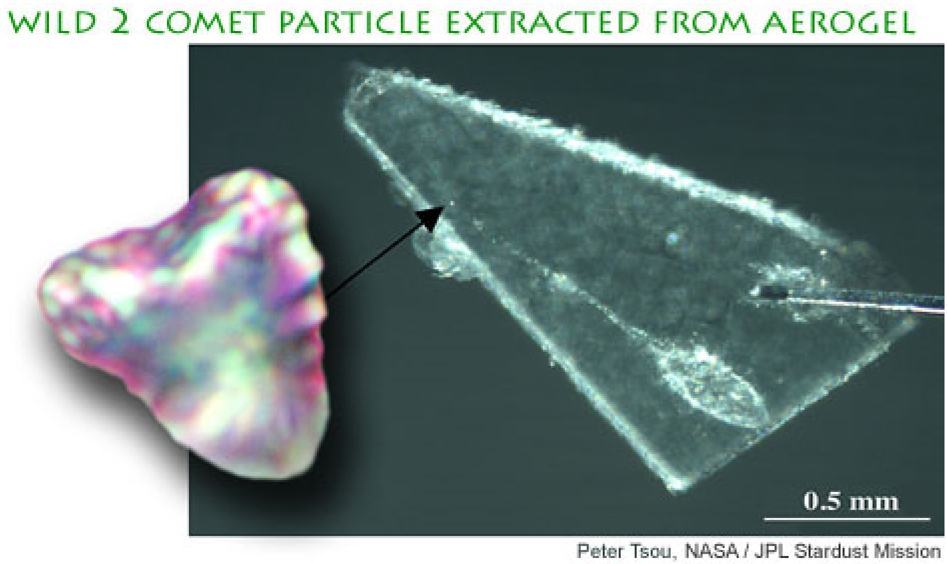
PLANETARY SCIENCE RESEARCH PSRD Discoveries

Hot Idea

December 14, 2008

Wee Rocky Droplets in Comet Dust

--- Tiny flash-melted objects in dust collected from comet Wild 2 were transported from the inner Solar System to the outer reaches where comets formed.



Written by G. Jeffrey Taylor and Linda M. V. Martel
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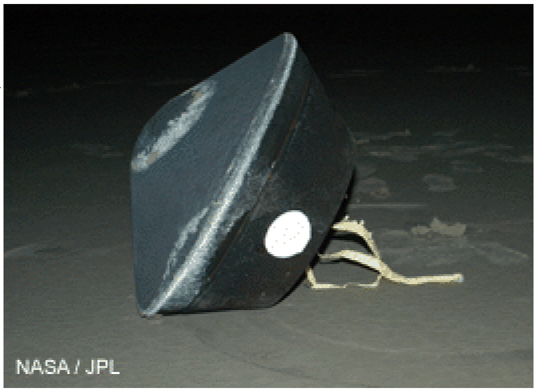
The Stardust mission collected countless dust particles from comet Wild 2 when it flew past it in 2004. Among the menagerie of 1 to 100 micrometer particles are crystalline silicates. Tomoki Nakamura (Kyushu University, Japan) and colleagues in Japan and the United States studied four particles that resemble chondrules, the millimeter-sized flash-melted objects that populate chondritic meteorites. These particles are smaller, about 10 to 40 micrometers across. Though substantially smaller than most chondrules, their mineral compositions and oxygen isotope compositions indicate close similarity with chondrules in typical carbonaceous chondrites that formed in the asteroid belt between Mars and Jupiter. Because comet Wild 2, like all comets, originated in the Kuiper belt beyond Neptune, these flash-melted rocky droplets must have been transported from the inner Solar System to its cold, icy reaches to be incorporated into a comet. The dust-gas cloud surrounding the primitive Sun was a dynamic system when comets, asteroids, and planets began to form.

Reference:

- Nakamura, T., Noguchi, T., Tsuchiyama, A., Ushikubo, T., Kita, N. T., Valley, J. M., Zolensky, M. E., Kakazu, Y., Sakamoto, K., Mashio, E., Uesugi, K., and Nakano, T. (2008) Chondrulelike Objects in Short-Period Comet 81P/Wild 2. *Science*, v. 321, p. 1644-1667. doi:10.1126/science.1160995.

PSRDpresents: Wee Rocky Droplets in Comet Dust --Short Slide Summary (with accompanying notes).

