PLANETARY SCIENCE RESEARCH PSRD Discoveries

Hot Idea November 20, 2008

Tiny Molten Droplets, Dusty Clouds, and Planet Formation

--- Roughly constant sodium concentration during chondrule crystallization suggests that these molten droplets formed in regions of the solar nebula that were enriched in rocky dust.

Written by G. Jeffrey Taylor
Hawai‘i Institute of Geophysics and Planetology

Chondrules, millimeter-sized spherules that formed as rapidly-cooled molten droplets, are characteristic of chondrite meteorites. If they formed at low pressure in the solar nebula (the cloud of gas and dust surrounding the infant Sun and from which the planets formed), then they should have lost almost all their inventories of volatile elements, such as sodium, because volatile elements would have boiled off the chondrules when they were molten. Conel Alexander (Carnegie Institution of Washington) and colleagues at Carnegie, the U.S. Geological Survey (Reston), and the American Museum of Natural History (New York) show that there was little sodium loss. They measured the sodium concentrations in numerous crystals of olivine inside chondrules in the Semarkona meteorite. The results show that the variations in concentrations from the centers of crystals to their edges are consistent with crystallization in a molten droplet that was not losing sodium to the surrounding gas. These results are supported by independent measurements by Alexander Borisov (Russian Academy of Sciences, Moscow) and colleagues at the University of Hannover, Georg-August-University Göettingen, and Köln University, all in Germany. Sodium loss could have been suppressed if the gas surrounding each chondrule had a much higher pressure of sodium than that expected for the solar nebula. Such a high pressure of sodium is most easily explained if chondrules formed in a region with a high density of solids. Alexander and his co-workers argue that such dense regions could have enough mass in a small space to collapse by gravity, perhaps forming planetesimals, the first step in constructing the inner planets.

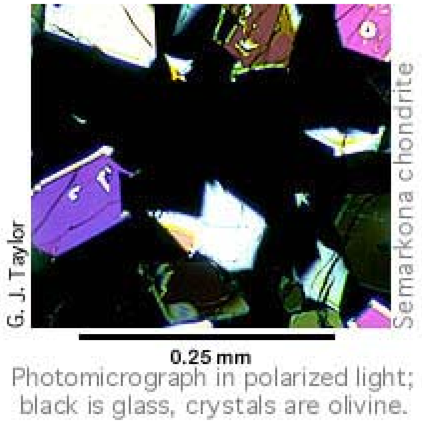
References:

- Alexander, C. M. O'D, Grossman, J. N., Ebel, D. S., and Ciesla, F. J. (2008) The Formation Conditions of Chondrules and Chondrites. *Science*, v. 320, p. 1617-1619. doi: 10.1126/science.1156561.
- Borisov, A., Pack, A., Kropf, A., and Palme, H. (2008) Partitioning of Na Between Olivine and Melt: An Experimental Study with Application to the Formation of Meteoritic Na2O-rich Chondrule Glass and Refractory Forsterite Grains. *Geochimica et Cosmochimica Acta*, v. 72, p. 5558-5573. doi:10.1016/j.gca.2008.08.009.

PSRDpresents: Tiny Molten Droplets, Dusty Clouds, and Planet Formation --Short Slide Summary (with accompanying notes).

Semarkona and Its Well-Preserved Chondrules

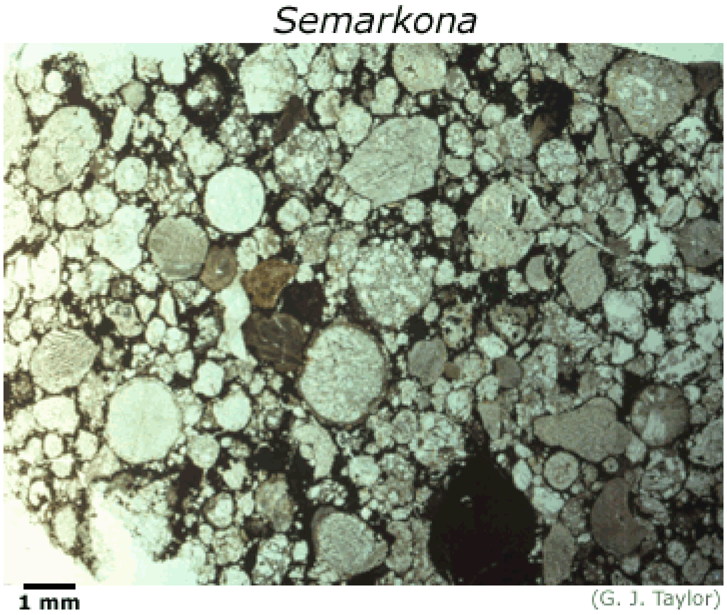
All cosmochemists agree that chondrules formed as molten droplets that cooled relatively rapidly. There is less agreement on how chondrules were melted, but their mineralogical, textural, and chemical properties contain important information about the conditions during their formation. For example, experiments suggest they cooled at rates of between 1 and 1000 K per hour, much slower than they would have cooled in the cold vacuum of space. Another key question, discussed since the early 1970s, is whether volatile elements such as sodium were lost during chondrule formation.



