LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-TR-218442

Dust That's Worth Keeping

A. Hazi

January 26, 2006

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Dust That's Worth Keeping

This image of the Horsehead nebula shows a large cloud of gas and dust in interstellar space. In the dark areas, absorption and scattering by dust particles block the light from stars. (Image courtesy of the National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation.)

IMAGES taken of interstellar space often display a colorful canvas of portions of the electromagnetic spectrum. Dispersed throughout the images are interstellar clouds of dust and gas—remnants ejected from stars and supernovae over billions and billions of years. For more than 40 years, astronomers have observed that interstellar dust exhibits a consistent effect at a spectral wavelength of 2,175 angstroms, the equivalent of 5.7 electronvolts in energy on the electromagnetic spectrum. At this wavelength, light from stars is absorbed by dust in the interstellar medium, blocking the stars' light from reaching Earth. The 2,175-angstrom feature, which looks like a bump on spectra, is the strongest ultraviolet–visible light spectral signature of interstellar dust and is visible along nearly every observational line of sight.

Scientists have sought to solve the mystery of what causes the 2,175-angstrom feature by reproducing the effect in the laboratory. They speculated a number of possibilities, including fullerenes (buckyballs), nanodiamonds, and even interstellar organisms. However, none of these materials fits the data for the unique spectral feature. Limitations in the energy and spatial resolution achievable with electron microscopes and ion microprobes—the two main instruments used to study samples of dust—have also prevented scientists from finding the answer.

A collaborative effort led by Livermore physicist John Bradley and funded by the National Aeronautics and Space Administration (NASA) has used a new-generation transmission electron microscope (TEM) and nanoscale ion microprobe to unlock the mystery. The Livermore group includes physicists Zu Rong Dai, Ian Hutcheon, Peter Weber, and Sasa Bajt and postdoctoral researchers Hope Ishii, Giles Graham, and Julie Smith. They collaborated with the University of California at Davis (UCD), Lawrence Berkeley National Laboratory, Washington University's Laboratory for Space Sciences in St. Louis, and NASA's Ames Research Center for their discovery.

The team analyzed micrometer-size interplanetary dust particles (IDPs), each about one-tenth the diameter of a human hair. Within the particles, they found carriers of the 2,175-angstrom feature: organic carbon mixed with amorphous silicates (glass with embedded metals and sulfides, GEMS), two of the most common materials in interstellar space. Ishii says, "Organic carbon and amorphous silicates are abundant in interstellar dust clouds, and abundant carriers are needed to account for the frequent astronomical observation of the 2,175-angstrom feature. It makes sense that this ubiquitous feature would come from common materials in interstellar space."

The group's results increase scientific understanding of the starting materials for the formation of the Sun, solar system, and life on Earth.

Where Does the Dust Come From?

Production of the 2,175-angstrom spectral feature is generally believed to originate from electronic transitions occurring at the surface of very small grains (about 15 nanometers) in interstellar space. The grains eventually aggregate to become part of what composes IDPs, some of which make their way to Earth and are collected from the stratosphere by NASA using ER2 aircraft. These aircraft fly at an altitude of 20 kilometers and carry a suite of instruments for atmospheric research and prototype satellite sensors.

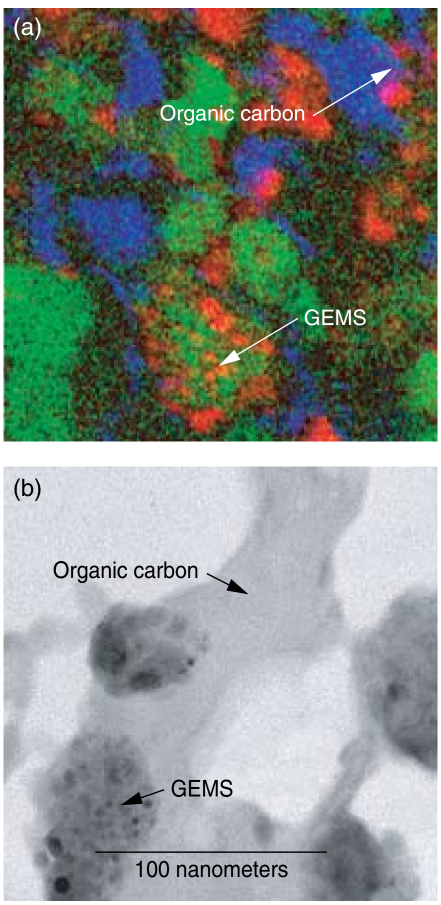
Reprinted from Science & Technology Review, September 2005
UCRL-TR-218442