The Stardust Mission: Capturing Comet Dust



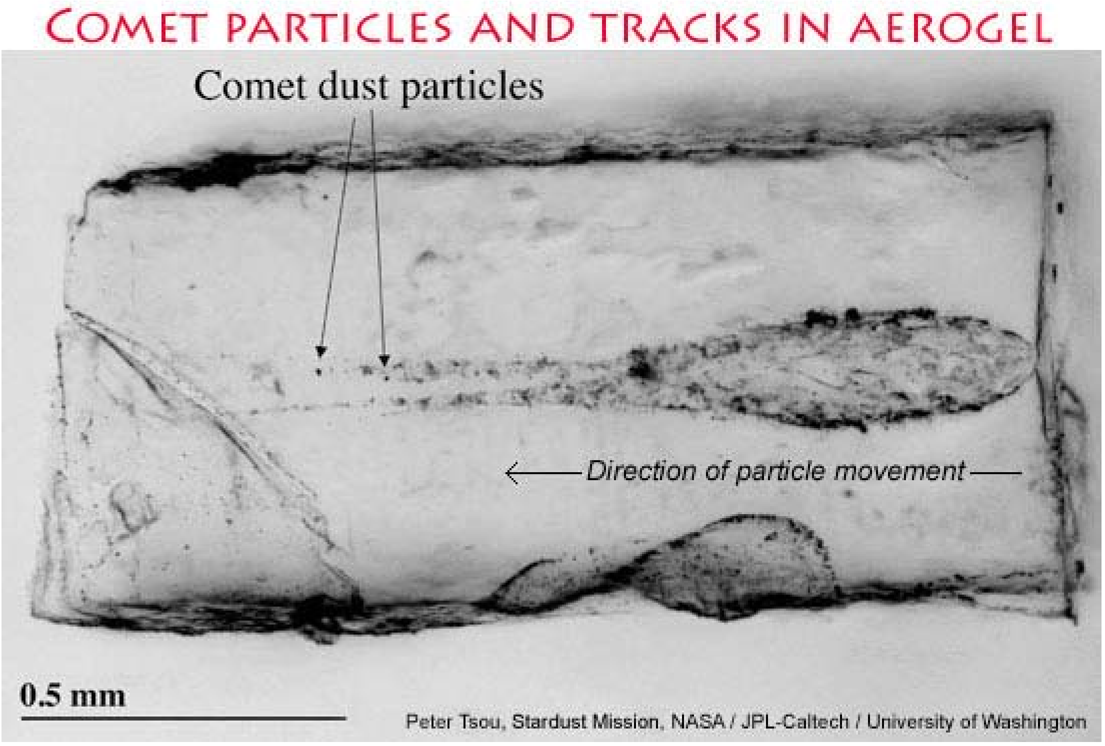
What is so special about this nondescript capsule lying on the Utah desert in the middle of the night (see photo, right)? It fell from space just as planned after seven years of deep-space travel, returning a remarkable cargo of tiny particles collected from a comet and interstellar space. Stardust, the NASA mission dedicated to the exploration of comet Wild 2 and the first to return extraterrestrial particles from beyond the orbit of Earth's Moon, has been a resounding success. Launched on February 7, 1999, the Stardust spacecraft performed a close fly-by of the comet nucleus of Wild 2 in January 2004, passing through the coma to capture more than 10,000 cometary particles (1 to 100 micrometers in size). It sent its sample-return capsule back to Earth for a landing on January 15, 2006.

NASA's Stardust sample-return capsule traveled 2.88 billion miles during its seven-year round-trip odyssey to comet Wild 2. Click the image for more landing photos.

Composite image from short- and long-exposure frames of comet Wild 2 taken by the Stardust Navigation Camera during the 2004 flyby. Click the image for a high resolution version.

Images taken by the Stardust Navigation Camera during the 2004 flyby showed jets of dust and gas streaming into space off the ~5-kilometer-diameter nucleus (see image). The particles impacted Stardust at 6.1 kilometers/second and were stopped inside a unique aerogel collector. Aerogel, a foamed glass, is a spectacular invention in its own right. Made at the Jet Propulsion Laboratory, this silicon-based substance is 99.8% empty space and has a density similar to air, earning it the nickname, "solid blue smoke." Yet aerogel is strong and capable of capturing hypervelocity particles without completely demolishing them. [Read more about aerogel here: http://stardust.jpl.nasa.gov/tech/aerogel.html.]

Scientists studying the large collection of samples returned from comet Wild 2 found a wider variety of grain sizes, densities, and compositions than anticipated. A good overview of Stardust results written by Donald Brownlee (University of Washington, Seattle), Principal Investigator of the Stardust mission, appears in the June, 2008 issue of Physics Today. The diversity of low- and high-temperature minerals speaks to a wide range of conditions or locations where these minerals formed. Researchers have determined that many of the solid particles did not form in the icy comet-forming zones. Thus, these precious tiny particles contain much sought-after information about the solar nebula and how our Solar System formed. Fortunately, a single cometary particle 10 micrometers across, only one-hundredth of a millimeter, can be sliced into numerous samples for analysis with a myriad of state-of-the-art analytical methods.



