Hot Idea

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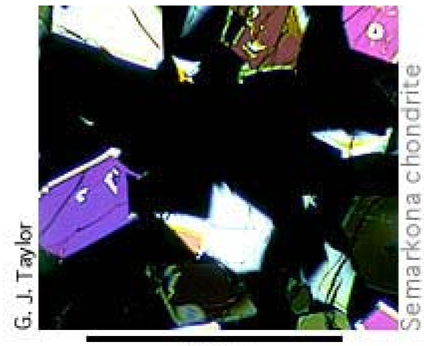

Photomicrograph in polarized light; black is glass, crystals are olivine.

Dry Droplets of Fiery Rain

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Chondrules are millimeter-sized spherical objects found in meteorites. Chondrules were molten so long ago that the planets had not yet formed. These fascinating droplets of fiery rain, as H. C. Sorby called them in 1877, are also the source of constant, enthusiastic, and heartfelt debate among meteorite specialists. Most think that chondrules formed by melting aggregates of tiny, rocky grains in the vast cloud of gas and dust from which the Solar System formed, whereas others believe that the molten droplets formed by impact onto growing asteroids. A few suggest chondrules formed by some sort of volcanism.

Whether they were made by melting in the gas-dust cloud or on an asteroid, there has always been a question about the chemical composition of the rock or dust that melted to form chondrules. An important compositional question is whether the precursor rock contained water in its mineral constituents or not. This is important because it bears on the chemical and physical environment in the dust-gas cloud. Understanding this cloud, called the solar nebula, is a prime objective of meteorite research.

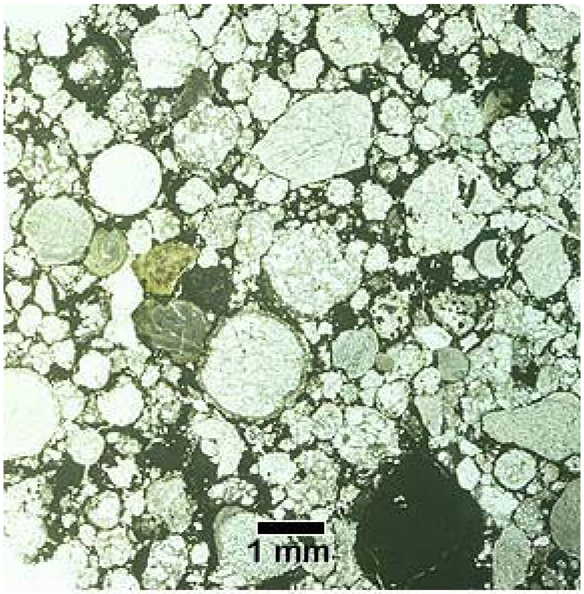
The question about water-bearing minerals has been answered by a series of elegant experiments by Susan Maharaj and Roger Hewins of the Department of Geological Sciences at Rutgers University. They showed that melting powders containing water-bearing minerals always produced products that contained gas bubbles, features **not** observed in real chondrules. They conclude that the precursor aggregates must have been composed entirely of water-free minerals.

Reference:

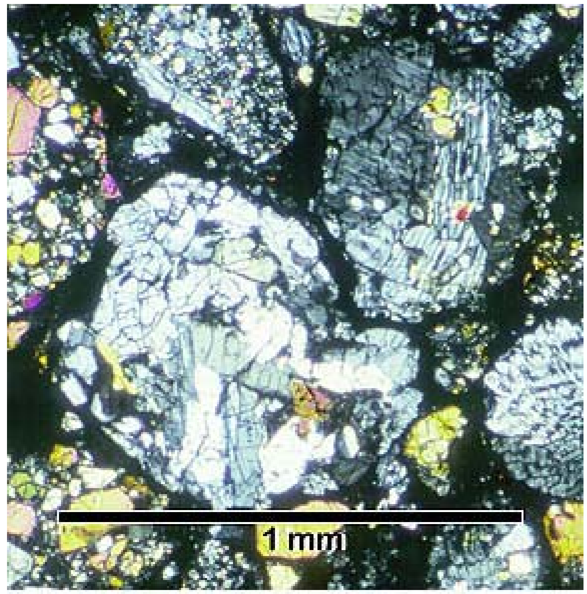
Maharaj, Susan V. and Roger H. Hewins ,1998, Chondrule Precursor Minerals as Anhydrous Phases. *Meteoritics & Planetary Science*, v. 33, p. 881-887.

