Headline Article
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New View of Gas and Dust in the Solar Nebula

--- The current view holds that gas and dust in the solar nebula began with the same oxygen isotopic composition, then changed by processes in the nebula. A new view suggests that dust and gas had vastly different mixtures of oxygen isotopes in the first place.

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The recognizable components in meteorites differ in their relative abundances of the three oxygen isotopes (^{16}O, ^{17}O, and ^{18}O). In particular, the amount of ^{16}O varies from being like that of the Earth to substantially enriched compared to the other two isotopes. The current explanation for this interesting range in isotopic composition is that dust and gas in the solar nebula (the cloud of gas and dust surrounding the primitive Sun) began with the same ^{16}O-rich composition, but the solids evolved towards the terrestrial value. A new analysis of the problem by Alexander Krot (University of Hawai'i) and colleagues at the University of Hawai'i, the University of Chicago, Clemson University, and Lawrence Livermore National Laboratory leads to the bold assertion that primordial dust and gas differed in isotopic composition. The gas was rich in ^{16}O as previously thought (possibly slightly richer in ^{16}O than the measurements of the solar wind returned by the **Genesis Mission**), but that the dust had a composition close to the ^{16}O-depleted terrestrial average. In this new view, the dust had a different history than did the gas before being incorporated into the Solar System. Solids with compositions near the terrestrial line may have formed in regions of the solar nebula where dust had concentrated compared to the mean solar dust/gas ratio (1 : ~100). The idea has great implications for understanding the oxygen-isotope composition of the inner Solar System and the origin of materials in the molecular cloud from which the Solar System formed.

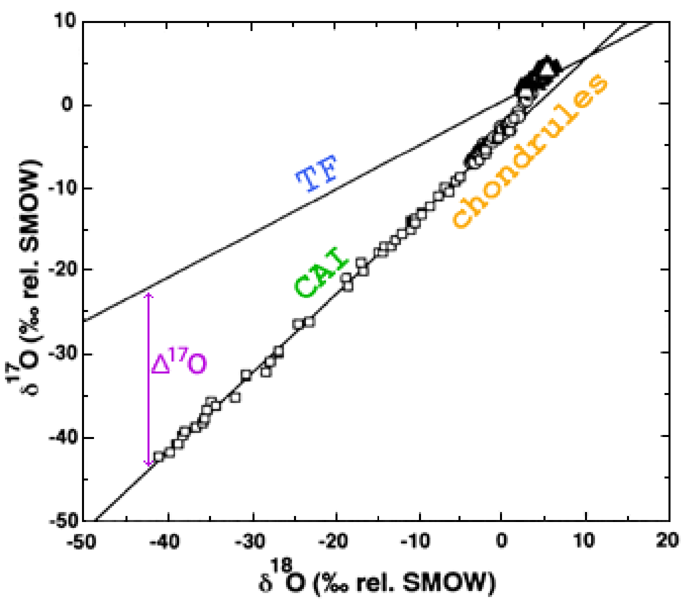
Reference:

- Krot, A. N., Nagashima, K., Ciesla, F. J., Meyer, B. S., Hutcheon, I. D., Davis, A. M., Huss, G. R., and Scott, E. R. D. (2010) Oxygen Isotopic Composition of the Sun and Mean Oxygen Isotopic Composition of the Protosolar Silicate Dust: Evidence from Refractory Inclusions. *The Astrophysical Journal,* v. 713, p. 1159-1166.
- **PSRDpresents:** New View of Gas and Dust in the Solar Nebula --**Short Slide Summary** (with accompanying notes).

Two Reservoirs of Oxygen Isotopes

The oxygen we breathe 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 exceedingly important information about how the Solar System formed and about geochemical processing on the planets.

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 striking 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.



(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 particles define a line with much steeper slope than the fractionation line (TF) line, which is consistent with loss or addition of ^{16}O. 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. We use it in subsequent diagrams.

