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Hot Idea

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Astronomical Society
of the Pacific Book



Cosmochemistry from Nanometers to Light-Years

--- Cosmochemists and astronomers test theories on the formation of stars and planets.

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A new book, *Chondrites and the Protoplanetary Disk*, reports the results of an exciting conference held on the island of Kaua'i in November 2005. The conference brought together an impressive interdisciplinary group of scientists seeking to understand our origins: Where did we come from? How did the stars and planets form? Did the planets around other stars form in the same way that ours did? The book summarizes new directions and new understanding in the chronology of the early Solar System, the important role of short-lived isotopes as heat sources to melt planetesimals well before planets formed, the origin of stars (including the Sun) in clusters, the extensive thermal processing of dust throughout the solar nebula, and why oxygen isotopes are not uniform in materials throughout the Solar System. Cosmochemistry and astronomy look at the same problems from different, complementary perspectives. Cosmochemists, astronomers, and astrophysicists work together to understand our origins.

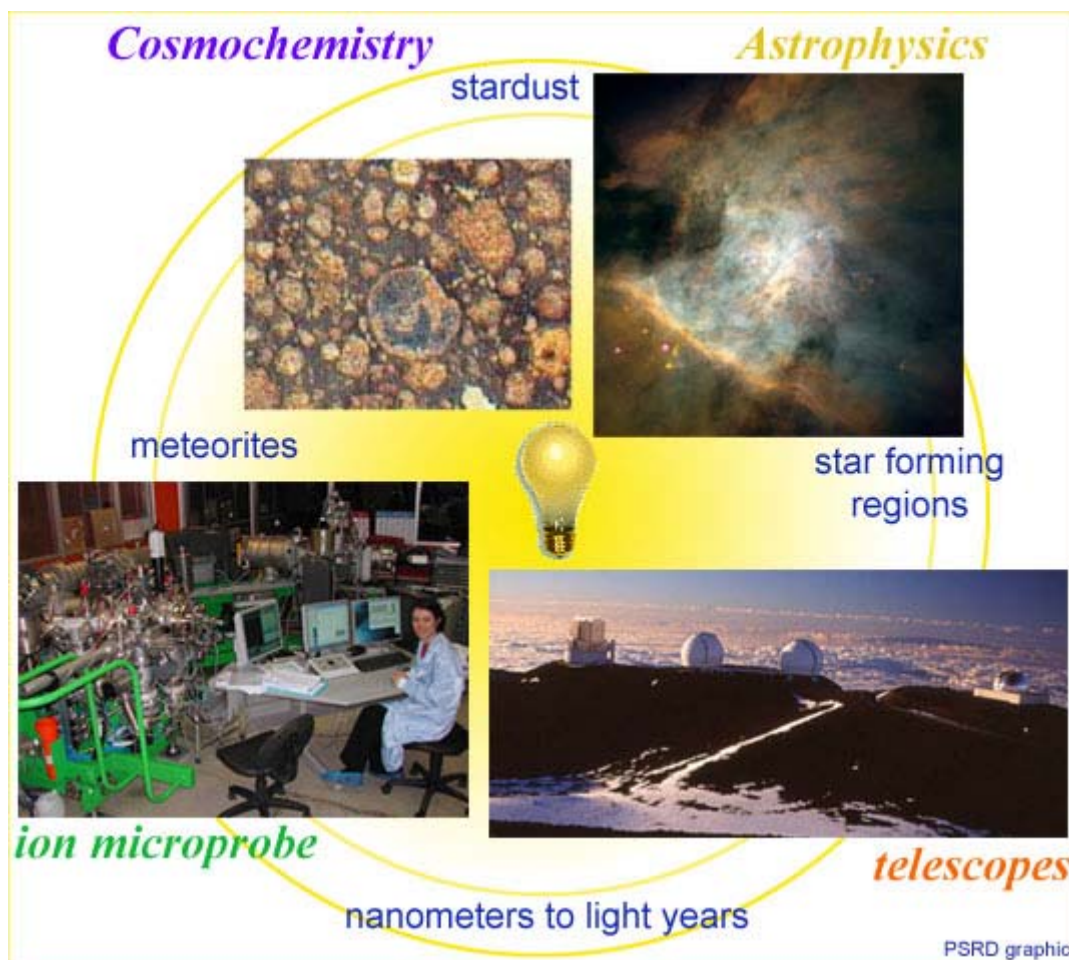
Reference:

