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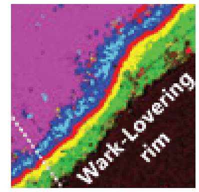
PSRD Discoveries



Headline Article
June 22, 2011

A Traveling CAI

--- Oxygen isotopes show that a calcium-aluminum-rich inclusion wandered throughout the inner Solar System before being incorporated into an asteroid.

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Calcium-aluminum-rich inclusions (**CAIs**) are the oldest solids to form in the Solar System. They occur in every type of **chondrite**, but are particularly abundant and well studied in the Allende carbonaceous chondrite. Justin Simon (University of California, Berkeley, but now at the Johnson Space Center) and colleagues at Berkeley, Lawrence Livermore National Laboratory, and the University of Chicago analyzed the oxygen **isotopic** composition of a CAI (designated A37) and its rim, using a nanoSIMS to obtain micrometer spatial resolution. They found that the abundances of oxygen isotopes varied: It is high in oxygen-16 in the center of the inclusion, low near the rim, and then high again in the outer rim.

Cosmochemists have concluded that CAIs formed close to the Sun (inside the orbit of Mercury, though Mercury was not present at the time), where oxygen-16 was highest. The decrease near the rim of the inclusion A37 indicates that the CAI must have traveled to a part of the dusty early Solar System where oxygen-16 was relatively less abundant, which is further from the Sun, perhaps around the asteroid belt. The increase in oxygen-16 in the rim indicates that the inclusion again moved to a region rich in oxygen-16, probably back to the region near the Sun, and then traveled back to where asteroids formed so it could be incorporated into the parent body of the Allende meteorite. This wandering is consistent with other observations that suggest transport of materials from the inner to the outer **solar nebula**, but this is the first documentation of small objects migrating back in towards the Sun.

Reference:

- Simon, Justin I., Ian D. Hutcheon, Steven B. Simon, Jennifer E. P. Matzel, Erick C. Ramon, Peter K. Weber, Lawrence Grossman, and Donald J. DePaolo (2011) Oxygen Isotope Variations at the Margin of a CAI Records Circulation Within the Solar Nebula. *Science,* v. 331, p. 1175-1178.
- **PSRDpresents:** A Traveling CAI --**Short Slide Summary** (with accompanying notes).

CAIs and Their Rims

CAIs are composed of highly **refractory** elements, including calcium, aluminum, titanium, and magnesium, and minerals composed of them; see the table below.

MINERAL	FORMULA	MINERAL	FORMULA
melilite	$Ca_2Al[AlSiO_7]$ and $Ca_2Mg[Si_2O_7]$ mixture	anorthite	$CaAl_2Si_2O_8$
spinel	$MgAl_2O_4$	perovskite	$CaTiO_3$
hibonite	$CaAl_{12}O_{19}$	Ca-rich pyroxene	$CaMgSi_2O_6$
forsterite	Mg_2SiO_4		

The CAI composition represents the first few percent of the solids that condense from a gas with the composition of the Sun, making CAIs the first solids to form in the Solar System. Their antiquity is proven by lead isotopic analyses (see PSRD article: **Dating The Earliest Solids in our Solar System**), and by high concentrations of the short-lived isotope ^{26}Al that is shown to be present by an excess in ^{26}Mg, to which it decays with a half life of only 700,000 years.

Concentric rims of somewhat less refractory materials often surround these old objects. The rims are called "**Wark-Lovering rims**" in honor of the Australian cosmochemists who first described them, David Wark and John Lovering. The rims, about 50 micrometers thick, typically consist of three concentric layers. From the border with the CAI and moving outwards, these are:

- Spinel with perovskite inclusions
- Melilite, often altered by aqueous fluids on meteorite parent asteroids to minerals such as sodalite
- Calcium-rich pyroxene

These three ubiquitous layers may be accompanied by other layers, such as an outer forsterite one or hibonite intergrown with the spinel layer. The rim sequence has been explored through thermodynamic calculations reported by none other than Justin Simon and others in a paper in 2005. The rim mineralogy is consistent with placing the melilite-rich CAI interior at high temperatures (almost 1700 **Kelvin**) in a gas rich in magnesium, silicon oxide, and oxygen. By moving through a gas at different temperatures, the entire rim mineral sequence can be formed, beginning with a melilite-rich CAI. Although the Wark-Lovering rims form after the CAI they cover, they still formed early in the history of the solar nebula, as demonstrated by the presence of the same amount of excess ^{26}Al as the CAIs.