Chondrules

Chondrules are striking in the microscope. In polarized light, they look like vibrant stained glass, with red and blue crystals of olivine interspersed with grayish to yellowish crystals of pyroxene. (Pyroxene and olivine are both silicate minerals containing iron and magnesium.) A small amount of glass surrounds the crystals. The generally regular, straight-sided shapes of the crystals and the presence of glass indicate that chondrules formed as molten droplets of rocky material that cooled rapidly. Meteorite specialists have identified several kinds of chondrules, classifying them on the basis of the types, abundances, shapes, and compositions of the minerals present. Radioactive dating measurements of the ages of chondrules suggest that they formed in the first few million years after the Solar System formed at 4.566 billion years ago.



(photomicrograph by G. J. Taylor)



(photomicrograph by G. J. Taylor)

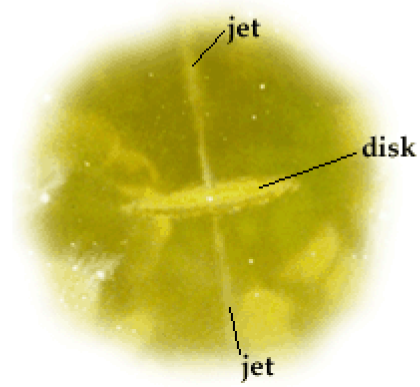
Stony meteorites called chondrites are chock full of chondrules, as shown, above, in the photograph on the **left** of the Semarkona chondrite. On the **right** is a closer view of some typical chondrules in the meteorite Tieschitz, as seen through a polarizing microscope. The colors are not the actual colors of the minerals, but are instead interference colors caused by the optical properties of the minerals and the polarized light of the microscope. Chondrules lack circular gas bubbles.

All types of chondrules have one thing in common: they do not contain any circular, empty regions that would indicate the presence of a frozen gas bubble. Such bubbles, called vesicles, are common in volcanic rocks on Earth, and indicate the presence of gases in the magma. (On Earth, most of the escaping gas is composed of carbon dioxide and water vapor.)

Ideas for Chondrule Formation

There are nearly as many ideas about how chondrules formed as there are scientists working on them. Everyone seems to have their pet idea: condensation from a hot cloud of gas and dust, melting of aggregates by lightning, intense heating as planetesimals plowed their way through the cloud of gas and dust, or highly turbulent interactions between gas and dust. Still others think that chondrules formed by impact melting of pre-existing asteroids or planetesimals. Others have suggested widespread volcanism. This glut of hypotheses is a testament to the richness of human imagination. It also points out the need to test ideas for the origin of chondrules.

This portion of a painting by scientist-artist Bill Hartmann depicts the formation of the Solar System from a cloud of gas and dust. Because the cloud was spinning, it flattens into a disk. Jets from the early Sun shoot out the top and bottom, probably driven by magnetic fields. One idea for chondrule formation is that they formed in the disk before the planets formed.



Wet or Dry? The Rutgers Test

Some stories depicting how chondrules formed require that the precursor material contain water-bearing (also called hydrated) minerals. This arises because calculations suggest that cooling of the gas-dust cloud below about 400 K causes the formation of hydrated minerals. Alternatively ice might condense and react to form hydrous silicates in lukewarm asteroids. If aggregates of such water-rich dust were melted, in space or on an asteroid or a planetesimal, the water would be released as a gas when the melting occurred. In fact, experiments show that the water would be lost in only a few seconds, forming bubbles in the magma. With enough bubbles, the magma might be disrupted into numerous droplets, perhaps forming chondrules in the process. However, it is far from certain that hydrated minerals would have formed in the gas-dust cloud because the chemical reactions involved are quite sluggish. Fortunately, whether hydrated minerals were in the pre-chondrule dust or not is a testable idea.

The complete lack of bubbles in chondrules suggests that no hydrated minerals were present. However, Maharaj and Hewins worried that chondrules might not retain bubbles even if they were there initially, depending on the conditions under which the chondrules formed. If they were flash heated and cooled very rapidly, preservation is likely. On the other hand, what would happen if they were flash heated repeatedly? Or heated at their melting points for a long time? What about the effects of heating a droplet in a vacuum? Maharaj and Hewins decided to do some experiments to answer these questions.

They first concocted a reasonable starting material. It consisted of chemical powders mixed thoroughly and melted to make a uniform glass. The composition of the mixture was the same as the average composition of a typical chondrule. The glass was ground to a powder. They then made a 50-50 mixture of the ground glass and a mineral called serpentine, which contains water in the form of the OH ion [$Mg_3Si_2O_5(OH)_4$]. This mixture was used in all their experiments.