This close-up view of a small block of aerogel from the Stardust collector shows the carrot-shaped, hollow track made by the incoming comet particles. The track is largest where the particles entered the aerogel. Scientists follow the tracks to find the embedded particles. Click the image for a high resolution version.

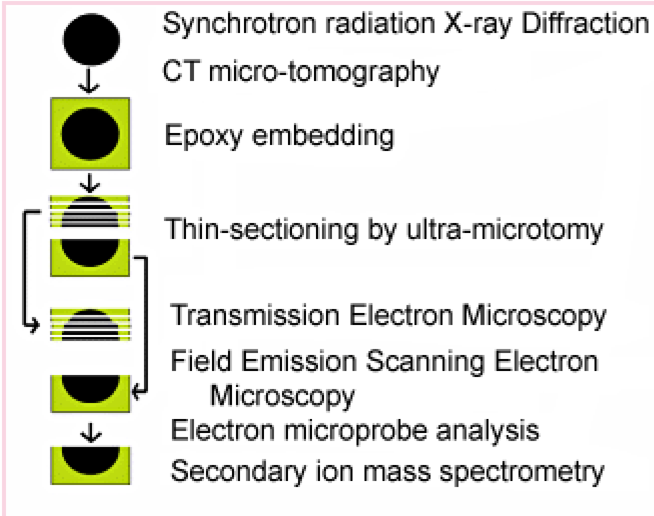
Analyzing Next to Nothing

The analytical capabilities of modern cosmochemistry are astonishing. Amazingly small samples can be analyzed by multiple techniques. We described some of these capabilities in the **PSRD** article Analyzing Next to Nothing, which was based on an article written by Mike Zolensky (Johnson Space Center), Stardust curator and co-investigator, and a co-author of Tomoki Nakamura's article.

Nakamura and colleagues used a series of analytical techniques on each of the four particles they studied, as summarized in the diagram below. Their first step was to place each particle in the beam of the SPring-8 synchrotron in the Hyogo Prefecture, Japan. (SPring stands for Super Photon ring.) Synchrotrons produce radiation by accelerating electrons to close to the speed of light. When bent by a magnetic field, the electron beam emits radiation. Modern facilities are optimized to produce X-rays in order to study the properties of materials.

This allowed two important measurements. First, they measured the X-ray diffraction pattern of an entire particle. This is a classic technique to determine what minerals are present in a sample, though the classic technique is done with more conventional X-ray devices on much larger samples. Second, using another beam line at the synchrotron, they did micro-tomography of three of the sample. That is, they did a CT scan, just like doctors use to check our insides without chopping us up first, but on a smaller scale.