Wark-Lovering Rim on a CAI in Meteorite NWA 4502

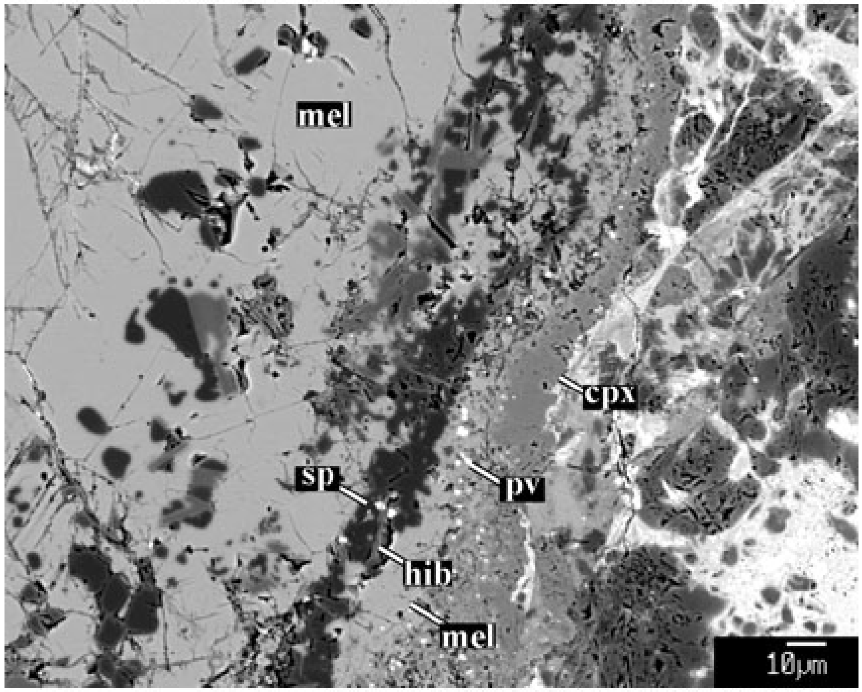


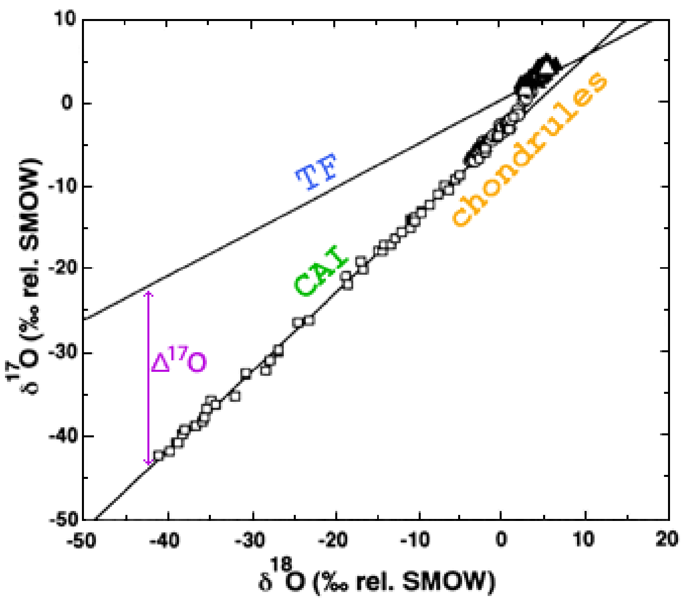
Image courtesy of Alexander Krot, University of Hawaii.

Back-scattered electron image of a Wark-Lovering rim surrounding a calcium-aluminum-rich inclusion (CAI) in the meteorite NWA 4502. Interior of the CAI (left half of the image) consists mostly of melilite (mel). The rim is a bit ragged, but is clearly marked by a region of spinel (sp) with hibonite (hib), melilite with perovskite (pv), and high-calcium pyroxene (cpx).