Photomicrograph of a chondrule in the Semarkona chondrite, viewed through polarizing filters located below and above the sample. Colorful crystals are olivine, about 50 micrometers cross. The olivine grains are surrounded by glass, which appears black when viewed through the two polarizing filters.

The record of chondrule formation is faithfully recorded only if they were not chemically or mineralogically modified after they formed. Most chondrites have been heated inside their parent asteroids, causing minerals to exchange elements and new minerals to form from original igneous glass. Fortunately, not all chondrites were heated, or heated enough to alter the original properties of their chondrules. One of the least heated is the Semarkona chondrite, which fell in India in 1940. Semarkona preserves glass inside chondrules (see photo above) and its mineral grains are compositionally zoned as expected for crystals forming from a droplet of magma. Thus, the meteorite records the record of chondrule formation, which is why Conel Alexander and Alexander Borisov and their co-authors studied chondrules in it.

The Semakona chondrite is composed of numerous chondrules, the round objects evident in this photograph of a thin slice of the meteorite. The chondrules are about a millimeter across. Semarkona is almost ideal for studies of the primitive components in chondrites, such as chondrules, because it has experienced little thermal metamorphism. It has, however, been somewhat altered by small amounts of water while still in its parent asteroid.



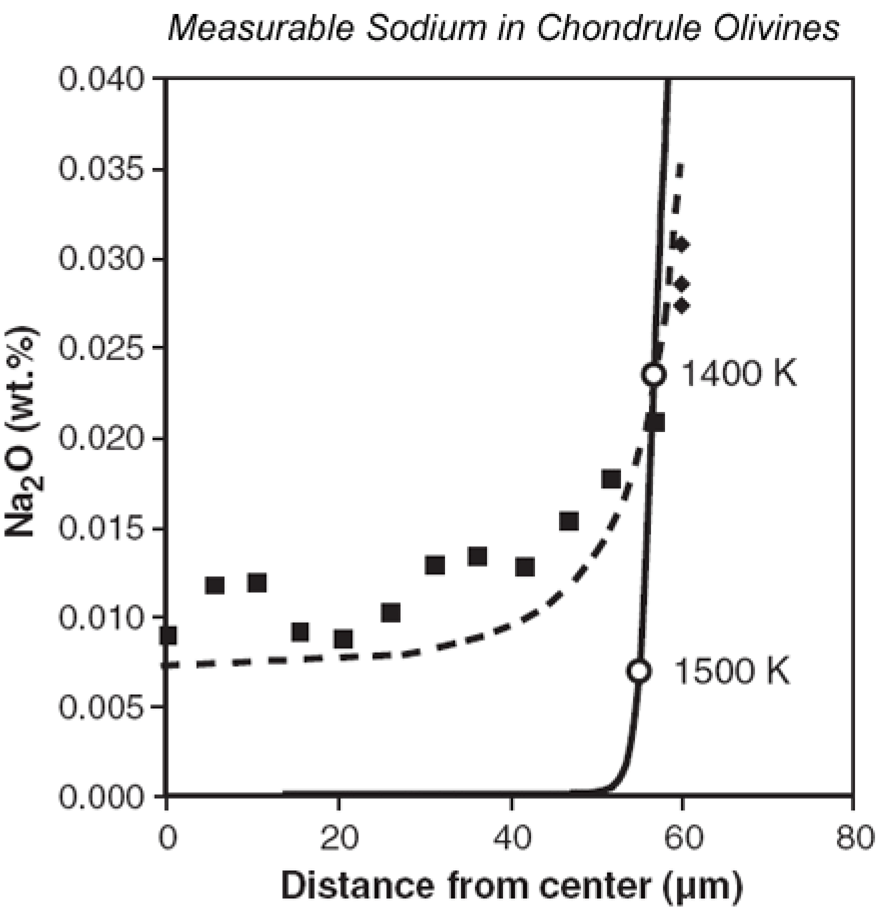
Measuring Sodium

Sodium is ideal for monitoring the extent to which volatile elements were lost during chondrule formation. It is moderately volatile and abundant enough to measure accurately. In fact, it reaches quite high values (up to 13 wt% Na_2O) in chondrule glass. However, the best way to monitor sodium loss is not by measuring it in the glass: doing so would not provide enough information to tell whether the sodium was retained by the cooling chondrule or entered during the time when the chondrule was crystallizing or later. Instead, the most useful monitor is to measure sodium in a crystal that grew as a chondrule cooled from very high temperatures. The mineral olivine is the first to form and it continues to crystallize throughout chondrule cooling. Olivine takes up much less sodium than is present in the chondrule melt, so as it crystallizes, sodium increases in the remaining melt. Because the amount of sodium that goes into olivine is proportional to the amount in the melt, the sodium content of the olivine increases as crystallization proceeds. Accurate measurements of the partitioning of sodium into olivine was done by Alexander and his colleagues, and confirmed by Borisov and colleagues through laboratory experiments.

