



Hot Idea

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Relicts from the Birth of the Solar System

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Two unusual meteorites may contain the record of heating and rapid transport by powerful jets while the Sun was still forming. The research, done by Alexander Krot (University of Hawai'i) and colleagues from Stanford University, the Natural History Museum of London, and the Carnegie Institution of Washington, supports ideas stemming from astronomical observations of young stars. The meteorites contain rounded objects that cooled very rapidly from a molten state. Their chemical compositions indicate formation from a cloud that had become enriched in dust before being completely evaporated. When the gas cloud cooled, the tiny droplets condensed, but were blown into much cooler regions far from the Sun before they had a chance to acquire moderately volatile elements such as sodium, potassium, and sulfur. They appear to have accreted into asteroids before other processes affected them, thus preserving the record of heating and jetting in the nebula that surrounded the infant Sun. The results support a theory of chondrule and star formation proposed by Frank Shu (University of California, Berkeley).

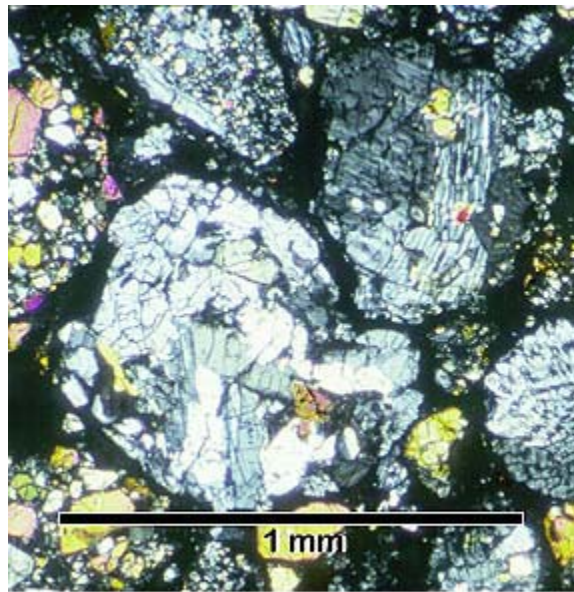
References:

Krot, Alexander N., A. Meibom, S. S. Russell, Conel M. Alexander, Timothy E. Jeffries, and Klaus Keil (2001) A new astrophysical setting for chondrule formation. *Science*, v. 291, p. 1776-1779.

Melted Dust Balls

Chondrites are meteorites that contain millimeter-sized objects called chondrules. In the 1960s and 70s, there was great hope that chondrules formed directly from the cloud of gas and dust that surrounded the Sun as it was still forming. The intellectual battle was between direct condensation from the solar [nebula](#), as the dusty cloud is called, or secondary processes such as impact or volcanism. The secondary processes fell by the wayside, though they still had their adherents. (In fact, small pockets of resistance survive today, and volcanism is gaining supporters. This will be the subject of a future article in PSRD.) Once the nebula became the place for chondrules, attention turned to using them to understand the processes that operated in it before the planets formed.

Proponents of direct condensation eventually had to confront something common in natural science: data. The chemical and mineralogical properties of chondrules and experiments designed to reproduce the mineral intergrowths in chondrules showed that they could not possibly have condensed from a gas. The condensation idea gave way in the 1980s to the hypothesis that chondrules formed from small aggregations of dust, like those fluffy dust balls that accumulate under your bed. Detailed studies showed that many chondrules were remelted after they formed. Nobody knew the cause of the melting. Leading candidates are lightning and shock waves, and the uncertainties have given hope to folks in the impact camp. The bottom line is that chondrules were thought to be secondary products--still interesting, but a bit removed from being the holy grail many of us hoped they were. To paraphrase [U2](#), we still hadn't found what we were looking for.