Most interstellar dust is thought to form in the ejecta of evolving stars and exploding stars, or supernovae. Some of the dust has unusual isotope ratios. In the formation of the solar system, the isotopes from various stellar sources became homogenized, resulting in identical isotopic ratios of the elements that formed the Sun, Moon, Earth, and other celestial bodies. Presolar system grains, on the other hand, retain the original isotopic ratios of their parent stars, and these isotopic ratios can be significantly different from solar system materials.

Presolar grains can be carried by comets or primitive asteroids and delivered to Earth in meteorites and IDPs. According to the U.S. Geological Survey, each year tens of thousands of tons of interstellar dust falls to Earth, carried mostly in IDPs.

Analyzing Specks of Interstellar Dust

Because presolar grains are typically a micrometer or smaller in diameter, sensitive equipment is needed to analyze them. The nanoscale secondary ion mass spectrometer (NanoSIMS), a new-generation ion microprobe, is capable of studying the isotopic ratios of grains at these small scales. Prior to the development of NanoSIMS, ion microprobes measured dozens of presolar grains at a time, providing only an average of the isotopic properties for the samples. In addition, the limited resolution was insufficient to detect an isotopic anomaly located in a single grain.



(a) A 200-kiloelectronvolt transmission electron microscope (TEM) image shows organic carbon and glass with embedded metals and sulfides (GEMS) within an interplanetary dust particle. (b) Using electron energy-loss spectroscopy in a monochromated TEM, researchers created energy-filtered maps of iron (red), magnesium (green), and carbon (blue) to determine the composition of any grains with anomalous isotopic ratios. These images show that GEMS and organic carbon give rise to a 2,175-angstrom feature similar to that seen in astronomical observations.

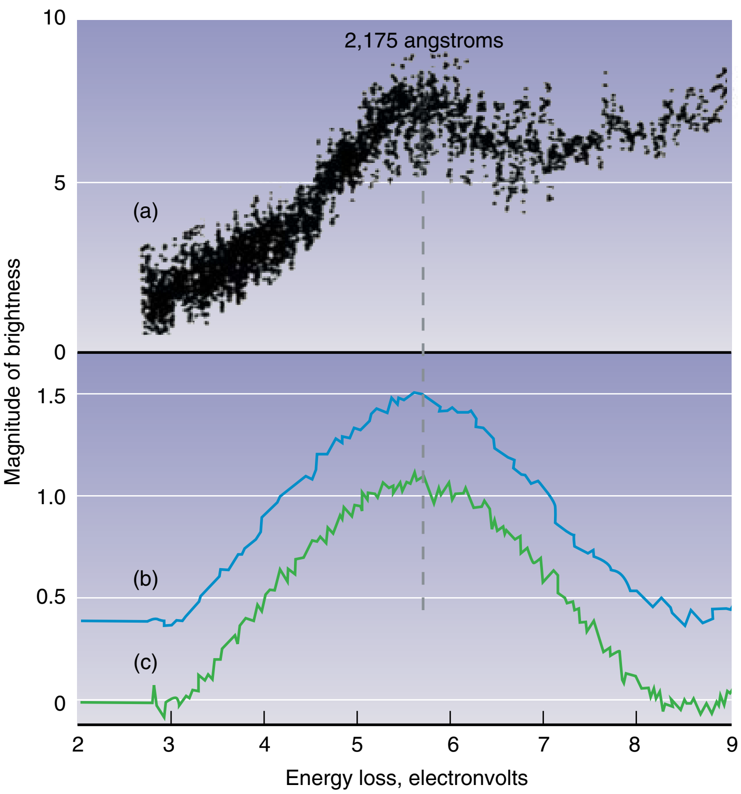
The first step in the analysis process is to determine the isotopic composition of an IDP, which confirms whether any of the grains within the IDP are presolar. NanoSIMS was used at Lawrence Livermore and the Laboratory for Space Sciences to measure the isotopic composition of IDPs. A 16-kiloelectronvolt cesium-133 primary ion beam was focused on a 100- to 150-nanometer-diameter area of the sample. Researchers compared the composition of isotopically anomalous hot spots (areas where the highest concentration of a given isotope is found) with the rest of the particle to identify anomalies. Results showed several submicrometer-size areas whose compositions of carbon, nitrogen, or oxygen clearly indicated presolar origin.