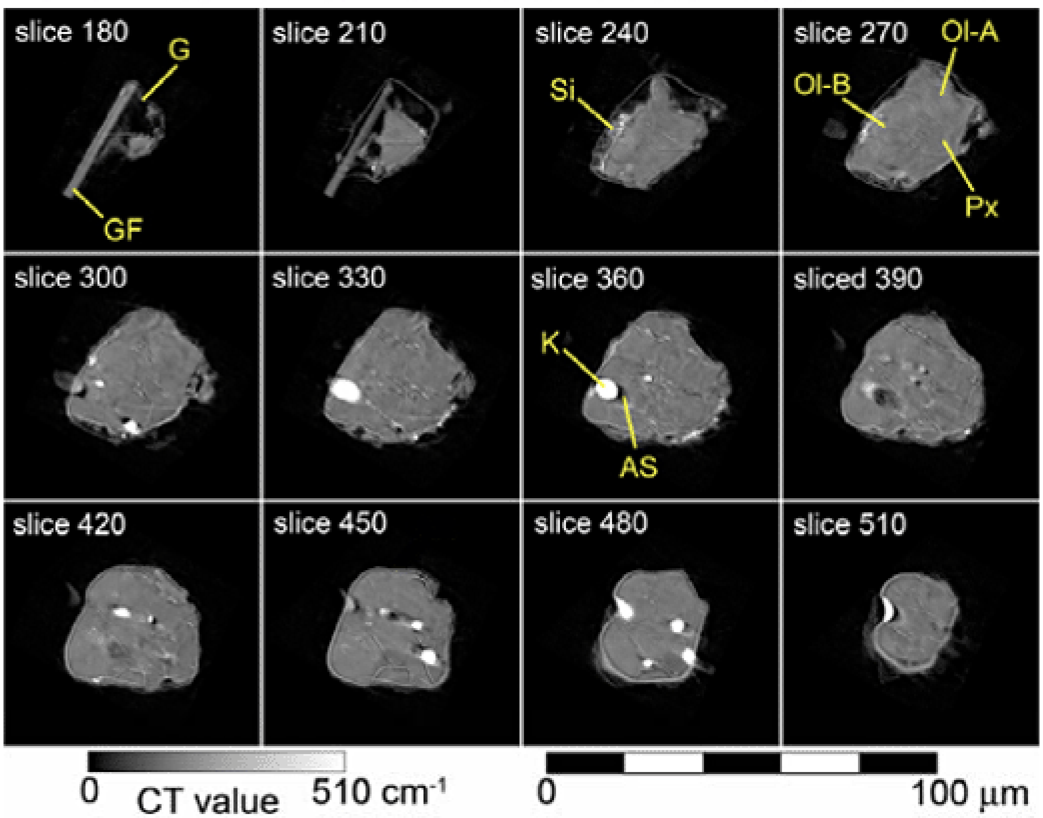
SAMPLE PROCESSING METHODS



(From Nakamura *et al.*, (2008) *Science*, v. 321, fig. S1.)

This is a schematic illustration of the steps Nakamura and his colleagues used to study the small particles collected by the Stardust mission. Black represents a particle; green represents epoxy.

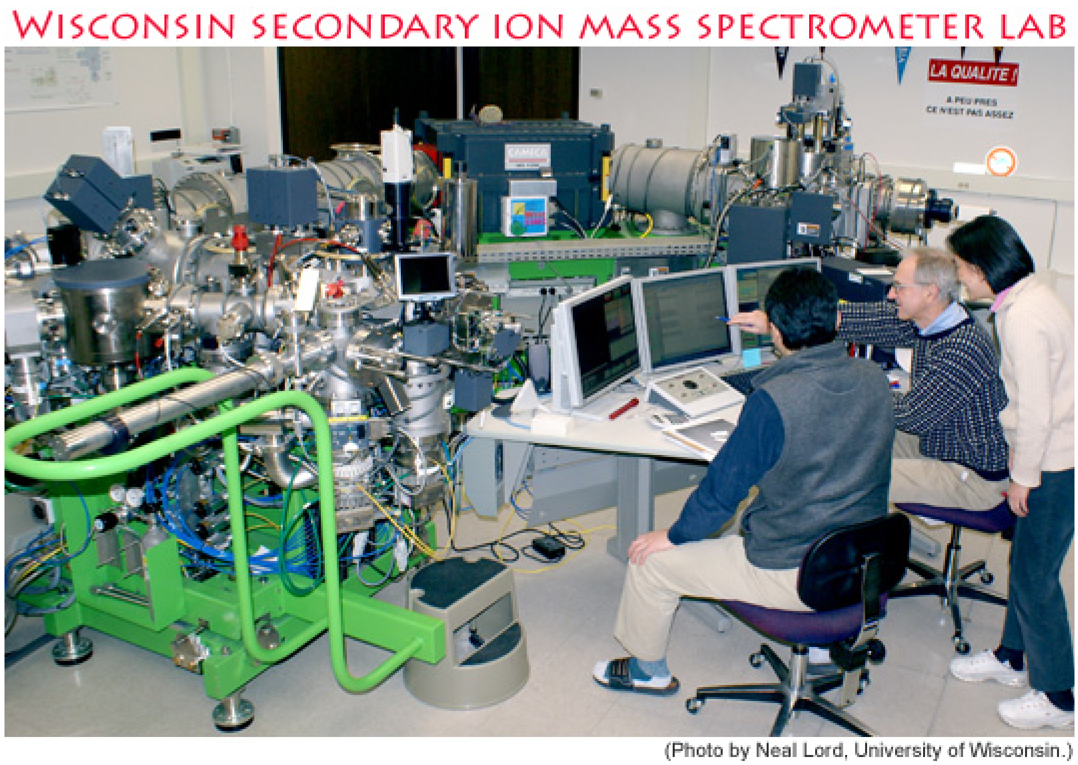
CT IMAGES OF COMETARY PARTICLE "GOZEN-SAMA"



(From Nakamura *et al.*, (2008) *Science*, v. 321, fig. S2.)

Successive CT images of one of the particles Nakamura and his colleagues studied. They named this one "Gozen-sama." The computed slices are roughly parallel to the microtomed sections used to study by electron microscopy. G is glue and GF is a glass fiber used to hold the particle. Si is melted silica aerogel. Ol is olivine. Px is pyroxene. K is kamacite. AS is a shadow of the kamacite grain.

