Sweeping the Skies: Stardust and the Origin of Our Solar System

NASA's Stardust mission will soon return cometary material to Earth. Analysis of this material will provide information of the evolution of our Solar System and may provide clues to the origin of life. Advanced analytical tools are being tested to prepare for the analysis of this precious material.

Fig. 1: Comet Wild 2 as seen by Stardust (source: NASA, JPL)

Fig. 2: Optical image of the IDPL2036V8 on Au-foil.

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The Stardust Mission and its Scientific Goals

The NASA *Stardust* mission (www.stardust.jpl.nasa.gov) is the first space mission dedicated to returning solid samples of a comet to Earth for laboratory study. Launched in February 1999, *Stardust* had a rendezvous with the comet *Wild 2* (Fig. 1) in January of this year. At *Wild 2,* it collected cometary dust during a close (ca. 100 to 150 km) flyby of the comet. Analysis of this celestial dust promises to yield novel clues to the evolution of our Solar System, the formation of our Sun, the planets and possibly even life itself. During its *Wild 2* encounter, Stardust performed multiple tasks, including recording counts of comet particles with the Dust Flux Monitor to determine the particle density around the comet. The Comet and Interstellar Dust Analyzer further provided real-time analyses of these particles and volatiles. The particles were captured and stored for their long journey back to Earth in a substance called aerogel, an extremely low-density "silica-foam". This technique will preserve the elemental, chemical and isotopic composition as well as morphology of these _m-sized and smaller particles. The spacecraft is scheduled to return in January 2006, when parachutes will bring the 125 kg probe back to the surface of the Earth.

Comets are small (usually < 10 km), fragile, irregular shaped bodies composed of a mix of small particles and frozen gases, including water. Their highly elliptical orbits swing them deeply into space, often beyond the orbit of Pluto, and repeatedly bring them close to the Sun. Only when a comet comes close to the Sun (ca. < 1 AU), it becomes visible in the sky. As solar radiation heats the comet up, sublimation of volatiles such as frozen water inside the comet's nucleus results in high pressure jets, ejecting material into space to form the coma. After hundreds or thousands of trips past the Sun, comets lose most of their volatiles and dust and will no longer form a coma. Because *Wild 2* has not been exposed to the sun more than five times, it likely contains volatiles and dust in a relatively pristine condition. Scientists believe comets are the oldest and most primitive planetary bodies in the Solar System, and they carry remains of the matter used in the formation of our Solar System. With their volatile freight, comets served to carry organic matter and water to Earth, making life possible at a later stage of its evolution.

Analysis

Since *Stardust* will return a very small volume of material, it is important to produce the best optical, chemical and physical analysis of that material with the greatest number of techniques deleted as possible [e.g. 1]. This is particularly challenging as these dust particles are expected to be small (1–100 µm in diameter) and heterogeneous on sub-µm scales. It will be important, though difficult, to resolve chemical and morpholog-

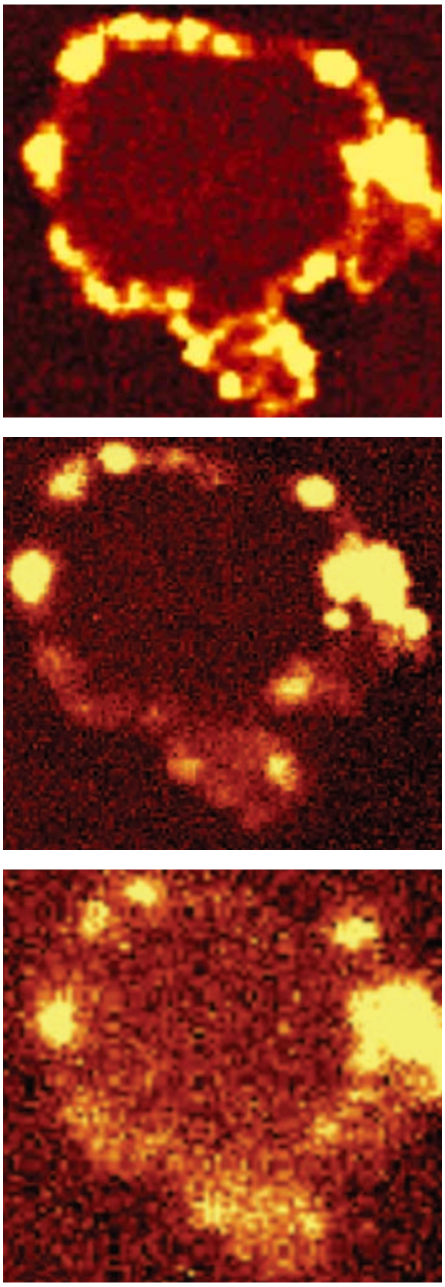

Fig. 3: Confocal Raman images of IDP L2036V8, lateral scans at different depths.

ical heterogeneity of these particles on a nanometer scale. Hence, extremely sensitive analytical techniques with high spectral and/or spatial resolution are desirable for these studies. It is hoped that each individual dust grain will be analysed by a variety of techniques to provide corroborative data and the best possible contextual information. Application of multiple techniques will require the use of non-destructive techniques and in situ analysis.