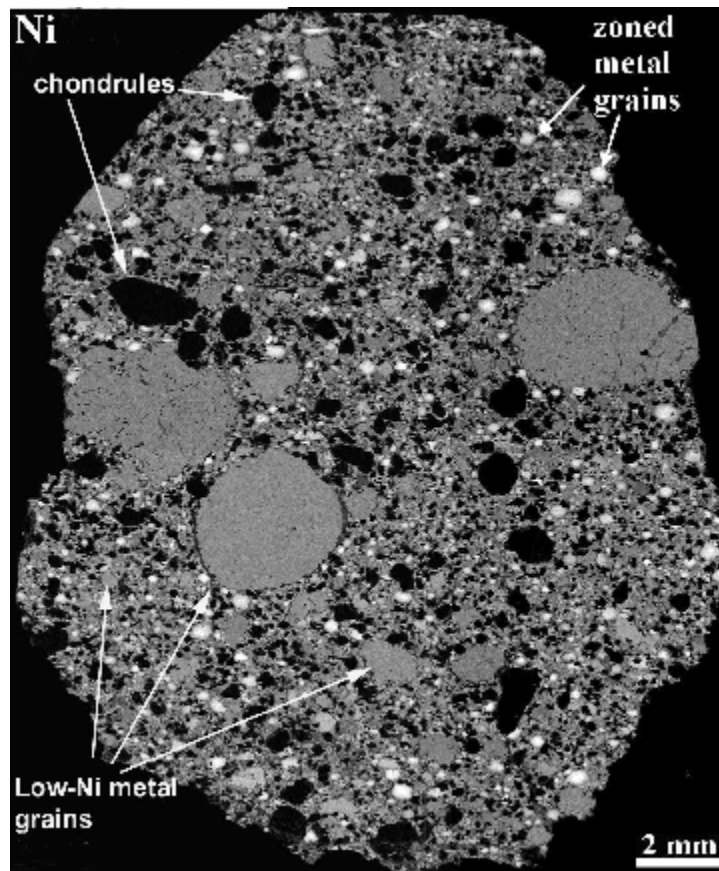
(photomicrograph by G. J. Taylor)

Microscopic view of some typical chondrules in the meteorite Tieschitz, as seen through a polarizing microscope. (The colors are not the actual colors of the minerals, but are instead interference colors caused by the optical properties of the minerals and the polarized light of the microscope.) Note the presence of numerous large crystals in each chondrule. Melting and crystallization experiments show that such mineral shapes and sizes can be produced only if tiny dust grains are present in the molten chondrule. If no dust is present, the final product will contain only very small crystals, as observed in the unusual chondrites studied by Sasha Krot and his colleagues.

Now seekers of the holy grail can take heart. Alexander (Sasha) Krot and his colleagues may have found direct condensates from the solar nebula. They studied the round, rapidly-crystallized chondrules in two unusual chondrites (meteorites that contain chondrules). They are unusual in more than their names, Hammadah al Hamra 237 and QUE 94411 (found in northern Africa and Antarctica, respectively). Both are loaded with metallic iron, which makes up about 70% of each rock. In contrast, metallic minerals make up only 5 to 10% of most chondrites. Chondrules comprise the remaining 30% of HH 237 and QUE 94411. The metal grains and chondrules tell the story of heat and wind in the solar nebula.

