is separated from the mineral matrix and forms inclusions close to and over the size of the wavelength. Due to:
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