Next, the team used a focused ion beam to extract samples smaller than 100 nanometers from targeted isotopically anomalous regions of the grains. These sections were then analyzed with the new-generation TEM to determine their chemical composition. Collaborators from UCD added a specialized monochromator to a 200-kiloelectronvolt TEM at Lawrence Berkeley's National Center for Electron Microscopy. The monochromator allowed researchers to observe the region known as the valence electron energy-loss region, which ranges from 0 to about 100 electronvolts and includes the 2,175-angstrom feature (at 5.7 electronvolts).

In the experiment, electrons in a tightly focused beam strike a sample and interact with its atoms, losing energy in the process. The lost energy is unique to each type of atom the electrons encounter. By measuring the energy of the scattered electrons and subtracting that amount from the known energy of the incident beam, researchers can determine what type of atoms the electrons interacted with and can identify the chemical composition and other details about a sample. The results showed that GEMS mixed with organic carbon give rise to a 2,175-angstrom feature similar to that seen in astronomical observations.

The team also measured infrared spectral properties in a sample grain. Using the Advanced Light Source (ALS) synchrotron facility at Lawrence Berkeley, they focused an infrared beam onto a 3- to 10-micrometer area of the grain. Synchrotrons can produce highly intense infrared beams that allow scientists to study very small objects and choose resolution in photon energy as small as tenths of electronvolts to observe a specific spectral feature. The infrared measurements confirmed the data acquired from the TEM and provided information on the chemical structure of the amorphous carbon grains. The infrared properties of the sample examined at ALS agreed with the chemical results obtained using electron energy-loss spectroscopy and verified that organic carbon is one carrier of the 2,175-angstrom feature.

Laboratory spectral signatures for the 2,175-angstrom feature show a peak at a wavelength consistent with astronomical observations of spectral signatures that cause the extinction of light. However, the bandwidths on laboratory signatures are broader than those on astronomical spectral signatures. The team theorizes this bandwidth difference is due to several factors. One factor, for example, is physical change over time. Ishii explains, "The grains are no longer free-floating in the interstellar medium where they originally averaged about 15 nanometers in diameter. After 5 billion years, they have changed physically by clumping together to form aggregate particles, which affects their spectral characteristics."



(a) The astronomical 2,175-angstrom spectral feature is compared with (b) an electron energy-loss spectrum from organic carbon in an interplanetary dust particle and (c) an electron energy-loss spectrum from amorphous silicates in another dust particle. The laboratory spectral signatures show a peak in the central portion of the wavelength that is consistent with astronomical observations of spectral signatures.

What Can Interstellar Dust Tell Us?

Particles entering the atmosphere are exposed to temperatures exceeding 350°C, which could potentially cause modifications to organic components and GEMS. Because the particles' physical properties can change as they interact with other elements in the atmosphere, scientists are particularly interested in cometary dust particles, which are more pristine and less processed than those from asteroids or in meteorites. Comets orbit beyond the giant planets and have experienced less heating and aqueous alteration. Bradley, who is director of the Laboratory's Institute of Geophysics and Planetary Physics, has formed a team that will analyze dust from the Comet Wild 2 when NASA's Stardust space mission returns to Earth in 2006. (See *S&TR*, June 2004, pp. 24–26.) The mission will be the first to deliver material from a comet to Earth.

Tiny specks of dust, such as those that will be returned from the Stardust mission, promise to provide answers to a number of long-pondered questions about how interstellar organic matter was incorporated into the solar system. Scientists will also learn about the nature of the particulate material found throughout the galaxy that is responsible for the collapse of interstellar clouds and the formation of stars, planetary systems, and ultimately, life.

—Gabriele Rennie

Key Words: 2,175-angstrom feature, focused ion beam, glass with embedded metals and sulfides (GEMS), interplanetary dust particle (IDP), nanoscale secondary ion mass spectrometer (NanoSIMS), presolar grains, transmission electron microscope (TEM).

For further information contact Hope Ishii (925) 422-7927 (ishii2@llnl.gov).

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.