Vaporized and Condensed Dust

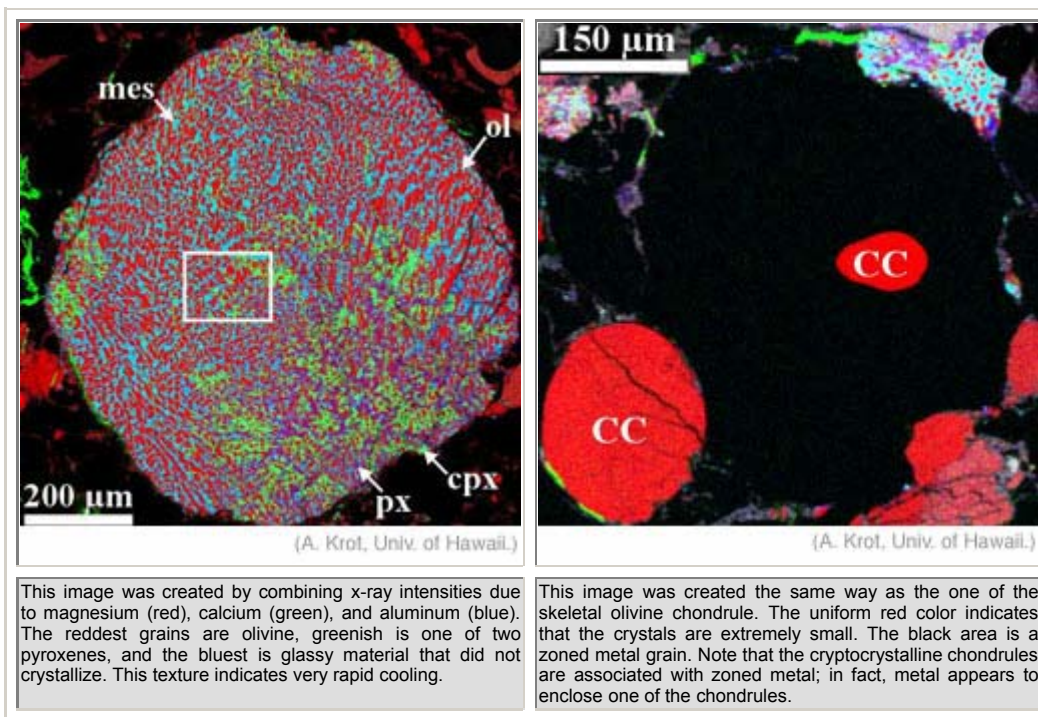
Some of the metallic grains in the two meteorites are chemically zoned. Krot, Anders Meibom (Stanford University), and colleagues from NASA Ames Research Center and the Harvard-Smithsonian Center for Astrophysics showed last year that the distinctive zoning was consistent with condensation of the metal from a gas. They calculated the composition expected for metal grains forming from a hot cloud, and found that the zoning pattern matched that in the metal grains in CH chondrites. [See [PSRD article: The Oldest Metal in the Solar System](#).] Their calculations suggest that the metal grains grew by condensation from a gas between 1100 °C and 1000 °C. Using astrophysical theory, they calculated that the gas was cooling at a rate of about 0.2 °C per hour. This cooling rate implies that the grains formed in a large-scale heating episode in the nebula, not in a localized event. Heating of the disk surrounding the young Sun caused evaporation of the solid materials. The hot gas rose in clouds over a million kilometers across. The clouds cooled as they rose, causing the metal grains to form.



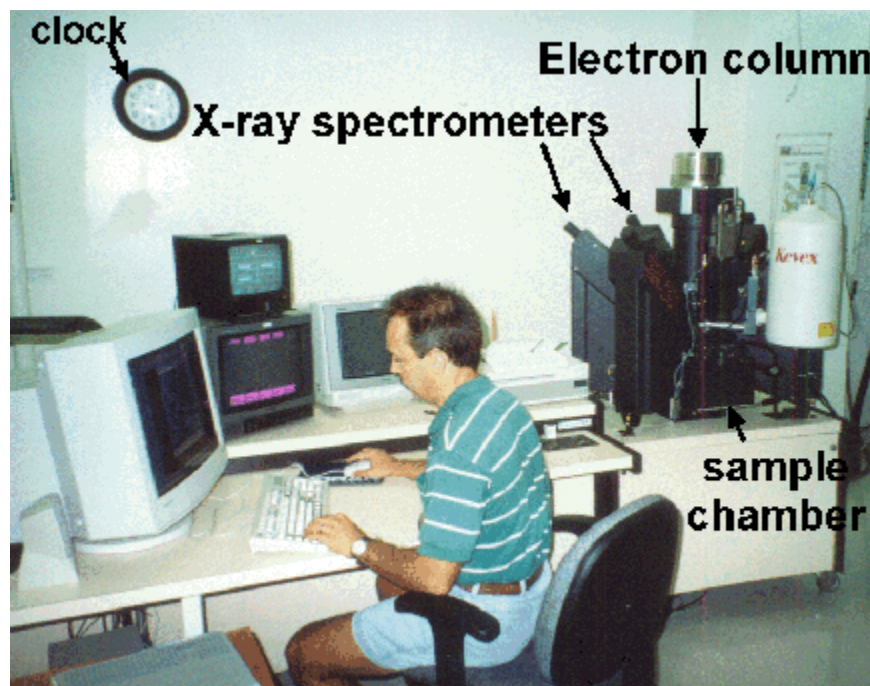
(A. Krot, Univ. of Hawaii.)