Oxygen Isotopes in Solar System Materials

The oxygen that makes up half of every rock and 21% of Earth's atmosphere is composed of three isotopes with atomic weights of 16, 17, and 18. ^{16}O is the most abundant (99.76% of all the oxygen), followed by ^{18}O, with ^{17}O bringing up the rear (only about 4 ten-thousandths the abundance of ^{16}O). In spite of ^{16}O being so abundant compared to the others, the set of three isotopes provides important information about the source of the raw materials to the Solar System and about processes operating in the solar nebula. The solar nebula, also called the protoplanetary disk, is the immense rotating cloud of gas and dust in which the Sun, planets, asteroids, comets, and other objects in the Solar System formed.

One informative way to plot oxygen isotopic data is to use all three isotopes by plotting the $^{17}O/^{16}O$ ratio against the $^{18}O/^{16}O$ ratio, as shown in the diagram below. In general, rocks in and on a given planet fall along a well-defined line with a slope of about ½; the line for terrestrial rocks is labeled "TF" in the graphs below. A remarkable discovery made more than three decades ago by Robert Clayton (University of Chicago) and coworkers was that primitive materials in chondrites plot along a line that suggests addition or subtraction of ^{16}O. Cosmochemists have concluded that the nebula had two distinct reservoirs of oxygen, one rich in ^{16}O (lower along the "CAI" line in the diagram below) and one somewhat depleted in ^{16}O. Justin Simon and his colleagues do not delve into the origin of these two reservoirs. Instead, they use oxygen isotopic variations throughout the Solar System as a monitor of the travels taken by the inclusion they studied, designated A37. For a discussion of the source of the two oxygen reservoirs, see PSRD article: **New View of Gas and Dust in the Solar Nebula**.



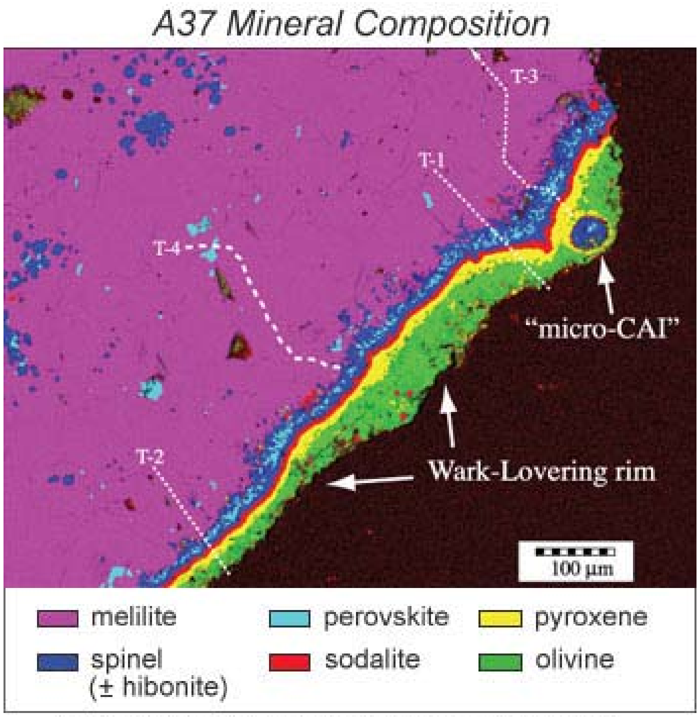
(From Clayton, R., 1993, Oxygen Isotopes in Meteorites, *Annu. Rev. Earth Planet. Sci.*, v.21, p. 123.)

Plot showing the $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios in chondrules and CAIs in meteorites in parts per thousand. Data have been standardized to standard mean ocean water (SMOW) and plotted as deviations from that value. The meteorite components define a line with much steeper slope than the fractionation line (TF) line, which is consistent with loss or addition of ^{16}O. Samples from the Moon plot on the TF line and meteorites from Mars and differentiated (melted) asteroids plot close to it. A shorthand way to show the deviation from the TF line is to plot the vertical displacement of any point from it, as indicated graphically in purple. This parameter ($\Delta^{17}O$) is called "big delta O-17" by cosmochemists. Justin Simon and colleagues present their oxygen isotopic data in terms of big delta O-17.