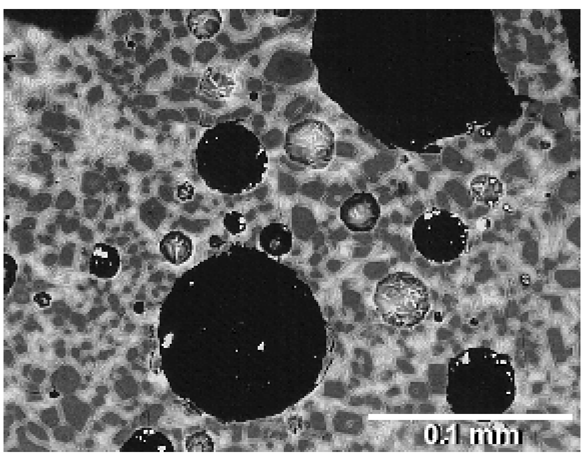
The experiments were done in a cylindrical furnace capable of heating to about 1600°C (1873 K). Devices called thermocouples measured the temperature inside the furnace. The temperature was continually monitored and was used to adjust the current being applied to the heating coils inside the furnace, thus maintaining a constant temperature. Samples can be held at a constant temperature for seconds, hours, days, or even months. When heated for the desired length of time (in the case of the Rutgers experiments 5 seconds to one hour), the samples can be cooled at a specified rate or rapidly quenched to room temperature. The Rutgers furnace is also capable of doing experiments in a vacuum (about 1/100,000 of atmospheric pressure).

The furnace used by Maharaj and Hewins is inside the white protective box. The box below it contains electronics for powering the furnace and controlling its temperature. Cylinders of gas are used to control the partial pressure of oxygen inside the furnace.

(Image courtesy of S. Maharaj.)

Always Bubbles

Every experiment Maharaj and Hewins conducted with the water-bearing mineral present produced artificial chondrules that contain gas bubbles. In one set of experiments, the powders were flash heated for 5 seconds and then cooled rapidly, and the same experimental charge was then heated again. This was repeated 5 to 25 times. Successive heating events caused a decrease in the percentage of bubbles, but even the charges flash heated and quenched 25 times still had a significant percentage of bubbles in them. In another set of experiments, the samples were heated to the melting point (1500^{o}C or 1773 K) for much longer than the 5-second flash melting. Those charges also had plenty of gas bubbles. Even the samples heated in vacuum, where escape of the gas should have been easier, contain significant percentages of gas bubbles.



Scanning electron microscope image of a typical experimental charge. This one was flash heated at 1500^{o}C for 5 seconds and quenched in a few seconds. The black, round areas are gas bubbles (also called vesicles). The dark areas with straight sides are crystals of olivine that formed during the rapid cooling of the experimental charge. Bright material is glass.

(Image courtesy of S. Maharaj.)

The table below summarizes the results of the experiments.

Experiment type	Time at 1500°C	Cooling rate	Number of melting events	Average % gas bubbles
Flash melting	5 seconds	500°C/hour	1	87
	5 seconds	500°C/hour	2	41
	5 seconds	500°C/hour	3	25
	5 seconds	500°C/second	1	70
	5 seconds	500°C/second	5	36
	5 seconds	500°C/second	25	21
Long duration	30 minutes	500°C/hour	1	16
	1 hour	500°C/hour	1	16
Vacuum	5 seconds	500°C/hour	1	37
	1 minute	500°C/hour	1	39
	30 minutes	500°C/hour	1	35

Significance of the Experiments

Maharaj and Hewins argue that they have explored enough variables to be sure that if chondrules were made from hydrated precursor materials they would contain numerous gas bubbles. Because chondrules do not contain any bubbles, Maharaj and Hewins conclude that they must have formed from aggregates of anhydrous (water-free) minerals. This tells us that the events that melted the dust aggregates must have taken place before any hydrated minerals formed, implying formation before the temperature dropped to about 400 K in the vast cloud of gas and dust from which the Solar System formed.

Alternatively, the experiments may mean that water vapor in the gas-dust cloud did not have time to react with previously formed water-free minerals. Instead, it may have condensed as ice. If an aggregate of ice and water-free minerals is flash heated, gas bubbles will also be produced. Or will they? No experiments on mineral-ice powders have been done. Until they are, we can only guess. Nevertheless, at least Maharaj and Hewins' experiments show that water-bearing minerals did not take part in the formation of chondrules.

Additional Resources

Exploring Meteorite Mysteries general information about meteorites and classroom activities from the Planetary Materials Curation Facility at Johnson Space Center. In order to view the documents, you may need to configure Adobe Acrobat Reader as your helper application.

Maharaj, Susan V. and Roger H. Hewins ,1998, Chondrule Precursor Minerals as Anhydrous Phases, *Meteoritics & Planetary Science*, v. 33, p. 881-887.