- Krot, Alexander N., Edward R. D. Scott, and Bo Reipurth, Editors (2005) *Chondrites and the Protoplanetary Disk*, Astronomical Society of the Pacific Conference Series, vol. 341, 1029 pp.

Meshing Cosmochemistry and Astrophysics

Cosmochemistry has always been an interdisciplinary field, and cosmochemists have always paid attention to discoveries by astronomers and imaginative theories conjured up by astrophysicists. Nevertheless, cosmochemistry and astronomy never meshed seamlessly. That seems to be changing as observations at all scales become progressively better and new discoveries make scientists in one field take notice of those in the other. A prime example of this is the discoveries of planets and disks around other stars, which have sparked greater interest among astronomers about what cosmochemists have to say about the formation of our Solar System.

Cosmochemistry and astronomy address fundamental questions about human existence. Where did we come from? How did the stars and planets form? Did the planets around other stars form in the same way that ours did? How did life arise? Significant breakthroughs have occurred because of a combination of new laboratory instruments, dramatic improvements in telescopes, discoveries such as presolar grains in meteorites that have opened up entirely new fields of study, the creation of the whole new science of astrobiology, and dramatic space missions that determined the composition of a comet (the Deep Impact mission) and brought samples of a comet and of interstellar particles to Earth (the Stardust mission). All these new data have led to new hypotheses for star and planet formation. In turn, the new ideas lead to new tests. This is a vibrant field in which cosmochemists, astronomers, and astrophysicists search for our origins.



Interdisciplinary research lies at the heart of cosmochemistry. New laboratory instruments and telescopes giving us views from [nanometers](#) to [light-years](#) are igniting research among cosmochemists and astronomers to understand star and planet formation. Presolar grains hold the keys to testing astrophysical models of how elements formed. Analyses of oxygen isotopes and now-extinct radionuclides in primitive chondritic meteorites and observations of star-forming regions such as the Orion nebula are leading to major leaps forward in our understanding of fundamental processes of star and planet formation.

The *Conference on Chondrites and the Protoplanetary Disk* was dedicated to Dr. John A. Wood, who retired at the end of 2005 from the Harvard-Smithsonian Center for Astrophysics. Nobody did more to foster the links between cosmochemistry and astronomy than he did, and few approached the problem with such an expansive mind and imagination.

This article tries to briefly summarize the major insights in Chondrites and the Protoplanetary Disk by identifying five areas where major advances have been made recently.

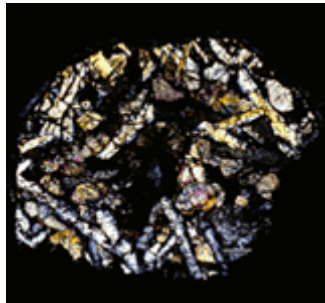
1. Chronology of the early solar system;
2. Solar system heat sources;
3. Formation of stars (including the Sun) in clusters;
4. Extensive thermal processing of dust throughout the solar nebula (the cloud of gas and dust surrounding the Sun from which the planets formed); and
5. Creation of anomalies in oxygen isotopic compositions by dissociation by ultra-violet radiation of carbon monoxide.

Readers will not find the details here. For that, read the book. It's only 1029 pages long, 232 pages shorter than my copy of *War and Peace*!