An important feature of oxygen isotopic variations in the Solar System is that there appears to be a systematic variation with distance from the Sun. CAIs formed closest to the Sun, where it was hottest (thus accounting for their refractory nature) have the most ^{16}O (lowest value of $\Delta^{17}O$). The iron-magnesium chondrules that occur in abundance in chondrites formed further out in the nebula and have the least ^{16}O (highest $\Delta^{17}O$), similar to the oxygen isotopic composition of planets. The fascinating feature of A37 is that it seems to have oxygen representative of both ^{16}O-rich and ^{16}O-poor environments. (The $\Delta^{17}O$ nomenclature, for the data from Simon and colleagues, is a bit confusing in that the large values are larger negative numbers than the small values, so when we say $\Delta^{17}O$ becomes larger, it means less negative, even though the numerical value of the negative number decreases. You have to know your signs in cosmochemistry.)

CAI A37 and its Oxygen Isotopes

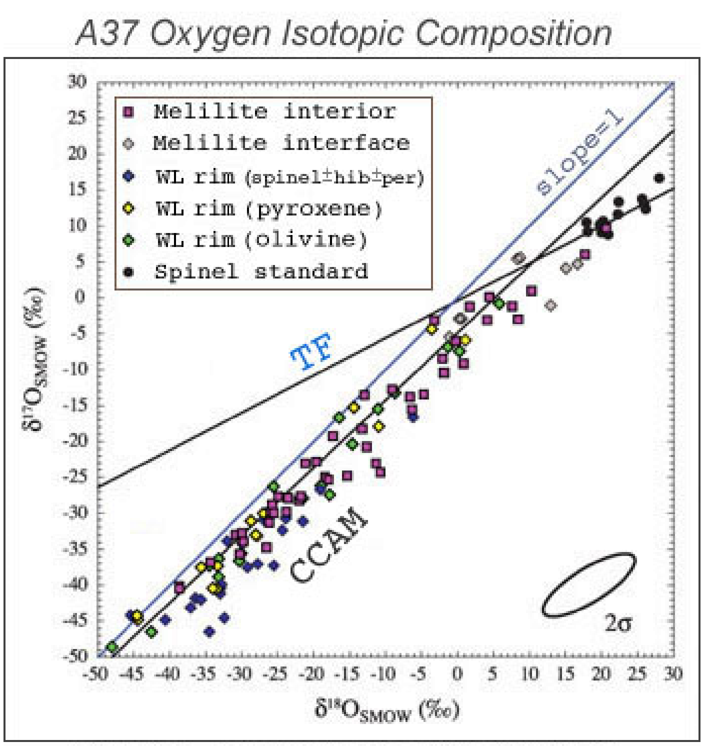
CAIs tend to be studied so intensely that they are usually given a name. In this case, A37, a 4 x 7-millimeter refractory inclusion in the Allende chondrite. The inclusion has a distinct Wark-Lovering rim. Simon and coworkers characterized the mineralogy of the CAI and its rim, and then used a nanoSIMS to measure the oxygen isotopic composition of different portions. (SIMS stands for secondary ion mass spectrometry. For more information, see PSRD article: **Ion Microprobe**.) Such a detailed study had not been done before because conventional SIMS has lower spatial resolution ("only" 10 micrometers). The nanoSIMS allows oxygen isotopic measurements at smaller scales, down to a micrometer, or even less.



(From Simon, *etal.* (2011) *Science*, v. 331, p.1175-1178.)