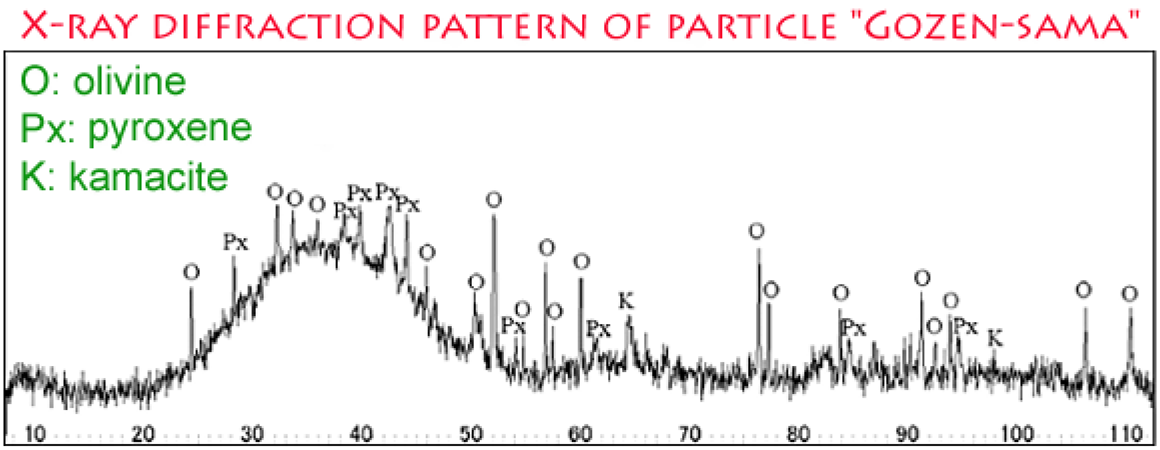
Step three was to make ultra-thin sections of the particles. Each slab was only 70 nanometers thick. (For comparison, typical household dust is larger than 1000 nanometers.) They did this on a device called a microtome, which is a high-tech knife equipped with a diamond blade. In this case the actual instrument is made by Leica-Reichert and called a Supernova Ultramicrotome (a triumph in instrument branding and marketing). This procedure required embedding the particles in epoxy. About half of each particle was cut into the ultra-thin sections for study in a transmission electron microscope, with the remainder reserved for observations in a high-resolution scanning electron microscope and electron microprobe, and then oxygen isotopic measurements by a secondary ion mass spectrometer (ion microprobe) done at the University of Wisconsin. The Wisconsin laboratory (Wisc-SIMS) specializes in high precision oxygen isotope analysis of small samples with beam spot diameters of <1 to 10 micrometers. Their IMS-1280 SIMS is the first of a new generation of large radius ion microprobes and has multiple detectors allowing the three oxygen isotopes to be measured simultaneously. [For general information see **PSRD** article Ion Microprobe.] And remember, all this was done on particles typically only 10 micrometers across!



Cameca 1280 secondary ion mass spectrometer (ion microprobe) at the University of Wisconsin, Madison (Wisc-SIMS). Pictured left to right are Taka Ushikubo, Wisc-SIMS Research Scientist; John Valley, Professor and Chair of the Wisc-SIMS Oversight Board; and Noriko Kita, Director of the Wisc-SIMS Lab. Taka Ushikubo and Noriko Kita made the oxygen isotopic measurements of the Wild 2 particles. Click the image for more information about Wisc-SIMS.

Tiny Chondrules, but Like Their Big Brothers in Chondrites

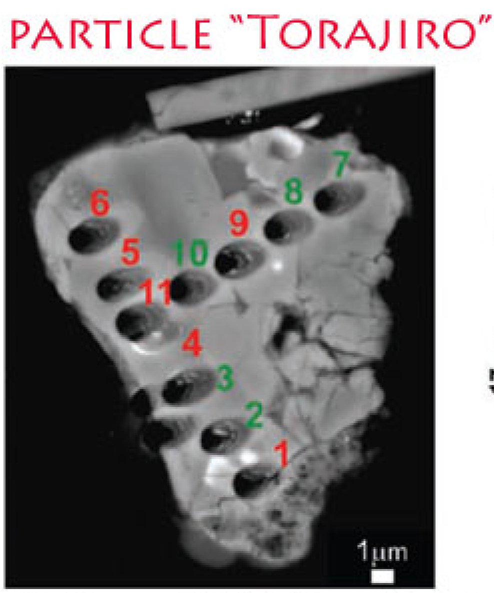
The CT scans and X-ray diffraction patterns show clearly that silicate minerals and metallic iron are present in the particles. Observations using scanning electron microscopy and mineral compositions determined by electron microprobe confirm the X-ray diffraction measurements. Taken together, the data show that these tiny objects are quite similar to typical chondrules, except for being smaller. Even the small size is not unique. Some chondrites have lots of tiny chondrules about the size of the Wild 2 particles.