The explanation for the difference between primitive materials and the terrestrial line is that the dust and gas that made up the primitive Solar System were both rich in ^{16}O, but that some process produced substantial amounts of dust depleted in it. Several imaginative ideas were invented by cosmochemists to explain the existence of two isotopically distinct reservoirs. One class of models depicts formation of the ^{16}O-poor reservoir (the one near the terrestrial fractionation line in the diagrams) by a chemical effect produced by irradiation of carbon monoxide (CO) by ultraviolet light. Observations of molecular clouds indicate that ultraviolet radiation inside the cloud can preferentially dissociate CO made with ^{17}O or ^{18}O. Ultraviolet light that can dissociate CO made with ^{16}O cannot penetrate beyond the surface of the cloud. The oxygen released from dissociated CO can combine with hydrogen to produce water ice that is rich in ^{17}O and ^{18}O. Evaporation of this ice in the inner Solar System creates a gas rich in water and depleted in ^{16}O. This dynamic process, called "self-shielding," can produce large variations in the proportions of ^{16}O relative to the other two isotopes. The theory predicts that the planets were made of material that contained excess water ice that was preferentially enriched in ^{17}O and ^{18}O, and that the Sun should have an oxygen isotopic composition like those meteoritic grains richest in ^{16}O in primitive materials in chondrite meteorites, such as calcium-aluminum-rich inclusions (**CAIs**).

Sasha Krot and his coauthors note that the self-shielding model explains the oxygen isotopic compositions of asteroids and the inner planets, but raise several warning flags. A key one is that self-shielding assumes that dust in the solar nebula started out rich in ^{16}O (large value of $\Delta^{17}O$), but no such samples of primitive dust have been found. Another problem is that self-shielding predicts that primitive materials should have some correlation of ^{16}O abundance and their ages (as measured by short-lived ^{26}Al decay), but except for CAIs being the oldest and richest in ^{16}O, there is no systematic variation in the age of other primitive objects such as chondrules and their oxygen isotopic compositions.

To reassess the problem, Krot and coworkers focused on trying to figure out the average $\Delta^{17}O$ of the dust in the solar nebula. To do so they used recently-measured values of the Sun's oxygen isotopic composition refractory inclusions, using a secondary ion mass spectrometer at the University of Hawai'i. Before looking at those new data, we'll look at measurements of oxygen isotopes in the Sun.

Measuring Oxygen Isotopes in the Sun

A primary goal of the Genesis mission was to determine the composition of the Sun by measuring the composition of the solar wind. It did so by traveling to a region of space where the gravitational pull of the Sun and Earth are balanced, a special location called the Lagrange 1 point. Located about 1.5 million kilometers from Earth, the spacecraft followed a looping path as it collected solar wind. The location is out of Earth's atmosphere, of course, but also far from its magnetic field, allowing an array of collectors to sample the solar wind.

Genesis carried several types of collectors. One was the Solar Wind Concentrator, which magnified the solar wind by a factor of about 20 by using grids held at high voltage. The high voltage caused 90% of the protons (hydrogen nuclei) to be deflected, thereby decreasing the background for the other elements and their isotopes. The solar wind ions slammed into high-purity collectors. Those for oxygen isotopic measurements were made of silicon carbide. The collection system is a triumph in instrument engineering and materials science.

Silicon Carbide Segment from the Genesis Mission

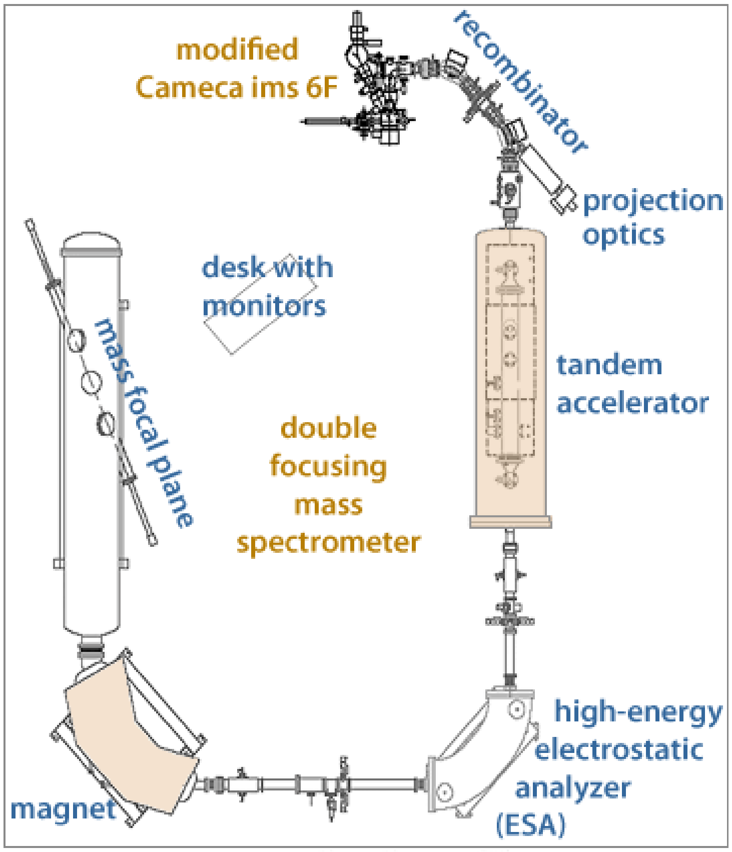
Portion of the high-purity SiC collector from the solar wind concentrator returned by the Genesis Mission. Samples are stored and handled in a special laboratory at NASA Johnson Space Center.