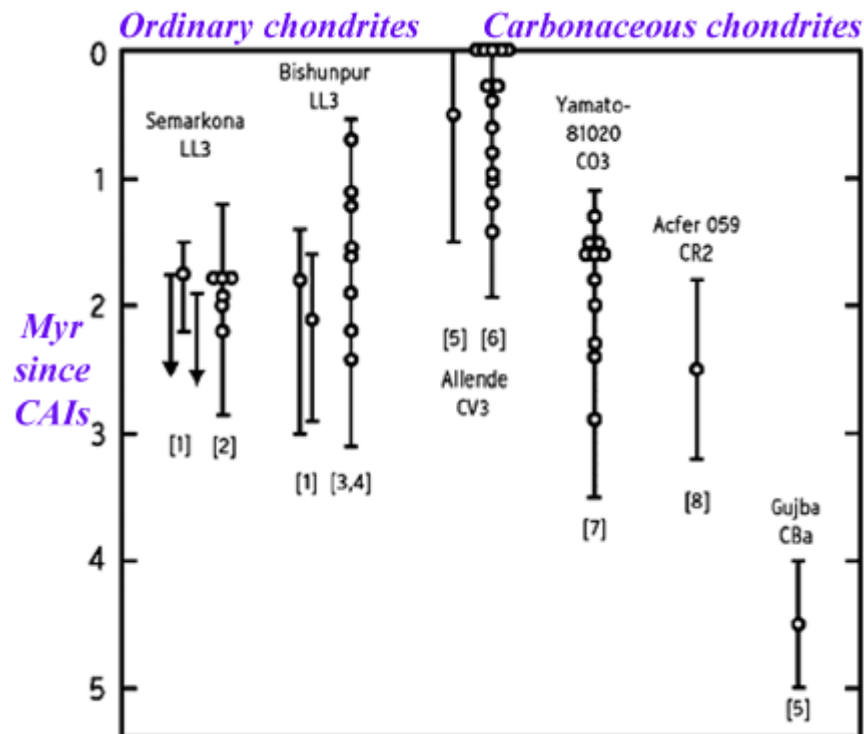
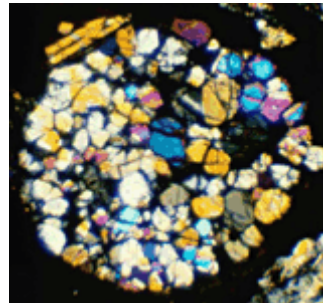
Chronology of the Early Solar System

Chondrites contain [chondrules](#) (millimeter sized silicate droplets) and calcium-aluminum-rich inclusions (CAIs), among other primitive materials that formed in the [solar nebula](#) before the planets formed. We have known for a long time that the CAIs were the oldest solids to form in the solar nebula, but it was not clear if chondrules formed at the same time, or later, and if later, how much later? Age-dating wizards in the cosmochemistry community have improved techniques to determine absolute ages using lead isotopes (see [PSRD article Dating the Earliest Solids in our Solar System](#)), and showed that relative ages determined using short-lived isotopes such as aluminum-26 (see [PSRD article Using Aluminum-26 as a Clock for Early Solar System Events](#)) are consistent. The great achievement is that the combination of long-lived lead isotopes and short-lived isotopes provide an astonishingly high-resolution time scale for the formation of CAIs and chondrules. CAIs appear to have all formed within a relatively short period of about 100,000 years. Some chondrules may have formed almost contemporaneously with CAIs, but most formed 1 to 4 million years later. This means that whatever process created chondrules operated for a long time. Preservation of chondrules with different ages indicates that the chondrule-forming process was local rather than nebula-wide.