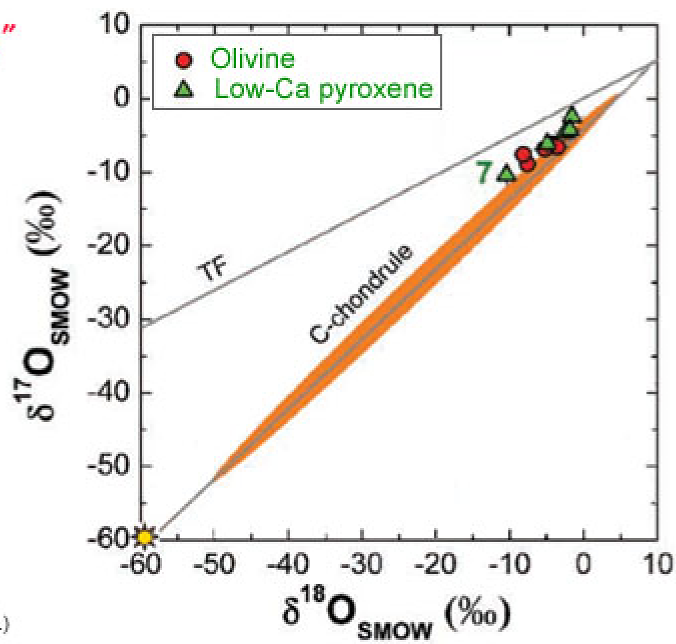
(From Nakamura *et al.*, (2008) *Science*, v. 321, fig. S4.)

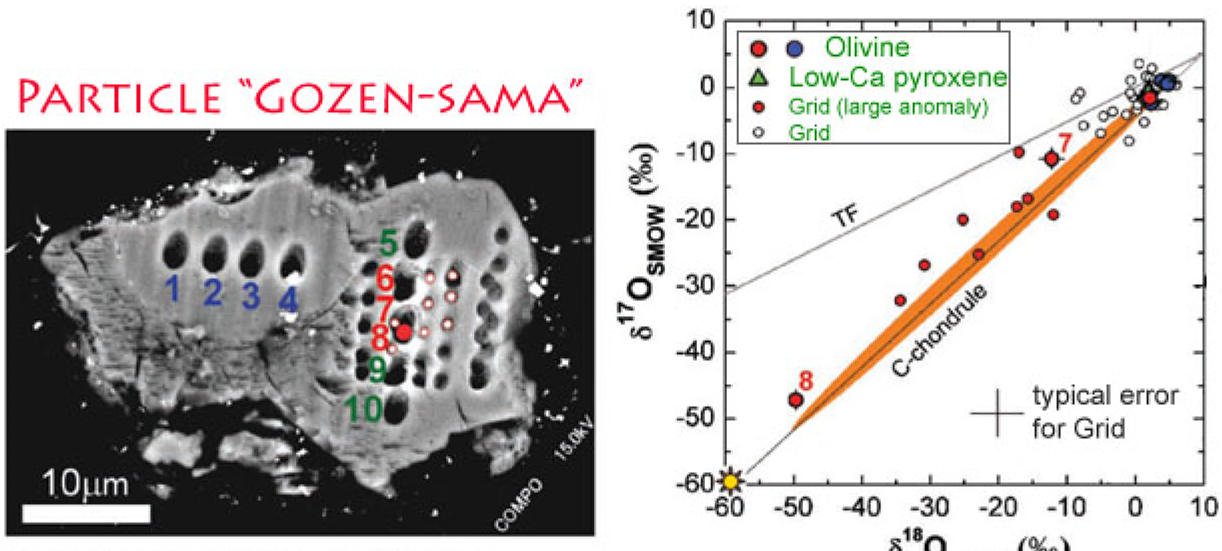
X-ray diffraction pattern of particle "Gozen-sama," obtained using synchrotron radiation. The horizontal scale is the diffraction angle (called 2-theta by crystallographers). The vertical scale is the relative intensity of the diffracted X-rays. Peaks provide information about the crystal structure, allowing identification of the minerals present. In this case, the silicate minerals olivine and pyroxene, and the metallic iron-nickel mineral kamacite are clearly present.

The most important link to inner Solar System chondrites like those we have is their similarity in oxygen isotopic composition. On the very popular three-oxygen isotope diagram (see below), chondrules and other water-free components in carbonaceous chondrites string out along a line that connects to a point at -60, -60 on the scale (represented by the sun symbol). This is thought to represent the isotopic composition of oxygen in the Sun. The key point is that all three particles from Wild 2 analyzed for oxygen fall along the same line as carbonaceous chondrites, establishing a strong compositional link.



(After Nakamura *et al.*, (2008) *Science*, v. 321, fig. 1.)

