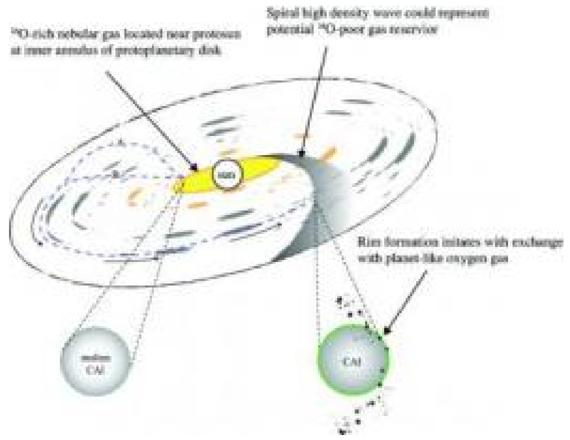
Oxygen isotope analysis tells of the wandering life of a dust grain 4.5 billion years ago

March 3 2011



All CAIs (calcium-aluminum-rich inclusions) are thought to have originated near the protosun, which enriched the nebular gas with the isotope oxygen-16. In a single CAI, the abundance of oxygen-16 was found to decrease outward from the center of the core, suggesting that the CAI formed in the inner solar system, where oxygen-16 was more abundant, but later moved farther from the sun, where the CAI lost oxygen-16 to the surrounding 16O-poor gas. Initial rim formation could have occurred as CAIs fell back into the midplane of the disk, indicated by the dashed path A; as they migrated outward within the plane of the disk, shown as path B; and/ or as they entered high density waves (i.e., shockwaves). Shockwaves would be a reasonable source for the implied 16O -poor gas, increased dust abundance and thermal heating. The first mineral layer outside the core had more oxygen-16, implying that the grain had subsequently returned to the inner solar system. Outer rim layers had varying isotope compositions, but in general indicate that they also formed closer to the sun, and/or in regions where they had lower exposure to the 16O -poor gas from which the terrestrial planets formed. Credit: Justin Simon/NASA

Scientists have performed a micro-probe analysis of the core and outer layers of a pea-sized piece of a meteorite some 4.57 billion years old to reconstruct the history of its formation, providing the first evidence that dust particles like this one experienced wildly varying environments during the planet-forming years of our solar system.

The researchers interpret these findings as evidence that dust grains traveled over large distances as the swirling protoplanetary nebula condensed into planets. The single dust grain they studied appears to have formed in the hot environment of the sun, may have been thrown out of the plane of the solar system to fall back into the asteroid belt, and eventually recirculated back to the sun.

This odyssey is consistent with some theories about how dust grains formed in the early protoplanetary nebula, or propylid, eventually seeding the formation of planets.

"This has implications for how our solar system and possibly other solar systems formed and how they evolved," said Justin I. Simon, a former University of California, Berkeley, post-doctoral fellow who led the research. "There are a number of astrophysical models that attempt to explain the dynamics of planet formation in a protoplanetary disk, but they all have to explain the signature we find in this meteorite."

"Justin showed not only that this dust grain moved around the solar system over quite large distances, but that it had seen the gamut of possible places it could have been in the solar system," said Donald J. DePaolo, UC Berkeley professor of earth and planetary science and director of the Center for Isotope Geochemistry.

Simon, now a researcher with the Astromaterials Research Office at

NASA's Johnson Space Center in Houston, Texas, along with DePaolo and colleagues at Lawrence Livermore National Laboratory (LLNL) and the University of Chicago report their findings in the March 4 issue of the journal *Science*.

Meteorites have puzzled space scientists for more than 100 years because they contain minerals that could only form in cold environments, as well as minerals that have been altered by hot environments. Carbonaceous chondrites, in particular, contain millimeter-sized chondrules and up to centimeter-sized CAIs (calcium-aluminum-rich inclusions) that were once heated to the melting point and later welded together with cold space dust.

