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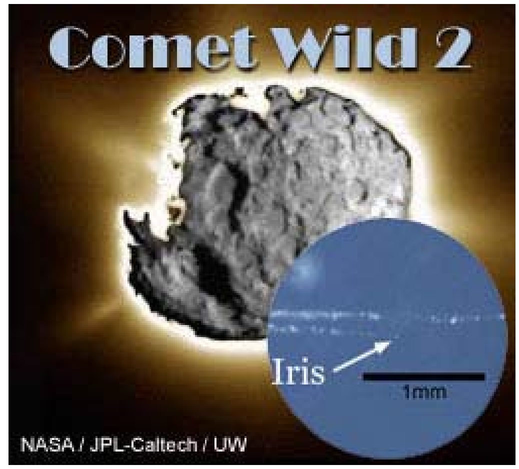
Headline Article
February 21, 2012

Chronicle of a Chondrule's Travels



--- Isotopic measurements of a chondrule in a Comet Wild 2 grain tell the story of outward migration of solar nebula solids, helping to set the formation age of Jupiter.

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Cometary particles returned in 2006 by NASA's Stardust spacecraft provide crucial information not only about the mission's target, comet 81P/Wild 2, but also about the dynamics in the solar nebula that brought the comet's materials together. Ryan Ogliore (University of Hawaii) and colleagues from the universities of Hawaii, California, and Washington, and the Lawrence Berkeley National Laboratory have focused attention on a tiny chondrule fragment from one of the Wild 2 particles. Using petrology, oxygen isotopes, and aluminum-magnesium isotopic measurements, they determined this chondrule formed relatively late (as chondrules go) in the inner solar nebula and moved out to the comet-forming region before Jupiter could have blocked its way. The timing implies Jupiter formed more than three million years after the formation of the first solids in our Solar System.

Reference:

- Ogliore, R. C., Huss, G. R., Nagashima, K., Butterworth, A. L., Gainsforth, Z., Stodolna, J., Westphal, A. J., Jowsiak, D., and Tyliszczak, T. (2012) Incorporation of a Late-forming Chondrule into Comet Wild 2, *The Astrophysical Journal Letters,* v. 745:L19-L23, doi:10.1088/2041-8205/745/2/L19.