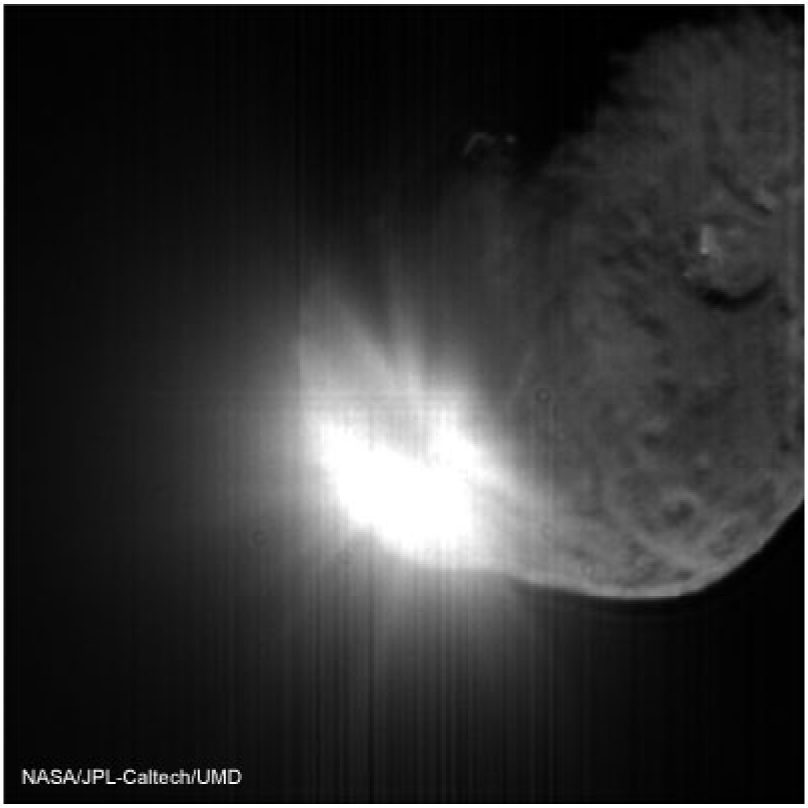




(After Nakamura *et al.*, (2008) *Science*, v. 321, fig. 2.)

Backscatter electron microscope images of cometary particles Torajiro (top, left) and Gozen-sama (bottom, left). Holes in pictures are analytical spots made during ion microprobe measurements. The graphs show the oxygen isotopic composition in the two particles. The delta nomenclature simply means $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios normalized to standard mean ocean water (SMOW), and expressed in parts per thousand. The black line labeled TF is where samples from Earth plot. The orange band labeled C-chondrite is where chondrules and other materials in carbonaceous chondrites plot. The data for the Wild-2 particles show that these little chondrules are related to those in chondrites formed in the asteroid belt, but found their way to the outer Solar System while comets were being assembled.

This is not the first evidence for crystalline silicates in comets. Previous infrared astronomical observations of comets and laboratory measurements of interplanetary dust particles thought to come from comets indicated that a lot of silicate in many comets is crystalline. The measurements made by the Deep Impact mission [Deep Impact homepage] when its projectile dramatically smashed into comet Tempel 1 also found silicate crystals. Other silicate grains have been identified in Stardust samples, suggesting that all comets contain crystalline silicates. However, Nakamura and his colleagues' analyses on the particles from the Stardust collection allow a much stronger link to known types of chondrites.