CAI



Chondrule

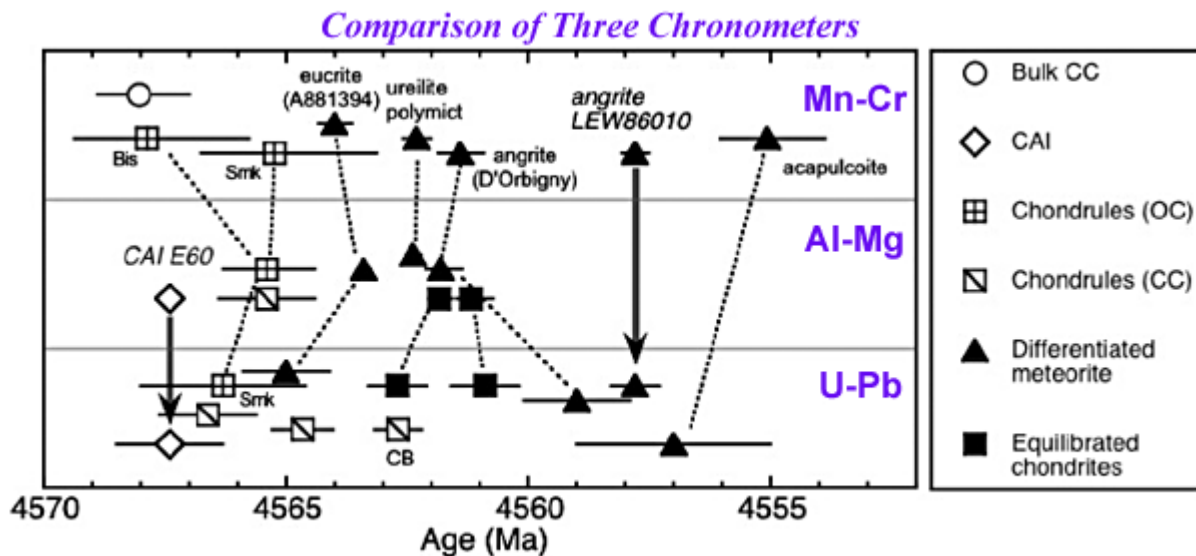


(from Wood, 2005, *Chondrites and the Protoplanetary Disk*, ASP Conf. Ser., v.341, p.955.)

Calcium-aluminum-rich inclusions (CAIs, example shown at top left) appear to have all formed at almost the same time and are used to establish the age of the Solar System, 4567 million years. Chondrules (example shown at top right) formed 1-4 million years after the CAIs (graph), which shows that the chondrule-forming process operated for at least 4 million years. [CAI image from chapter by MacPherson *et al.*, p. 228. Chondrule image from chapter by Hewins *et al.*, p. 289. Graph showing ranges in ages of chondrules from chapter by Wood, p. 955.]

