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Characterization of Meteorites, Interplanetary Dust, and Other Extraterrestrial Materials by Confocal Raman Imaging

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Raman spectroscopy has long been used as an important tool for the study of extraterrestrial materials, from meteorites (e.g. Wang et al) and inclusions such as calcium-aluminum inclusions (CAIs) (e.g. Hofmeister et al) to interplanetary dust (e.g. Wopenka). As time and technology have progressed, Raman spectroscopy has improved in such terms as spectral sensitivity, data collection speed, decreased sampling area, and decreased laser power required to produce usable spectra. The latest improvement in this technique is confocal Raman imaging, where the excitation laser is rastered over a sample and the resulting data is collected as a "data cube". Spectral features of interest are then selected, fitted, and used to produce images. The resulting images illustrate the location and distribution of selected phases in addition to the structural and crystallographic information revealed by point Raman spectroscopy.

The device used here is a WITec GmbH α-SNOM atomic force microscope with Raman imagery equipment installed. A frequency-doubled solid-state YAG laser emitting at 532 nm wavelength provides excitation, with output power selectable between 0 and 50 mW. Detection gear includes an Acton 2300i spectrometer with a CCD detector. The device is built on a standard microscope body, allowing imaging in reflected, transmitted, and transmitted/cross-polorized modes with interchangeable objective lenses. The sample stage is controlled by manual coarse adjustment and piezoelectric X-Y drivers which raster the sample in imaging mode to produce the data cube. The device functions as a confocal microscope with an optical fiber used as the confocal aperture, allowing the user to change the aperture size and hence the sampling depth of the instrument. Visual imagery and Raman data are collected through the upper microscope optic train and illumination is provided from below in transmission mode. This device can achieve minimum spatial resolutions of 360 nm in air and 260 nm in silicone oil as defined by Rayleigh's limit to spatial resolution. This combination of features provides a powerful, relatively simple, and fast new tool for crystallographic, textural, and morphological characterization of extraterrestrial materials.

Meteorites and Their Inclusions

Raman imaging requires no sample preparation, and imagery can be obtained from bulk samples, thin sections, or other prepared specimens. Raman imaging in transmission/cross-polarized mode has proven to be especially revealing for meteorite thin sections. Many characterization methods commonly used in meteorite research, such as SEM/EDS and electron probe analysis, are surface measurement techniques. Imaging Raman allows characterization of materials trapped within transparent mineral grains such as olivine and pyroxene. Data collected from inclusions in chondrule mineral grains is a new endeavor made possible by Raman imagery that is providing new information relevant to the formation history and chemical environment during the formation of the oldest materials known in our solar system. Research utilizing Raman imagery of meteorite matrices has recently begun, and not only provides crystallographic and phase distribution information, but has also proven to be especially useful when coupled with SEM, ToF-SIMS and other elemental data to provide a complete picture of many aspects of the same material. In this role, Raman imagery functions very well as not only a characterization method in its own right but also as a triaging method and first analysis tool for more invasive, destructive methods.

Interplanetary Dust

One of the most important attributes of Raman spectroscopy is the fact that it requires very little power and no invasive sample preparation. These attributes are especially vital in the study of interplanetary dust particles (IDPs), which is small and fragile. Arguably, the most important pieces of information that can be obtained from IDPs are the types, distribution, and isotopic abundance of mineral phases in the particles. While Raman spectroscopy cannot reliably generate isotopic abundance information, it is very well suited to the first two pursuits. When coupled with a fine-resolution isotopic imager such as nano-SIMS, this full suite of information can be provided even on particles only microns in diameter, with crystallographic information thrown in for good measure. Since applied power can be restrained to single mW values with acceptable spectral sensitivity, confocal Raman imagery is especially well suited for first examination of even fragile IDPs. By extension, this technique is especially useful for analysis of returned samples from cometary (such as STARDUST), asteroidal, or planetary missions.

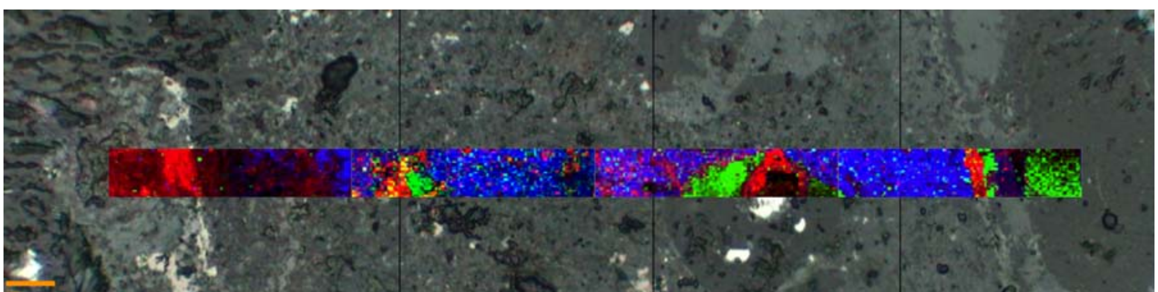

Figure 1: RGB overlay of three Raman images on a confocal optical microscopy image of a fine-grained chondrule rim in the weathered CO3 DaG 749. Red is goethite and magnetite iron-rich oxides, blue is carbon, and green is pyroxene. To the far right in the image is the pyroxene chondrule as shown by the green Raman signature. Thin layers of carbon, pyroxene, and oxides are seen on the edge of the chondrule. The red ring to the right of center is an oxidation rim on a small metal grain with associated pyroxene. The particle on the far left is the oxidized remnant of what was probably a metal grain in the meteorite matrix. Each pixel in the overlay contains an entire Raman spectrum, and analysis of the carbon showed it to be structurally homogenous throughout. The scale bar is 10 μm long.

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