Image of the intensity of x-rays from a polished slice of HH 237. (The x-rays were made by bombarding the sample with a beam of electrons in an electron microprobe.) The brighter the spot, the higher the Ni concentration. The dark areas are chondrules. Brightest are the zoned metal grains. Medium gray areas, making up most of the rock, are metallic nickel-iron grains that are relatively low in Ni (about 5 wt%).

The chondrules in the two meteorites are nothing like those in other chondrites. There are two main types, which Krot names skeletal olivine chondrules (SO for short) and cryptocrystalline chondrules (CC--scientists love abbreviations). The skeletal olivine chondrules are so named because the main mineral in them, [olivine](#), forms an open, skeleton-like network. "Cryptocrystalline" means that the crystals are so small you cannot identify them even with a microscope. The cryptocrystalline chondrules have mineral intergrowths that are almost the opposite of the typical chondrule, like the one shown above.



The lack of big crystals inside the chondrules indicates that they had become quite hot, thus eliminating any tiny seed crystals of the type present in conventional chondrules. Krot and coworkers suggest that the chondrules condensed directly from a very hot gas. To bolster the argument, they determined the chemical composition of the chondrules. If they formed in a hot gas, the elemental abundances should reflect that. The team analyzed the samples with an electron microprobe for abundant elements and with a technique called laser ablation, inductively-coupled plasma mass spectrometry (usually shortened to LA-ICP-MS). It may be a mouthful, but it is incredibly useful in figuring out how rocks form.



(Jeff Taylor)

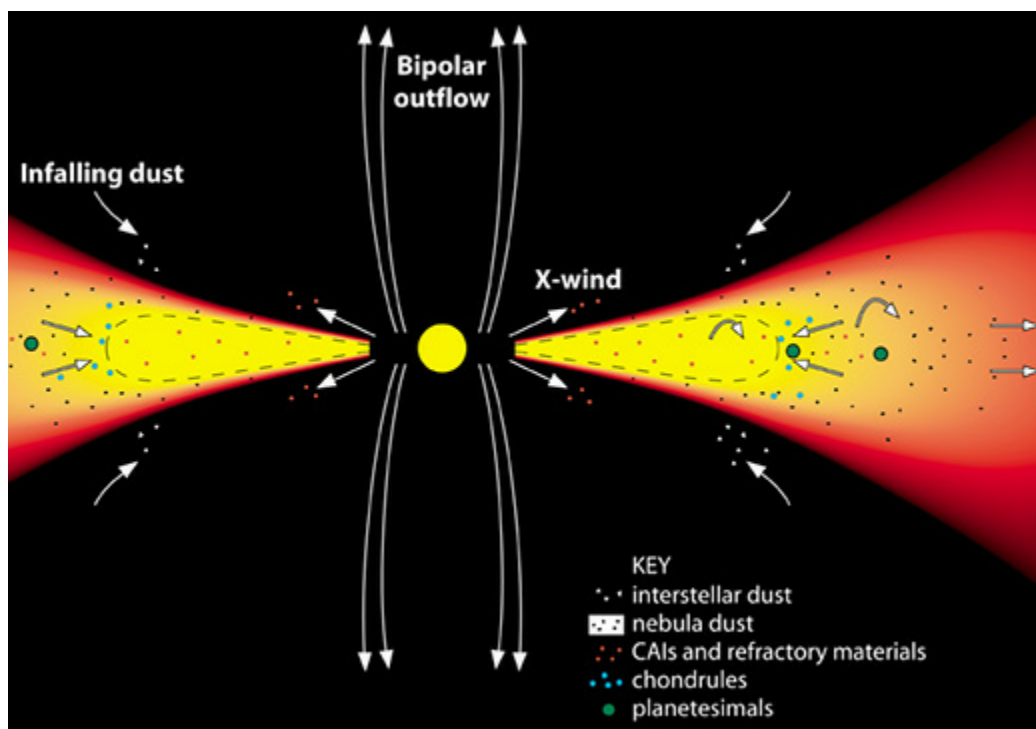
Sasha Krot measured the abundances of major elements in SO and CC chondrules using this electron microprobe. This high-tech contraption works by focusing electrons on a polished sample, which resides in a vacuum chamber. The electrons produce x-rays in the sample, which the spectrometers select and send to x-ray detectors. By measuring the number of x-rays from the sample and comparing that to the number obtained from a mineral of known composition, we can calculate the elemental abundances in the sample.