Funded partly through NASA's SRLIDA program (Sample Return Laboratory Instrument and Data Analysis), the Geophysical Laboratory is one of several laboratories tuning up for the comet samples. For this purpose, a non-destructive analytical microscopy system (Witec GmbH, Ulm, Germany) has been integrated into the existing laboratory infrastructure. This system combines confocal transmission and reflection microscopy, scanning near-field optical microscopy, atomic force microscopy, confocal Raman spectroscopy and fluorescence microscopy. It can provide 3D information on sample structure and composition and allows direct measurements of particle size, using very little laser energy [2, 3]. Raman spectroscopy is an ideal tool for initial high-resolution optical and chemical characterisation, from which mineralogical and structural information can be obtained (instead of characterised), and the presence of organic substances can be determined. Samples analysed with the above system

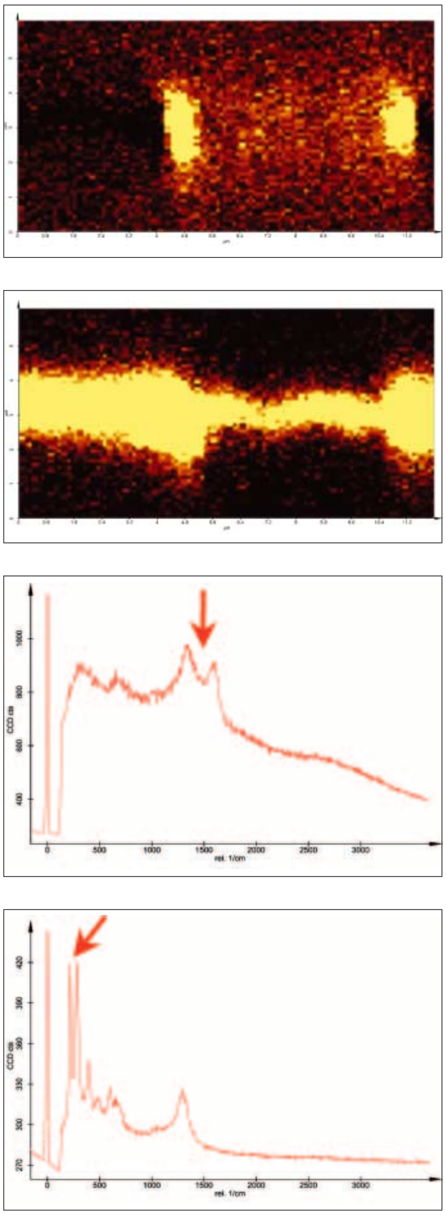

Fig. 4: Confocal Raman images of IDP L2036V8, depth scan.

remain unaltered and can be studied further to obtain important information on their exact chemical and physical properties, e.g. using electron or ion probes for elemental and isotopic distribution and composition, or analytical transmission and scanning electron microscopy for physical characterisation. Since all these techniques require intrusive and/or destructive sample preparation, initial characterisation of samples using the Raman system described above is indispensable.

To demonstrate feasibility, materials comparable to cometary dust, so-called interplanetary dust particles (IDPs) collected in the Earth stratosphere, have been studied using a WITec CRM 200 Raman microscope with a laser wavelength of 532 nm, laser power of approximately 3mW and scan time of 0.1 s/pixel. Fig. 2 shows an optical image of IDP L2036V8 pressed in Au foil. The images in Fig. 3 are lateral confocal Raman images of the same particle at different depth (0, 2 and 3 µm in to the sample), with each pixel containing a full Raman spectrum providing insight into the chemical composition in a focal plane (120 x 120 pixel, 14,400 spectra, scan area 15 x 15 µm). The image shows the integral intensity for the signals between 1089 – 1721 cm^{-1}, which are dominated by two peaks indicative of D- and O-bands (see upper spectrum Fig. 4) of graphitic and disordered carbon. The images in Fig. 4 show depth scans through the same particle (100 x 64 pixel, 6,400 spectra, scan area 12 x 6 µm). Integral intensities are shown from 100 to 363 cm^{-1} in the lower (peaks characteristic for iron oxides, Fe2O3, Fe3O4) and 1,089–1,721 cm^{-1} in the upper spectrum. The comparison of both scans indicates different distributions of the iron oxides and carbon-rich substances in distinct areas. Lateral and depth scans combined allow three-dimensional information at sub-micron resolution to be obtained with the sample undisturbed for further analysis. In total, these data demonstrate Raman imaging as a method for phase characterisation on very small spatial scales.

Only by means of advanced space exploration techniques, combined with sophisticated analytical equipment, are we able to take on this great scientific endeavor. This example is only the beginning of investigations that hold great promise to provide us with novel insights into the cradle of the Solar System and possibly even aspects of the origin of life.

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