Even with ultra-pure material and concentration of the solar wind, it is still difficult to measure the small concentrations of oxygen collected during the mission. This is particularly true for the tiny amounts of ^{17}O and ^{18}O. To make the measurements, Kevin McKeegan and his colleagues at the University of California, Los Angeles and the University of Bristol, United Kingdom built a hybrid contraption composed of a secondary ion mass spectrometer (SIMS) and an accelerator mass spectrometer, which they dubbed the MegaSIMS. The SIMS front-end is a standard ion microprobe (specifically, a Cameca ims 6f), which sputters ions off a sample and sends them through the mass spectrometer system (see **PSRD** article, **Ion Microprobe**). The accelerator mass spectrometer part of the MegaSIMS accelerates the ions to extraordinary energies before sending them through the mass spectrometer and onto detectors. The high energy allows complete destruction of ions of OH made from ^{16}O, which have masses of 17, the same as ^{17}O. This allows an accurate measurement of ^{17}O by removing the troublesome interfering molecule.

UCLA MegaSIMS Developed for the Genesis Mission

The MegaSIMS at UCLA resembles the flight deck of the starship Enterprise.

UCLA MegaSIMS Schematic Diagram



MegaSIMS at UCLA

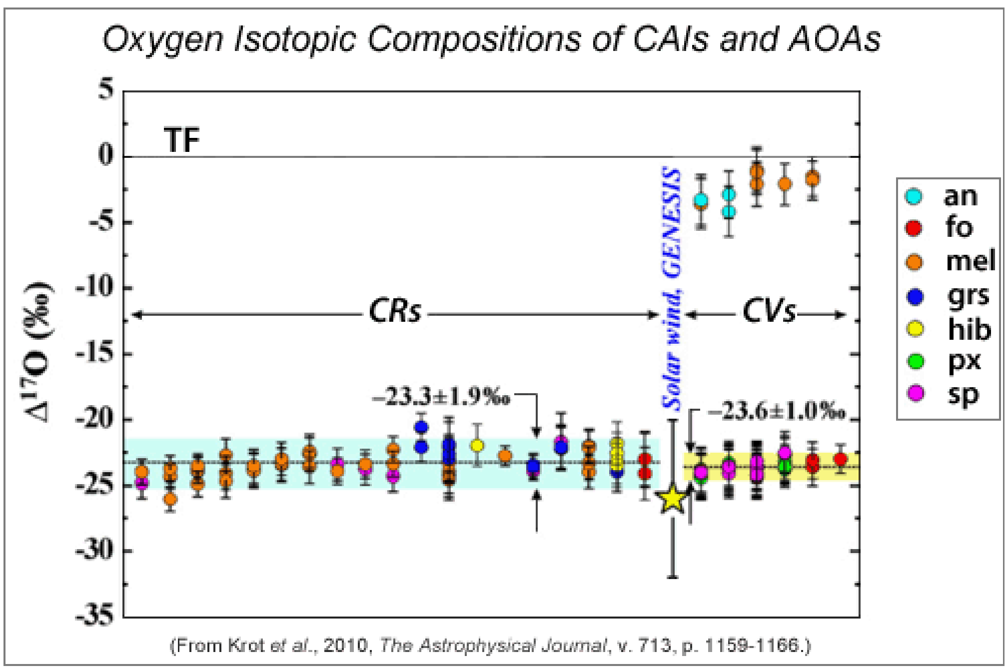
The MegaSIMS is a hybrid instrument consisting of a secondary ion mass spectrometer (Cameca ims 6f) front-end combined with an accelerator mass spectrometer, whose purpose is to eliminate molecular interferences via dissociation. See the labeled schematic diagram for names of parts shown in the photos.

Kevin McKeegan and his colleagues are still working on getting final values for the solar wind oxygen isotopic composition, but preliminary results give a value for $\Delta^{17}O$ of –26 ± 5.6 parts per thousand. That value is used in the diagrams that follow. It is similar to the most refractory materials in chondrites, the **CAIs**.