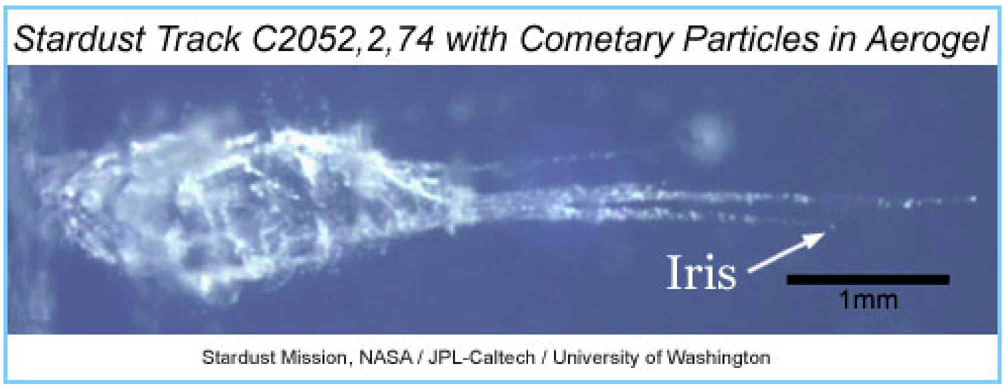
Hot-Cold Comet Oxymoron

Any comet fact sheet will tell you that these icy-dusty bodies, with dust and **plasma** tails, formed in the cold, outer regions of our Solar System from **presolar grains** and fragments of planetary building blocks. Comets travel on elliptical orbits around the Sun and those with orbital paths that reach near Jupiter are called Jupiter-family comets. After NASA's Stardust mission encountered one of these comets, named 81P/Wild 2, and brought samples to Earth, whole new extraordinary facts about comets began to be revealed (see **PSRD** article: **Wee Rocky Droplets in Comet Dust**). One phenomenal discovery in the Wild 2 particles is the predominance of rocky materials formed at high temperatures. What could be more contradictory than high-temperature objects from the innermost region of the Solar System–such as fragments of **chondrules** and calcium-aluminum-rich inclusions (**CAIs**)– inside an icy comet? Comets formed in the frigid Kuiper belt out beyond Neptune, but they are composed of low-temperature and high-temperature materials that must have formed in completely different environments. The high-temperature objects in the cometary particles are nearly irrefutable evidence, says Stardust mission Principal Investigator Donald Brownlee (University of Washington, Seattle), that materials from the inner solar system were transported outward to the comet-forming region in what he calls the "Grand Radial Express."

Out of ~200 Wild 2 particles and fragments in the Stardust aerogel that Ogliore and colleagues examined, they chose one called "Iris" for extraction and further analysis. It appeared to resemble a chondrule and has an interesting assemblage of olivine grains as well as chromium-, nickel-, and aluminum-rich phases. This cometary particle, a mere 23x10x15µm in size, was bound for **petrologic** and **isotopic** analyses that would help Ogliore and collaborators explain its history of formation, routing, and accretion into Wild 2.

A Chondrule in Comet Wild 2

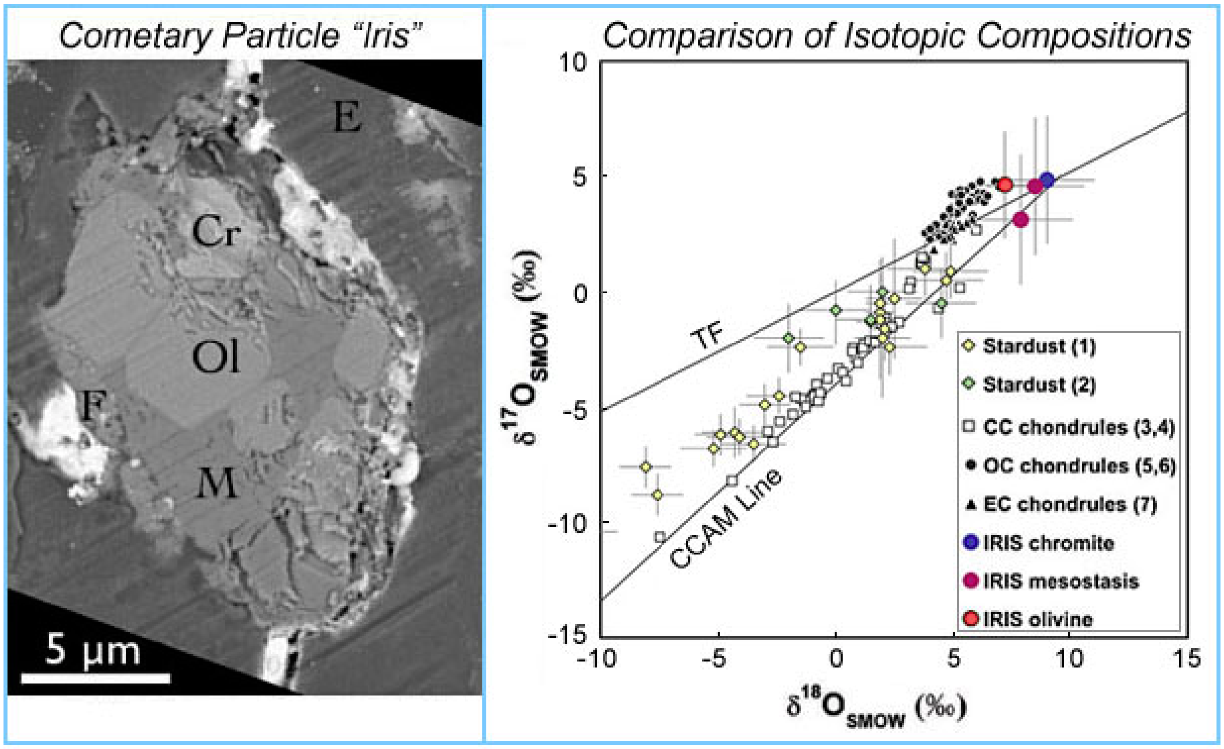
Ogliore and colleagues extracted the cometary particle Iris from a track in a wedge of aerogel (see image below). Iris has a complex assemblage of grains with at least nine distinct crystals including iron-rich **olivine**, **spinel**, and **plagioclase** surrounded by silica-rich glass. Olivine (iron-magnesian silicate) and spinel (iron-magnesian-chromium oxide) exchange iron and magnesium. The ratio of iron to magnesium is not the same in the two minerals and it correlates with temperature. Ogliore and coworkers applied the olivine-spinel thermometer and determined that Iris formed at greater than 1100 ^{o}C and cooled rapidly, perhaps in only a few hours. These results, along with chemical and textural details, led the researchers to conclude that Iris strongly resembles the type II chondrules seen in **chondritic** meteorites. (Iris doesn't have the typical spherical shape of a chondrule, which may have something to do with its hasty collision into the aerogel collector at 6.1 kilometers/second!)