The analyses show that both types of chondrule have very low concentrations of elements expected to condense from a gas at low temperature, such as sodium, potassium, and sulfur. They are even a bit depleted in manganese, which condenses at moderate temperature. Overall, the SO and CC chondrules have complementary compositions. The skeletal olivine chondrules tend to be enriched in the elements expected to condense at the highest temperature (calcium, aluminum, titanium, rare earth elements), while the cryptocrystalline chondrules contain much lower amounts of these elements.

These chemical trends are consistent with calculations of condensation in evaporated Solar System dust. The first liquids to condense would contain lots of calcium, aluminum, etc. The formation of these chondrules would deplete the remaining gas in those elements, so the next batch of chondrules would contain much less of them. This is what we see in the cryptocrystalline chondrules. Metallic iron-nickel would condense slightly after these chondrules, explaining why cryptocrystalline chondrules sometimes reside inside metal grains. It makes a nice, consistent story.

A New Setting for Chondrule Formation

The association of zoned metal grains with the chondrules indicates that the environment in which they formed was similar. Using the results from their previous work, Krot and coworkers suggest that the ingredients in HH 237 and QUE 94411 formed in a somewhat oxidizing gas that was heated to at least 2000 °C. Vast clouds of the gas rose to cooler regions above the disk surrounding the infant Sun. The rising gas cooled and chondrules began to condense as liquids. The plumes of chondrules and gas, a million kilometers across, continued to rise and cool, but still remained above the condensation temperature of most elements. When a plume reached the top of the nebular disk, strong winds from the Sun blew the materials to much cooler regions of the solar nebula much farther from the Sun. Some must have ended up in the region that would become the asteroid belt, where it promptly assembled into a small body, thereby preserving the record of its formation.



(PSRD graphic by Nancy Hurbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

This shows some of the general processes that might have operated when the Sun and planets were forming. The yellow region near the Sun is very hot, which vaporizes all the dust falling into the nebula. The young Sun emits vast quantities of energetic particles, which create winds in the nebula. Rising plumes above the dashed lines are blown out to cooler parts of the disk, where they accrete into asteroids. In some places, shown by the green dots, normal chondrules are made by melting pre-existing dust balls.

This story provides strong evidence for a theory of star formation developed by Frank Shu (University of California, Berkeley). Using Hubble Space Telescope images of disks around young stars as a guide, Shu proposes that the inner part of a disk becomes

hot enough to melt silicates. He suggests that powerful jets accelerate chondrules to hundreds of kilometers per second, allowing them to reach the asteroid belt in only a day or two.

So, meteorite evidence supports theory. Additional observations of disks around other stars and more studies of meteorites will provide additional tests of Shu's theory. But just because a theory seems to explain the facts does not necessarily mean it is correct. Rest assured that other scientists will devise other explanations for the chondrules and zoned metal grains in these (and some related) meteorites. In particular, the band of renegades who still believe that chondrules formed by impact will not let the matter rest here. The argument promises to be enlightening!

Additional Resources

Krot, Alexander N., A. Meibom, S. S. Russell, Conel M. Alexander, Timothy E. Jeffries, and Klaus Keil (2001) A new astrophysical setting for chondrule formation. *Science*, v. 291, p. 1776-1779.

[Space Telescope Science Institute](#)

Taylor, G. Jeffrey, "The Oldest Metal in the Solar System." *PSR Discoveries* Sept. 2000.
<<http://www.psrд.hawaii.edu/Sept00/primitiveFeNi.html>>.



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