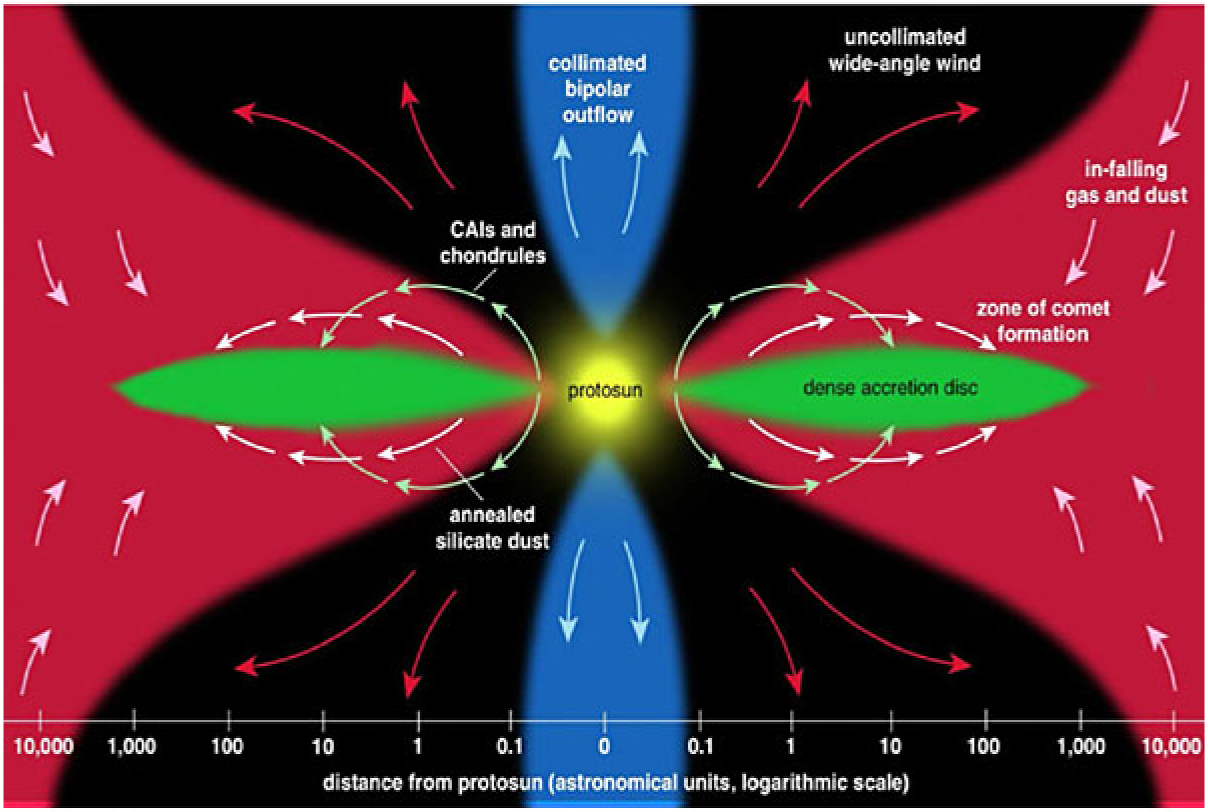


Measurements of the material ejected from comet Tempel 1 when a massive projectile whacked into it at 10 kilometers per second showed that crystalline silicates were present, not just noncrystalline materials and ice. [Deep Impact image gallery]

The Solar System Transportation System

Interstellar space contains dust. Most of it is not made of well-ordered silicate crystals like those in typical planetary rocks. It is made of disordered, amorphous (non-crystalline) smoke particles. The current view of Solar System formation depicts comets forming far out in the Solar System, in the Kuiper belt beyond Neptune. If true, comets ought to be made entirely of silicate smoke particles (plus ice) like those in interstellar space. This region is too cold to provide enough heat to convert the smoke to crystalline minerals. Where did the Wild 2 chondrules come from then?

A reasonable answer, supported by Nakamura and colleagues, is that dust processed at high temperature in the inner part of the solar nebula must have been transported from the inner nebula to the outer, frigid reaches where comets formed. Don Brownlee (University of Washington, Seattle), Principal Investigator of the Stardust mission, calls this the "Grand Radial Express." Astrophysicists and cosmochemists have suggested several mechanisms for transporting materials within and above the nebular disk surrounding the highly-active infant Sun. The Stardust results give experimental evidence that such vigorous transport took place.



(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

A schematic diagram of the solar nebula as it was still accreting dust to it. Planets have not yet formed. Materials heated near the protosun circulate to the outer Solar System to the cold regions where comets formed, driven by forces originating near the early Sun. [Diagram from chapter by Nuth et al. (2005) *Chondrites and the Protoplanetary Disk,* p. 678.]

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Wee Rocky Droplets in Comet Dust --Short Slide Summary (with accompanying notes).

- Brownlee, D., and co-authors (2006) Comet 81P/Wild 2 Under a Microscope. *Science,* v. 314 (5806), p. 1711-1716, doi: 10.1126/science.1135840.
- Brownlee, D. (2008) Comets and the early solar system. *Physics Today,* v. 61(6), p. 30-35.
- Ishii, H. A., Bradley, J. P., Dai, Z. R., Chi, M., Kearsley, A. T., Burchell, M. J., Browning, N. D., and Molster, F. (2008) Comparison of Comet 81P/Wild 2 Dust with Interplanetary Dust from Comets. *Science,* v. 319 (5862), p. 447-450, doi: 10.1126/science.1150683.
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- Nakamura, T., Noguchi, T., Tsuchiyama, A., Ushikubo, T., Kita, N. T., Valley, J. M., Zolensky, M. E., Kakazu, Y., Sakamoto, K., Mashio, E., Uesugi, K., and Nakano, T. (2008) Chondrulelike Objects in Short-Period Comet 81P/Wild 2. *Science,* v. 321, p. 1644-1667. doi:10.1126/science.1160995.
- Stardust Mission website
- Taylor, G. J. (April 2000) Analyzing Next to Nothing. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/April00/analyzingSmall.html
- Zolensky, M. E., and co-authors (2006) Mineralogy and Petrology of Comet 81P/Wild 2 Nucleus

Samples. *Science*, v. 314(5806), p. 1735-1739, doi: 10.1126/science.1135842.

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