Stardust Track C2052,2,74 is 6 millimetes long and contains three terminal particles and other fragments of comet Wild 2. Ogliore and coauthors made measurements on a particle identified as Iris (see arrow). Direction of particle movement was from left to right. The blue background is the aerogel collection material. The bulbous entry site and particle tracks are indicative of the fragmentation, rapid deceleration, and heating that occurred when the comet particle collided with the aerogel.

The research team measured three oxygen isotopes in Iris by secondary ion mass spectrometry (see **PSRD** article: **Ion Microprobe**). Cosmochemists traditionally use oxygen isotopes to classify chondritic meteorites and measure the $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios in terms of deviations (delta ^{18}O and delta ^{17}O) in parts per thousand from a standard, which is usually the Earth value of Standard Mean Ocean Water (**SMOW**). These measurements on Iris help to compare it with terrestrial materials and other chondritic objects. Ogliore and colleagues found the olivine, chromite, and glassy phase (called the mesostasis) in Iris have oxygen isotopic compositions indistinguishable from terrestrial oxygen (see colored-circle Iris data points in relation to the TF line in the graph below). Whereas the meteorite data (black and white points) and other chondrule-like

Stardust particles (diamond points) define a line with much steeper slope than the TF line, which is consistent with loss or addition of ^{16}O. The higher values of $^{18}O/^{16}O$ and $^{17}O/^{16}O$ in Iris may indicate processing due to interaction with water or evaporation. Ogliore and colleagues suggest the oxygen isotopic comopositions in Iris indicate its formation in a relatively evolved oxygen isotopic reservoir in the inner solar nebula.

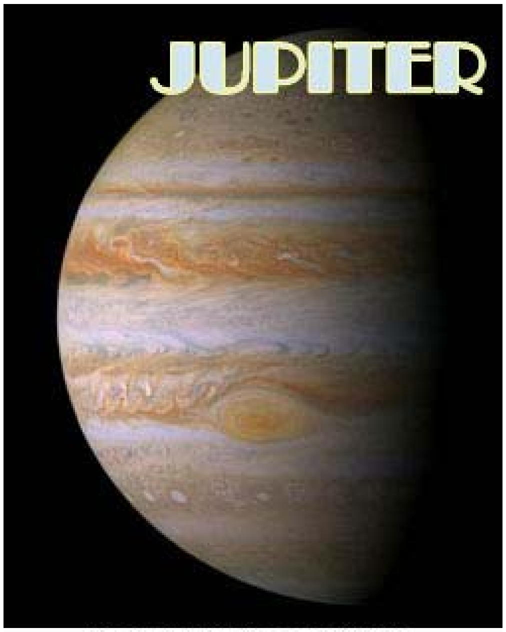


(From Ogliore *et al.*, 2012, *Astrophysical Journal*, 745:L19, Fig.1, Fig. 2.)