"These primitive meteorites are like time capsules, containing the most primitive materials in our solar system," Simon said. "CAIs are some of the most interesting meteorite components. They recorded the history of the solar system before any of the planets formed, and were the first solids to condense out of the gaseous nebula surrounding our protosun."

Perhaps the most popular theory explaining the composition of chrondrules and CAIs is the so-called X-wind theory propounded by former UC Berkeley astronomer Frank Shu. Shu depicted the early protoplanetary disk as a washing machine, with the sun's powerful magnetic fields churning the gas and dust and tossing dust grains formed near the sun out of the disk.

Once expelled from the disk, the grains were pushed outward to fall like rain into the outer solar system. These grains, both flash-heated chondrules and slowly heated CAIs, were eventually incorporated along with unheated dust into asteroids and planets.

"There are problems with the details of this model, but it is a useful framework for trying to understand how material originally formed near the sun can end up out in the asteroid belt," said cosmochemist and coauthor Ian D. Hutcheon, deputy director of LLNL's Glenn T. Seaborg Institute.

Competing theories account for the composition of meteorites by moving dust from the inner solar system to the outer solar system without exiting the plane of the disk.

Simon teamed up with Hutcheon to use a relatively new ion microprobe called NanoSIMS (secondary ion mass spectrometer) to sample oxygen isotope composition in a CAI with approximately 2-micron resolution, about one-quarter the diameter of a red blood cell. Because the relative abundance of oxygen isotopes varied in the protoplanetary disk, it is possible to pinpoint where a mineral formed based on the relative abundances of the isotopes oxygen-16 (16O) and oxygen-17 (17O).

"NanoSIMS made this study possible by enabling us to look at the isotopic composition of oxygen on a very small scale," said Hutcheon. This contrasts with past studies of the isotopic composition of CAIs, which involved sampling over a much larger area.

Simon chose a pea-sized CAI – named for the high abundances of calcium and aluminum – from the Allende meteorite, the largest carbonaceous chondrite ever found on Earth. Estimated to have been the size of a car, it broke up as it fell through the atmosphere in 1969, showering the ground in Chichuahua, Mexico, with hundreds of pieces, many collected for subsequent study.

"I chose the Allende CAI because most of what we know about CAIs has come from the Allende meteorite, and therefore any record that I found would likely reflect the histories of CAIs in general," he said.

After cross-sectioning the small CAI, Simon and Hutcheon probed its core and four distinct mineral layers that had formed along the rim of the core like layers of an onion.

They found that the abundance of 17O increased outward from the center of the core, suggesting that the CAI originally formed in the inner solar system, where 16O was more abundant, but later moved farther from the sun, where the CAI's outer layers lost 16O to the surrounding 16O-poor gas.

They were surprised, however, that the first mineral layer outside the core had more 16O, implying that the grain had subsequently returned to the inner solar system. The other layers, too, had isotope levels indicating that they formed closer to the sun, in regions where they had lower exposure to the 16O-poor gas from which the terrestrial planets form.

"If you were this grain, you formed near the protosun, then likely moved outward to a planet-forming environment, and then back toward the inner solar system or perhaps out of the plane of the disk," Simon said. "Of course, you ended up as part of a meteorite, presumably in the asteroid belt, before you broke up and hit the Earth."

In terms of today's planets, the grain probably formed within the orbit of Mercury, moved outward through the region of planet formation to the asteroid belt between Mars and Jupiter, and then traveled back toward the sun again.

"It may have followed a trajectory similar to that suggested in the X-wind model," Hutcheon said. "Though after the dust grain went out to the asteroid belt or beyond, it had to find its way back in. That's something the X-wind model doesn't talk about at all."

Simon plans to crack open and probe other CAIs with NanoSIMS to determine whether this particular CAI (referred to as A37) is unique or typical of all CAIs.

Provided by University of California - Berkeley

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