The Aluminum-26 Furnace

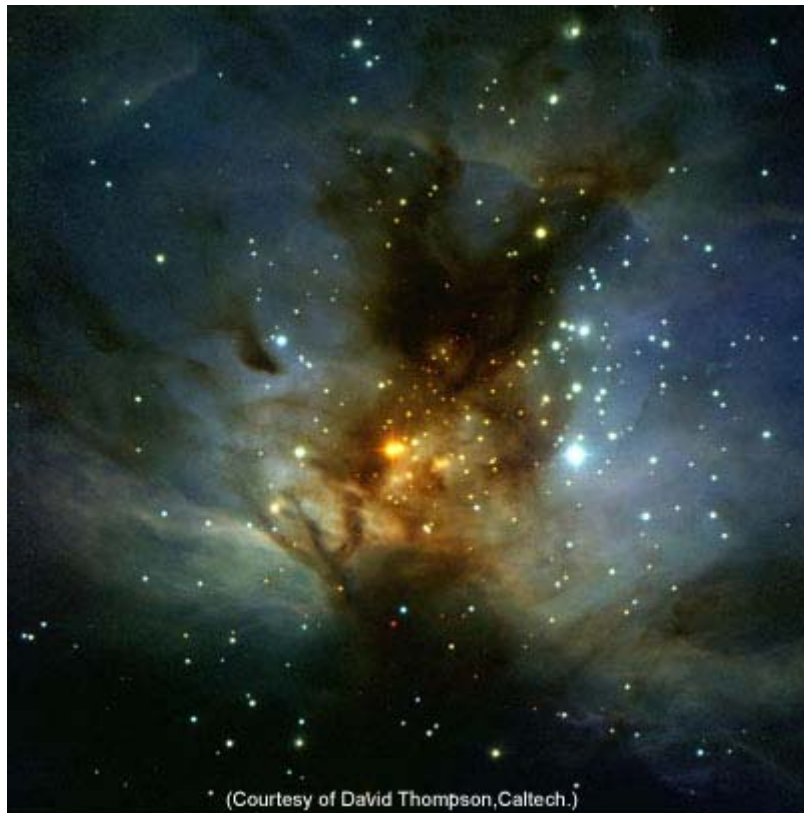
Studies of isotopes in chondrites and differentiated (melted) meteorites show that aluminum-26 (^{26}Al) was present when the Solar System formed. Although not abundant (a few parts in 100,000) compared to the stable aluminum isotope (^{27}Al), its half-life is so short (only 730,000 years) that its decay produces a lot of heat. So much heat, in fact, that rocky bodies larger than about 10 km melt readily if they form quickly enough. Thermal models (by Ian Sanders, Trinity College, Dublin, Ireland) showed and isotopic data (by Thorsten Kleine and coauthors, Universität Münster, Germany) confirmed that planetesimals formed less than 1.5 Myr after CAIs were melted so that chondrules were forming when differentiated asteroids were present in the solar system. Planetesimals formed later would not have had enough ^{26}Al to melt, so would preserve the primitive nebula components we see in chondrites. The presence of widespread molten, partly molten, and solid-but-hot planetesimals lead some investigators to suggest that chondrules formed by impact among these objects. However, in general cosmochemists and astronomers favor the idea that chondrules formed by the passage of shock waves through the solar nebula.



Timeline of events in the very early history of the Solar System, using different chronometers referenced to the absolute scale established by the lead-lead system (listed as "U-Pb" in the diagram). Chondrule formation overlaps with formation of differentiated planetesimals. [Diagram from chapter by Kita *et al.*, p. 580.]

The Early Lives of Stars: Nature or Nurture?

There are a lot of stars, including the Sun, sitting by themselves in the cosmos. Astronomers used to think that stars formed as isolated objects in small groups in molecular clouds but many now believe that most stars form in dense clusters and that isolated stars like the Sun may all be derived from multiple systems. Because massive stars form in dense clusters, burn hydrogen and then explode before the cluster has finished producing new stars, the early lives of stars may be profoundly affected by nearby siblings and more distant gigantic cousins that all formed in the same neighborhood. The evidence for the presence of short-lived isotopes like ^{26}Al and ^{60}Fe in meteorites provides strong evidence that the Sun probably formed in such a neighborhood and was peppered with stardust from an exploding star before most of the CAIs had formed. Close passage of a sibling star may have tilted the sun's rotation axis relative to the plane of the planets' orbits and perhaps even have generated disturbances that created chondrules.



Infrared color image of NGC 2244, an extremely dusty region of young star formation in the constellation of Orion. Use of infrared allows astronomers to see into this very dusty region to observe the numerous stars making up a cluster. [Image from chapter by Reipurth, p. 70.]

