Infrared spectroscopy of astromaterials in the electron microscope

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Vibrational electron energy loss spectroscopy (VEELS) is a new method that allows characterization of optical properties in the near-to-mid IR at the nanometer scale in a monochromated transmission electron microscope [1]. In VEELS, molecular vibrational modes in a sample are excited by illumination with a high energy electron beam, and measured as the change in energy intensity distribution of the electron beam transmitted through the sample. For a microscope with 10 meV resolution, energy loss features at 50 meV or higher energies are visible, corresponding to 25 μm or shorter wavelengths. This allows for direct observation at the indivudal grain scale of many features of interest for IR astronomical spectroscopy and remote sensing IR, including the 3-μm –OH strectch [2], and the "10-μm" and "18-μm" silicate Si-O stretch and bend features.

To illustrate the potential of VEELS as a tool for IR spectroscopy of sub-μm astromaterials, we measured a series of silicate grains in a cross section extracted from the LAP 02342 meteorite. High angle annular dark field (HAADF) imaging and energy dispersive x-ray (EDX) spectroscopy studies of the section were performed with the Nion UltraSTEM 200-X at NRL. VEELS analysis was performed with the Nion Hermes STEM at Rutgers University equipped with a custom energy losss spectrometer.

Our VEEL spectra from individual sub-μm meteoritic silicates show good agreement with the published IR spectra for crystalline and amorphous silicates [3]. The spectrum from a 300-nm olivine grain (Fo_{90}) resolves the expected split of the 10-μm feature (130 meV) into sharp peaks at 9.9 μm and 11.2 μm. Amorphous silicate grains show spectra with a single broad Si-O stretch feature and a less prominent Si-O bend feature. After electron beam-induced amorphization, the 10-μm feature of the olivine grain was similar to that of the primary amorphous silicates, and consistent with astronomical observations attributed to grain amorphization.

[1] Krivanek *et al.* (2014) *Nature* **514**, p. 209. [2] Crozier, Aoki & Liu (2016) *Micros. & Microanal* **169**, p. 30-36. [3] Molster, Waters & Tielens (2002) *Astron. & Astrophys*. **382**, p. 222.