Oxygen Isotopes in Meteorites

Chondrites contain two refractory components, calcium-aluminum-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs). CAIs are the oldest solids to form in the Solar System and are composed of (not surprisingly) minerals that contain calcium, aluminum, and titanium. (See **PSRD** article, **Dating the Earliest Solids in our Solar System**.) Some CAIs have irregular shapes and porous textures, indicative of materials condensed from a gas. Others have igneous textures, indicative of remelting of previous condensates. AOAs have irregular shapes and tiny grain sizes (mineral grains are smaller than 20 micrometers). Some AOAs contain small CAIs inside them.

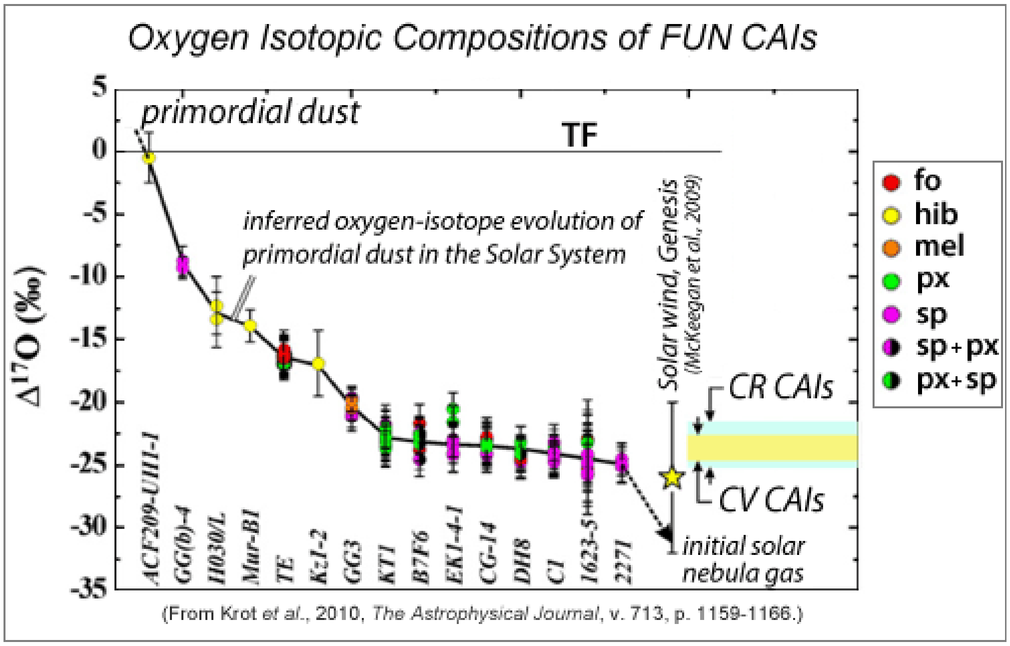
On the basis of detailed studies of CAIs and AOAs, theroretical calculations, and condensation, vaporization, and melting experiments, cosmochemists have concluded that two types formed by condensation in a gas of solar composition. The condensation happened in a region where the dust/gas ratio was solar (1 : ~100), so oxygen isotopic compositions in AOAs and CAIs ought to reflect the composition of the solar gas, hence of the Sun. Sasha Krot and his colleagues show that the big delta oxygen-17 for minerals in CAIs and AOAs (as measured by regular, non-megafied ion microprobes) cluster around –23 parts per thousand, not much different from the solar value measured by Kevin McKeegan's team on the Genesis samples.



Oxygen isotopic compositions of refractory inclusions (CAIs and AOAs) expressed as the deviation from the terrestrial fractional line (TF). Symbols are color-coded to identify the specific mineral measured. A small group of minerals that responded to metamorphism on the CV carbonaceous chondrite body have values close to the terrestrial line.

Krot and coworkers conclude that gas of solar composition and the Sun had a big delta O-17 of around –23 (plus or minus 1.9) parts per thousand. But what was the composition of the dust? Was it the same as the gas and the Sun, as the self-shielding model assumes, or different? Clues to answer those questions come from study of an unusual class of CAI, the F and FUN inclusions. (You have to like acronyms in cosmochemistry.) The F stands for fractionation, which means that the minerals in one inclusion string out along a line parallel to the terrestrial fraction line. UN stands for unidentified nuclear effects. FUN inclusions have large isotopic anomalies in many elements. The preservation of these anomalies suggests that the dusty precursors to FUN inclusions escaped complete evaporation in the solar nebula, so they retain a record of the oxygen isotopic composition of the primordial dust.