[Left] Backscatter electron image of cometary particle "Iris." Cr:chromite, Ol:olivine, M:mesostasis, F:fusion crust, and E:epoxy+aerogel. **[Right]** Graph showing the oxygen isotopic compositions of phases in the chondrule fragment Iris compared with previous oxygen isotope measurements of chondrule-like Stardust particles. The delta nomenclature simply means $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios standardized to standard mean ocean water (SMOW), and plotted as deviations from that value in parts per thousand. The line labeled TF is the terrestrial fractionation line, where samples from Earth plot. The line labeled CCAM is the carbonaceous chondrite anhydrous mineral line, designating where chondrules and other materials in carbonaceous chondrites plot. The data points for Iris (colored circles) show oxygen isotopic compositions indistinguishable from samples from Earth, which plot higher than most chondrules in meteorites and other chondrule-like objects in the collection of Stardust mission samples.

Ogliore and colleagues also measured three isotopes of magnesium (^{24}Mg, ^{25}Mg, ^{26}Mg), which are the decay products of the short-lived radioactive isotope ^{26}Al, and elemental aluminum ^{27}Al in Iris in order to bracket its formation age. Aluminum-26 (^{26}Al), with a 730,000-year half-life, is an excellent chronometer that can date events back to the beginning of our Solar System. The initial $^{26}Al/^{27}Al$ ratio appears to have been 5 x 10^{-5}, as determined from the ratio in the oldest components in chondritic meteorites, the calcium-aluminum-rich inclusions (CAIs). Ogliore and team found no evidence of extinct ^{26}Al in Iris, with $(^{26}Al/^{27}Al)_0$ less than 3 x 10^{-6}. Assuming homogenous distribution of ^{26}Al in at least the inner solar nebula, they suggest Iris formed at least three million years after CAIs —relatively late compared to most chondrules in meteorites, which other research suggests was 1–3 million years after CAIs.

This Chondrule's Outward Migration–What's Jupiter Got to Do With It?



Cassini Orbiter image PIA04866
NASA/JPL/Space Science Institute

Iris does not appear to be unique in the Stardust collection of cometary particles. In fact, high-temperature objects (chondrules and CAIs) are not rare in the Wild 2 particles, and they provide solid support of the idea of grand migration of materials from the hot, inner regions of the solar nebula to the cold, outer comet-forming regions. If Iris formed in the inner nebula, then it must have moved out to the Kuiper Belt (35–50 AU) where it was incorporated into comet Wild 2 at least three million years after the first solids (CAIs).

Interestingly, researchers posit that the growing embryo of Jupiter would have accreted material efficiently, thus opening a gap in the solar nebula. This gap would have posed a barrier to the outward migration of any material formed nearer the Sun than Jupiter's orbit, such as the Iris particle. The careful work by Ogliore and colleagues on this tiny cometary particle thus constrains the formation of Jupiter to be more than three million years after CAIs.

Additional Resources

Links open in a new window.

- Ogliore, R. C., Huss, G. R., Nagashima, K., Butterworth, A. L., Gainsforth, Z., Stodolna, J., Westphal, A. J., Jowsiak, D., and Tyliszczak, T. (2012) Incorporation of a Late-forming Chondrule into Comet Wild 2, *The Astrophysical Journal Letters,* v. 745:L19-L23, doi:10.1088/2041-8205/745/2/L19.
- Taylor, G. J. and Martel, L. M. V. (December 2008) Wee Rocky Droplets in Comet Dust. *Planetary Science Research Discoveries,* **http://www.psrd.hawaii.edu/Dec08/cometDust.html.**
- Taylor, G. J. (June 2011) A Traveling CAI. *Planetary Science Research Discoveries,* **http://www.psrd.hawaii.edu/June11/traveling_CAI.html.**

2012
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