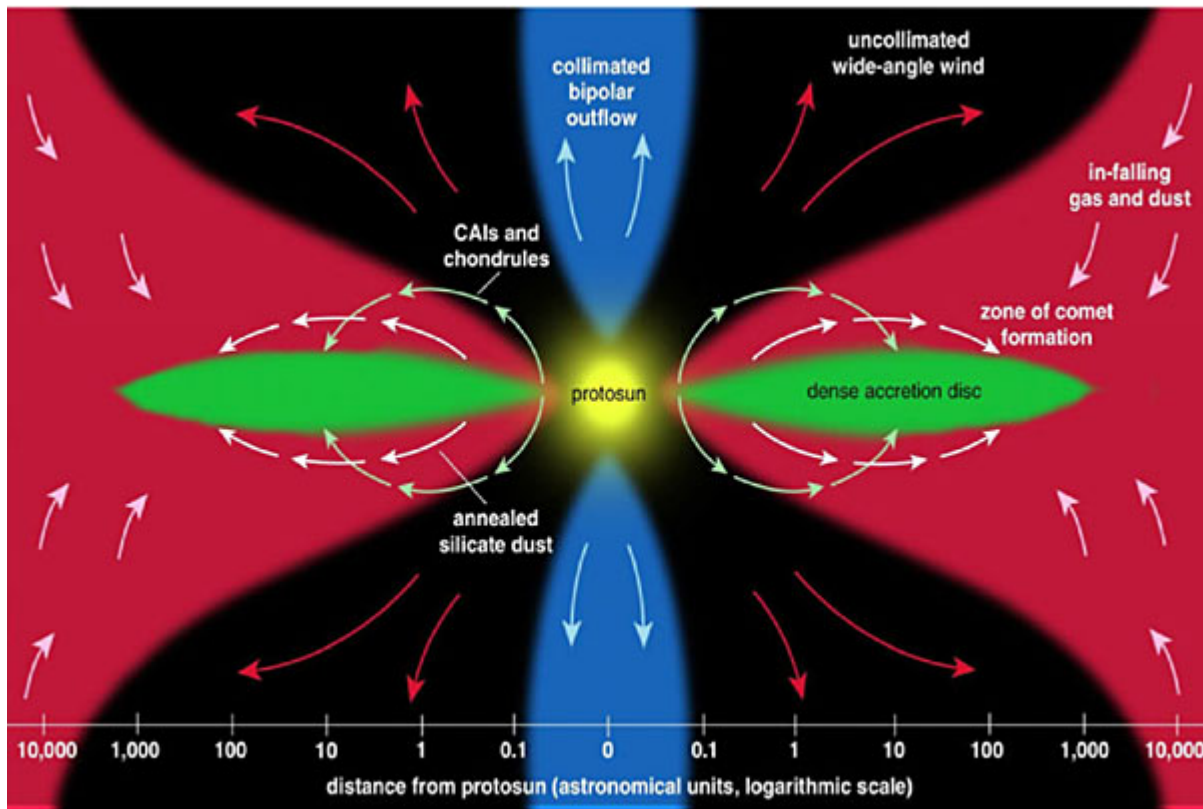
The Nebular Oven

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. Cosmochemists expected that comets might be made entirely of silicate smoke particles like those in interstellar space because comets formed far from the Sun, in a cold place with no heat to convert the smoke to crystalline minerals. Good story, but not true! Infrared astronomical observations of comets and laboratory measurements of interplanetary dust particles that are thought to come from comets indicate that a lot of silicate in many comets is crystalline. The recent dramatic measurements made by the Deep Impact mission when its projectile smashed into comet Tempel 1 found previously undetected silicate crystals suggesting that all comets contain crystalline silicates.



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. [[Deep Impact image gallery](#)]

The presence of crystalline silicate in comets shows that heating was ubiquitous in the accretion disk surrounding the young Sun. Not only were CAIs and chondrules formed at high temperatures, but even the dust was hot enough to make crystals. This dust must be transported from the inner nebula to the outer reaches where comets formed. Alternatively, the heating occurred throughout the solar system. Silicate crystals have also been observed in other protoplanetary disks, showing that heating processes were ubiquitous in disks around other young stars.