Results from published and new measurements show that, in contrast to most CAIs and AOAs, FUN CAIs show a large range in big delta O-17, from the terrestrial value all the way down to the solar value. Because they all show strong evidence for chemical processing (they lie along lines parallel to the terrestrial fractionation line on plots of $^{18}O/^{16}O$ and $^{17}O/^{16}O$), this range in oxygen isotopic composition indicates that the FUN inclusions or their precursor dust grains have exchanged oxygen with gas in the solar nebula. Sasha Krot and coauthors conclude that the range in big delta O-17 points to different extents of equilibration between ^{16}O-poor dust and ^{16}O-rich nebula gas. Chondrules and fine-grained matrix materials in chondrites, which lie not far from the terrestrial fractionation line, probably formed in regions of the nebula where dust was substantially concentrated (see **PSRD** article, **Tiny Molten Droplets, Dusty Clouds, and Planet Formation**). Those objects, including many asteroids and the terrestrial planets, may have formed in these regions, hence reflect the composition of the nebular dust, not the gas.



FUN refractory inclusions record a range in oxygen isotopic compositions, from values similar to the Earth (TF line) to those similar to the Sun. Sasha Krot and his colleagues suggest that this was caused by varying amounts of isotopic exchange between a gas rich in ^{16}O (large negative $\Delta^{17}O$) and dust with much less ^{16}O (about zero $\Delta^{17}O$, like the Earth).

Why Were the Dust and Gas Different?

If Sasha Krot and coauthors are right, the Solar System formed from a cloud in which gas and dust differed in the relative abundances of the three oxygen isotopes. What caused the difference? It might have been a natural product of galactic chemical evolution. Standard theory of element formation depicts ^{16}O being produced linearly with time, while the other two oxygen isotopes increase in abundance with the square of the time. This translates to ^{17}O / ^{16}O and ^{18}O / ^{16}O increasing steadily with time. Thus, if the dust in interstellar space is on average older than the gas, and the two do not exchange isotopes, then formation of the Solar System from that volume of the molecular cloud would result in the dust being more enriched in ^{16}O than is the gas, opposite to what is observed. On the other hand, if the molecular cloud was dominated by dust from highly active or exploding stars that added material shortly before the Solar System formed, then solar nebula dust would have been enriched in ^{17}O and ^{18}O, hence poorer in ^{16}O, as observed.

Team Krot suggest three tests of their hypothesis. One is that the least thermally processed dust in extraterrestrial samples, such as amorphous (noncrystalline) dust in the interplanetary dust collection and probably present in Kuiper Belt Objects ought to have oxygen that is poor in ^{16}O ($\Delta^{17}O$ much closer to the Earth value than to CAIs). Another test is that ^{16}O-rich crystalline objects should be very rare and related to CAIs and AOAs. A third test involves the oxygen isotopic composition of chondrules. These objects formed in dust-rich environments, so ought to reflect the ^{16}O-poor nature of the dust. Thus, ^{16}O-rich chondrules should be extremely rare (perhaps absent).

Meteorites, the Genesis Mission, astrophysical theory--this type of cosmochemical research is at the interface with astrophysics.

Additional Resources

Links open in a new window.

- **PSRDpresents:** New View of Gas and Dust in the Solar Nebula --**Short Slide Summary** (with accompanying notes).

- Krot, A. N., Nagashima, K., Ciesla, F. J., Meyer, B. S., Hutcheon, I. D., Davis, A. M., Huss, G. R., and Scott, E. R. D. (2010) Oxygen Isotopic Composition of the Sun and Mean Oxygen Isotopic Composition of the Protosolar Silicate Dust: Evidence from Refractory Inclusions. *The Astrophysical Journal,* v. 713, p. 1159-1166. [**NASA ADS entry**]
- Krot, A. N. (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. (2006) Ion Microprobe. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Feb06/PSRD-ion_microprobe.html**
- McKeegan, K. D. and nine others (2009) Oxygen Isotopes in a Genesis Concentrator Sample. *40th Lunar and Planetary Science Conference,* abstract #2494. [**pdf**]
- McKeegan, K. D. and nine others (2010) Genesis SiC Concentrator Sample Traverse: Confirmation of ^{16}O-depletion of terrestrial oxygen. *41st Lunar and Planetary Science Conference*, abstract #2589. [**pdf**]
- Taylor, G. J. (2008) Tiny Molten Droplets, Dusty Clouds, and Planet Formation. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Nov08/chondrule_sodium.html**