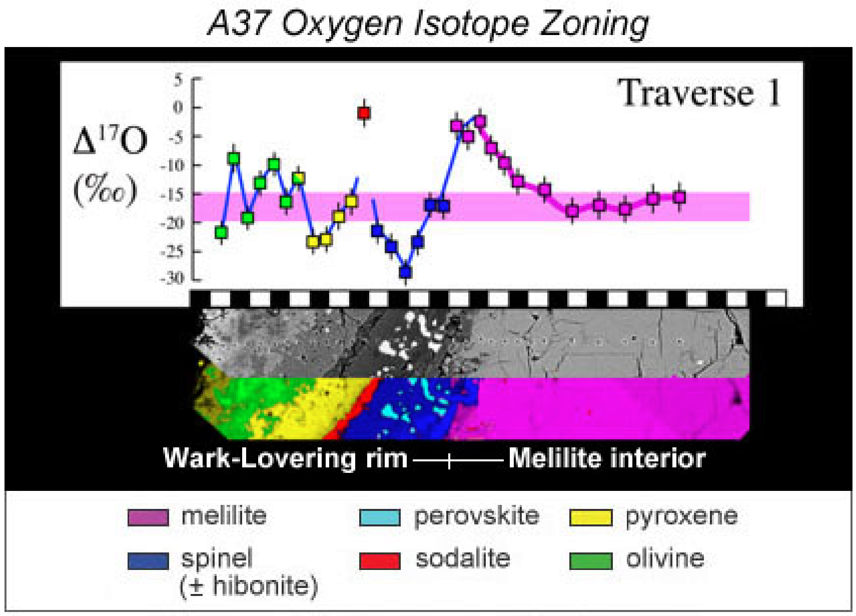
Map of the minerals in inclusion A37 made from elemental X-ray maps. Note the distinctive Wark-Lovering rim and its layers: blue represents the spinel and perovskite layer, yellow the pyroxene-rich layer, and green the layer dominated by forsterite (magnesium-rich olivine). The sodalite (red spots) formed by alteration of the rim materials. Melilite makes up most of the CAI. The labeled dashed lines show where nanoSIMS or electron microprobe measurement traverses were made.

Oxygen isotopic compositions in the A37 CAI and its rim cover a vast range on the classic oxygen diagram (see below). The interior of the CAI is enriched in ^{16}O (low $\Delta^{17}O$), but ^{16}O decreases ($\Delta^{17}O$ increases) in the melilite near the rim, as shown clearly in the traverses (see traverse diagram below), approaching the value for planets. The rim itself is again rich in ^{16}O (low $\Delta^{17}O$).



(From Simon, *etal.* (2011) *Science*, v. 331, p.1175-1178.)

Oxygen isotopic composition of CAI A37 and its rim. The data fall along the line designated CCAM (carbonaceous chondrite anhydrous mineral, basically the same as the "CAI" line in the oxygen diagram above), where data from numerous carbonaceous chondrites plot. Symbols represent different minerals and regions of the inclusions and its rim. Black circles are terrestrial spinel standards used for calibration.