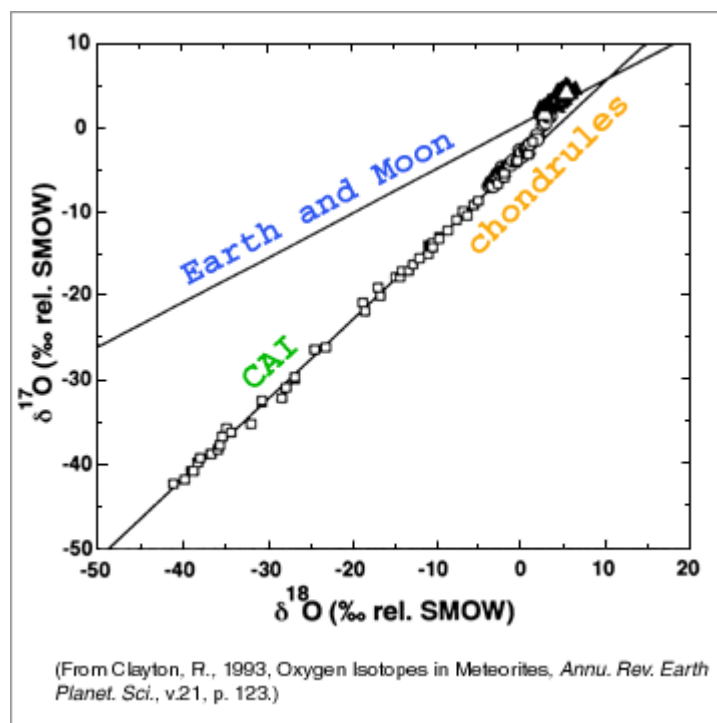


(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

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. [Diagram from chapter by Nuth et al., p. 678.]

Oxygen Isotopes Explained?

Oxygen isotopic compositions of primitive materials in chondrites plot along a line that suggests addition or subtraction of ^{16}O (see diagram below). An old explanation for this trend was that pre-solar grains were enriched in ^{16}O , but now cosmochemists and astronomers believe that it is more likely to be a chemical effect produced by irradiation of carbon monoxide (CO) by ultraviolet light. Observations of molecular clouds indicate that ultraviolet radiation can dissociate preferentially CO inside the cloud 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 . 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 CAIs. Ion microprobe measurements of solar wind implanted onto some metallic grains on the lunar surface (which of course contain no oxygen originally) suggest that the Sun's oxygen isotopic composition is like those of the CAIs.



Plot showing the $^{18}\text{O} / ^{16}\text{O}$ and $^{17}\text{O} / ^{16}\text{O}$ ratios in chondrules and CAIs in meteorites. These particles define a line with much steeper slope than the Earth line consistent with loss or addition of ^{16}O . Note that the variations in oxygen isotopic ratios are much larger than those shown by rocks from the Earth, Mars, and Vesta (see diagram above). The cause of the oxygen isotope variations may be selective dissociation by ultraviolet radiation of CO molecules containing ^{17}O or ^{18}O in the molecular cloud or solar nebula, leaving behind CO enriched in ^{16}O .

Interdisciplinary Research

Cosmochemistry is at the heart of fascinating interdisciplinary research. It overlaps with astronomy and astrophysics. In consort with geophysics it assesses the bulk compositions of the planets, and interprets those compositions in terms of dynamical models of Solar System formation. Cosmochemistry contributes to our understanding of the construction and modification of the crusts of planets, and it is central to unraveling the history of life on Earth and the search for life elsewhere. Perhaps this central role is illustrated best by its importance in understanding the nature of protoplanetary disks.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Kleine, T., Mezger, K., Palme, H., Scherer, E., and Münker, C. (2005) Early core formation in asteroids and late accretion of chondrite parent bodies: Evidence from ^{182}Hf - ^{182}W in CAIs, metal-rich chondrites, and iron meteorites. *Geochim. et Cosmochim. Acta*, v. 69, p.5805-5818.
- Krot, Alexander N., Edward R. D. Scott, and Bo Reipurth, Editors (2005) *Chondrites and the Protoplanetary Disk*, Astronomical Society of the Pacific Conference Series, vol. 341, 1029 pp.
- Krot, A. N. (2002) Dating the Earliest Solids in our Solar System. *Planetary Science Research Discoveries*. <http://www.psrhawaii.edu/Sept02/isotopicAges.html>
- Zinner, E. (2002) Using Aluminum-26 as a Clock for Early Solar System Events. *Planetary Science Research Discoveries*. <http://www.psrhawaii.edu/Sept02/Al26clock.html>