But it's not easy to measure sodium in olivine. The concentrations are low, only a few hundredths of a weight percent, so special procedures must be used to analyze it by electron microprobe. Not only are sodium concentrations low, but the olivine crystals are surrounded by a sea of sodium-rich glass. This is particularly troublesome near the edges of olivine grains. If there are inclusions of melt trapped inside olivine grains they will give incorrectly high sodium contents in olivine. Both teams worked around this problem by measuring aluminum, which is low in olivine but high in the surrounding glass. If there was too much aluminum in an olivine analysis, the analysis was rejected.

Little Sodium Evaporation

Individual olivine crystals in Semarkona chondrules contain more sodium at their edges than at their edges, which is exactly what we would expect from crystallization with little or no sodium loss as the chondrules cooled (see diagram below). The dotted line in the diagram below shows the calculated compositional change assuming that all olivine crystals grow to 60 micrometers across. Note that the data points for an actual Semarkona chondrule fall close to that line. In contrast, predictions of sodium loss to the solar nebula indicate that there should be no measurable sodium in the olivine, except at the very edge (solid line in the diagram below).


Measurable Sodium in Chondrule Olivines

(from Alexander C. et al (2008) Science, v. 320, p. 1617-1619. doi: 10.1126/science.1156561.)

Data for an olivine crystal in a Semakona chondrule (squares) fall close to a theoretical curve calculated for closed-system (no sodium loss) crystallization. The calculation assumes that the ratio of the amount of sodium that goes into olivine compared to that remaining in the melt is constant, and makes olivine in small increments throughout olivine crystallization. The solid line shows the concentration in olivine for different temperatures of the surrounding gas. Sodium begins to reside in crystals only below about 1500 K, after more than 400 K of cooling and olivine crystallization. It thus would concentrate only at the rim of the olivine crystals. The gas is assumed to have been enriched in dust by a factor of 1000 over what we expect in the solar nebula. With no dust enrichment, sodium would not be present even on olivine rims.

Alexander and Borisov and their teams also show that the concentrations in the cores and rims of numerous olivine crystals in numerous chondrules are consistent with closed-system crystallization, hence with no loss of sodium. It thus seems certain that chondrule formation did not lead to loss of sodium (and presumably other volatile elements such as sulfur) after their formation.