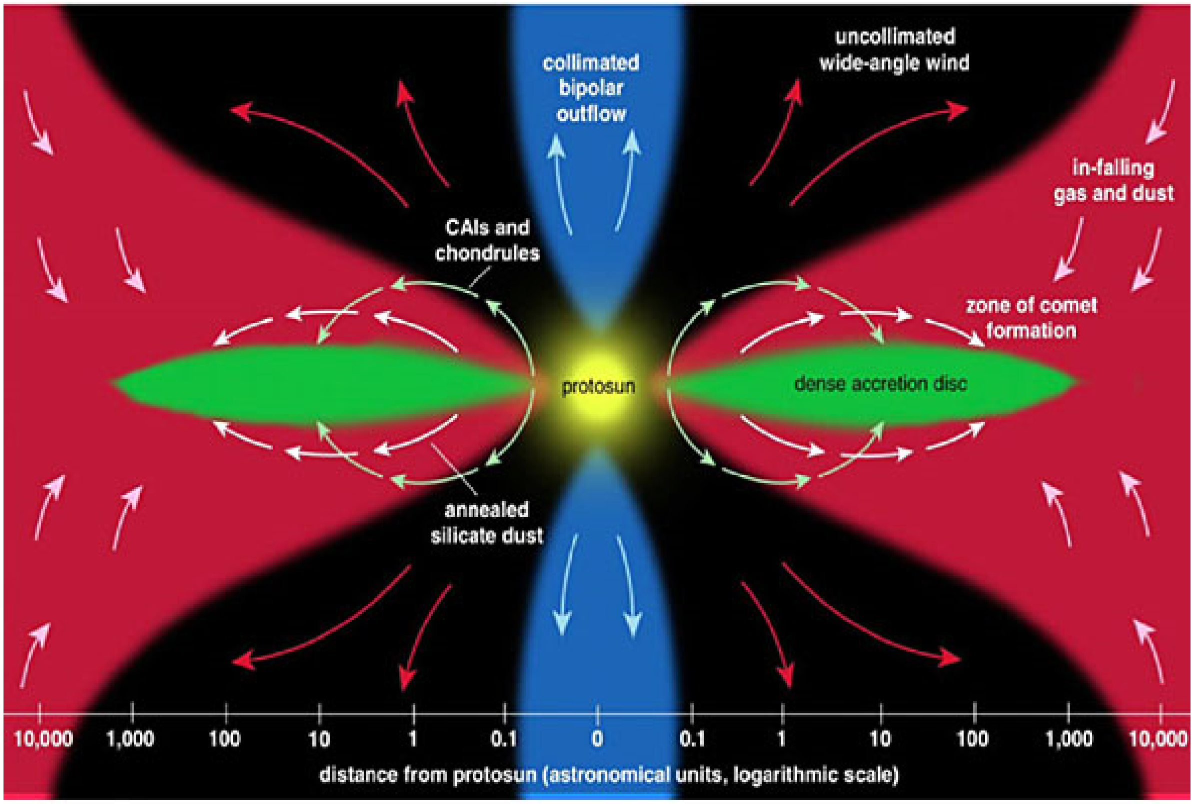
(From Simon, *etal.* (2011) *Science*, v. 331, p.1175-1178.)

One of the nanoSIMS traverses across A37 and the Wark-Lovering rim. The tiny nanoSIMS spots can be seen in the gray image, which is a backscattered electron image taken with a scanning electron microscope. Mineral distributions (color map) of the same region were obtained from elemental X-ray maps. The black and white scale bar has 10-micrometer increments. The traverse shows low $\Delta^{17}O$ in the CAI's melilite interior. $\Delta^{17}O$ increases (approaching zero) towards the rim, then plummets to extremely low values, before oscillating around the value typical of the CAI interior. Simon and colleagues suggest that this variation in oxygen isotopic composition indicates formation of the CAI in an ^{16}O-rich (low $\Delta^{17}O$) environment close to the Sun, followed by immersion in a gas low in ^{16}O further from the Sun. The inclusion and its rim were added in an environment that was again rich in ^{16}O, implying migration back in towards the Sun.

A37's Journey

The inclusion, A37, formed relatively close to the Sun where the temperature of the dusty disk was hot and ^{16}O was highest. The high temperature led to condensation of refractory elements and minerals formed from them. The inclusion, not yet decorated with its Wark-Lovering rim, traveled further from the Sun, to a region where ^{16}O was lower. The ^{16}O-depleted gas reacted with the outer part of A37, producing the region with a gradual increase in $\Delta^{17}O$ in the inclusion (see traverse diagram above). Diffusion calculations by Simon and coworkers indicate that A37 was exposed to the ^{16}O-depleted gas for about 500 years if the temperature was 1600 Kelvin, or possibly as long as 500,000 years if the temperature was only 1200 Kelvin.

The Wark-Lovering rim may have begun to form in the region where ^{16}O was low (like that in the planets), but most seems to have formed when A37 had traveled back to an environment richer in ^{16}O. Considering the variations in $\Delta^{17}O$ in the Wark-Lovering rim and distinct increase in the margin of the melilite interior, Simon and colleagues conclude that the inclusion experienced at least three nebular oxygen isotopic environments: Formation of the CAI, exchange with a ^{16}O-poor gas, and formation of the rim in a largely ^{16}O-rich environment. The data indicate this CAI traveled to and from distinctive, oxygen isotopic reservoirs in the solar nebula.