Preventing Sodium Loss: A Cloud of Dust

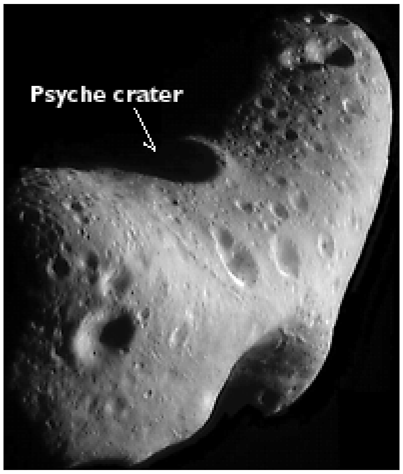
To prevent sodium loss from a hot molten droplet, the droplet has to be surrounded by a gas with enough sodium in it to prevent evaporation. Dean Lewis and his mentor Gary Lofgren and others at the Johnson Space Center showed experimentally in 1993 that sodium loss could be prevented if there was enough of it in the surrounding gas. They put a basalt in a gas mixing furnace and saturated the atmosphere in the furnace with sodium, and found that there was little loss of sodium from the molten droplet of basalt. Conel Alexander and co-workers calculated the gas pressure and then used it to calculate the density of dust in the chondrule-forming region of the solar nebula. The calculations tie the amount of vaporized sodium to the amount of sodium in the chondrules studied. The results indicate that the density of this dusty cloud was tens to thousands of grams per cubic meter. For comparison, rocks have densities of a few million grams per cubic meters. Thus, the chondrule-forming clouds consisted of roughly 0.01 to 0.1% dust floating in a low-pressure gas.

This is a high concentration of dust. How did that happen? Calculations by astrophysicists suggest that dust can settle to the mid-plane of the disk surrounding the Sun, but that turbulent motion in the gas-dust mixture prevents them from concentrating to anywhere near this amount. On the other hand, some calculations suggest that turbulent motion might concentrate dust in some regions, perhaps leading to enrichments like those apparently required to prevent loss of volatiles from molten chondrules. The bottom line is that much more work needs to be done by theoreticians to figure out how to concentrate so much dust in at least some places in the solar nebula.

Chondrule formation remains a mysterious process, with numerous ideas floated by numerous cosmochemists. One idea is that shock waves sent out from the primitive Sun or generated by large planetestimals passing through the dust-rich region heated and melted the materials, forming chondrules. However, Alexander and his colleagues point out that these dust densities present severe problems to the shockwave model, especially because numerical simulations at these very high densities are extremely challenging and have yet to be done. An alternative is that the dust had already accreted into planetesimals, and that collision between them caused extensive melting and chondrule formation.

Dusty Clouds to Planetesimals and Planets

Conel Alexander and his colleagues calculate that if the dusty, chondrule-forming regions were larger than about 4000 kilometers across, they would have enough mass to self-gravitate; that is, they would collapse. This could rapidly cause formation of chondrite parent bodies about 100 kilometers across. Alexander and his co-authors suggest that this hints that chondrule formation and planetesimal formation might be linked: chondrules formed in regions that had become heavy with dust, so heavy and massive that they could rapidly collapse to form asteroid-sized bodies, the first step in building planets. However, these are just preliminary ideas--we are just beginning to examine the consequences of chondrule formation on planetary accretion.



Peanut-shaped asteroid Eros, 33 x 13 x 13 kilometers, may be a fragment of a chondritic planetesimal. Eros is pockmarked with craters, the largest of which is Psyche (5.3 km in diameter) indicated by the arrow.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Tiny Molten Droplets, Dusty Clouds, and Planet Formation --Short Slide Summary (with accompanying notes).

- Alexander, C. M. O'D, Grossman, Jeffrey N., Ebel, Denton S., and Ciesla, Frank J. (2008) The Formation Conditions of Chondrules and Chondrites. *Science*, v. 320, p. 1617-1619. doi: 10.1126/science.1156561.
- Borisov, Alexander; Pack, Andreas; Kropf, Andreas; and Palme, Herbert (2008) Partitioning of Na Between Olivine and Melt: An Experimental Study with Application to the Formation of Meteoritic Na2O-rich Chondrule Glass and Refractory Forsterite Grains. *Geochimica et Cosmochimica Acta*, v. 72, p. 5558-5573. doi:10.1016/j.gca.2008.08.009.
- Lewis, R. D., Lofgren, G. E., Franzen, H.F., and Windom, K. E. (1993) The Effect of Na Vapor on the Na Content of Chondrules. *Meteoritics*, v. 28, p. 622-628.

HOME

[About PSRD | Archive | Search | Subscribe]

[Glossary | General Resources | Comments | Top of page]

2008
psrd@higp.hawaii.edu
main URL is http://www.psrd.hawaii.edu/