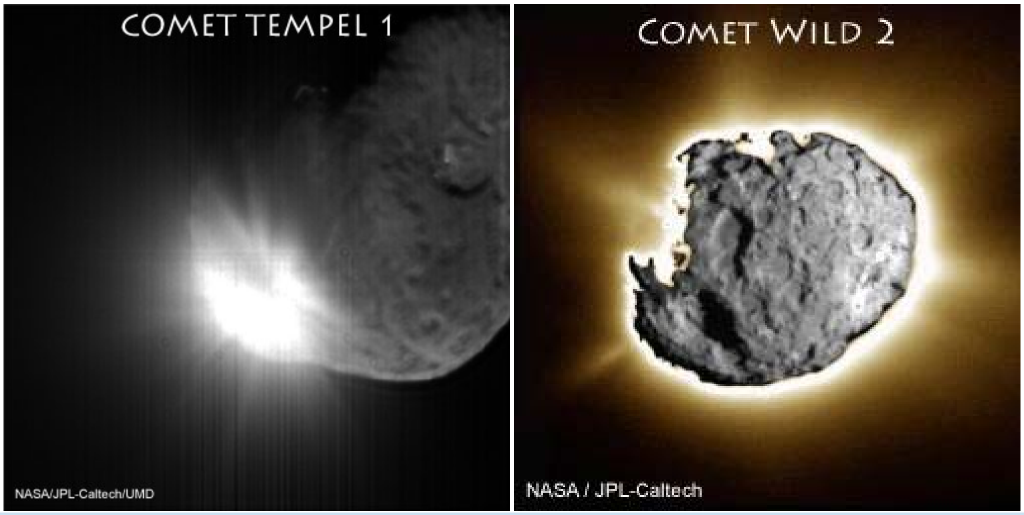
(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

A schematic diagram of the solar nebula as it was still accreting dust to it. Planets have not yet formed. Materials heated near the Sun circulate to the outer Solar System to the cold regions where comets formed. The work by Justin Simon suggests that materials also traveled back in towards the Sun, or at least out of the mid-plane of the disk.

The Dynamic Solar Nebula

The solar nebula is more of a process than a place, and it was a dynamic process, as illustrated by Justin Simon's traveling CAI. Cosmochemists already knew that materials transferred from the inner to the outer parts of the Solar System (see diagram above), as evidenced by the presence of crystalline silicates in comets. Olivine and other silicates have been observed in interplanetary dust particles (many from comets), in samples returned from comet Wild 2 by the Stardust mission, and in the impact plume generated when the Deep Impact mission smashed a 500-kilogram chunk of copper into comet Tempel-1. The inclusion A37, however, suggests migration of materials further from the Sun and then back again, showing even more dynamic behavior of the gas and dust cloud in which the planets formed.

A37 is just one inclusion, of course. Cosmochemists will be examining more of them, using the latest analytical devices, such as the nanoSIMS. The CAI road trip is just beginning to be understood.



[Left] Measurements of the material ejected from comet Tempel 1 in 2005, when a massive projectile from the Deep Impact mission whacked into it at 10 kilometers per second, showed that crystalline silicates were present--not just noncrystalline silicates and ice. [Right] Composite image of the close approach made by the Stardust spacecraft to comet Wild 2 during the 2004 flyby. Data from the returned samples indicate the presence of refractory silicates, showing transfer of materials from inner, high-temperature regions of the solar nebula to its outer reaches where comets formed. (Click images for more information.)

Additional Resources

Links open in a new window.

- **PSRDpresents:** A Traveling CAI --**Short Slide Summary** (with accompanying notes).

- Krot, A. N. (September, 2002) Dating the Earliest Solids in our Solar System, *Planetary Science Research Discoveries*, **http://www.psrd.hawaii.edu/Sept02/isotopicAges.html**.
- Martel, L. M. V. and Taylor, G. J. (February, 2006) Ion Microprobe, *Planetary Science Research Discoveries*, **http://www.psrd.hawaii.edu/Feb06/PSRD-ion_microprobe.html**
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- Wark, D. A. and Lovering, J. F. (1977) Marker Events in the Early Evolution of the Solar System: Evidence from Rims on Ca-Al-Rich Inclusions in Carbonaceous Chondrite Meteorites. *Proc. Lunar Sci. Conf. 8th*, 95-1 12.