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Hot Idea posted October 21, 2005

Little Chondrules and Giant Impacts

--- Chondrules in metal-rich meteorites formed a couple of million years after most other chondrules, possibly by impact between moon-sized or larger objects.

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Alexander (Sasha) Krot (University of Hawaii), Yuri Amelin (University of Toronto), Pat Cassen (SETI Institute), and Anders Meibom (Museum National d'Histoire Naturelle, Paris) studied and then extracted frozen droplets of molten silicate (chondrules) from unusual meteorites rich in metallic iron-nickel. Called CB (Bencubbin-like) chondrites, these rare but fascinating meteorites contain chondrules with different properties than those in other types of chondrites. Most notably, the chondrules contain very small concentrations of volatile elements and variable concentrations of refractory elements. (Volatile elements condense from a gas at a relatively low temperature, or are boiled out of solids or liquids at relatively low temperature. Refractory elements are the opposite.) Some of the metal grains in CB chondrites are chemically zoned, indicating that they formed by condensation in a vapor cloud.

The most intriguing feature of chondrules in CB chondrites is their relatively young age. Lead-lead isotopic dating of chondrules separated from two CB chondrites show that they formed 5 million years after formation of the first solids in the solar system (calcium-aluminum-rich inclusions), which is about at least two million years after formation of other chondrules, and after energetic events in the solar nebula stopped. Krot and his colleagues suggest that the CB chondrules formed as the result of an impact between Moon- to Mars-sized protoplanets. Such impacts were so energetic that huge amounts of material were vaporized and then condensed as chondrules or chemically zoned metal grains. This event enriched refractory elements and depleted volatile elements. Such large impacts appear to play important roles in planet formation, including the formation of the Moon.

Reference:

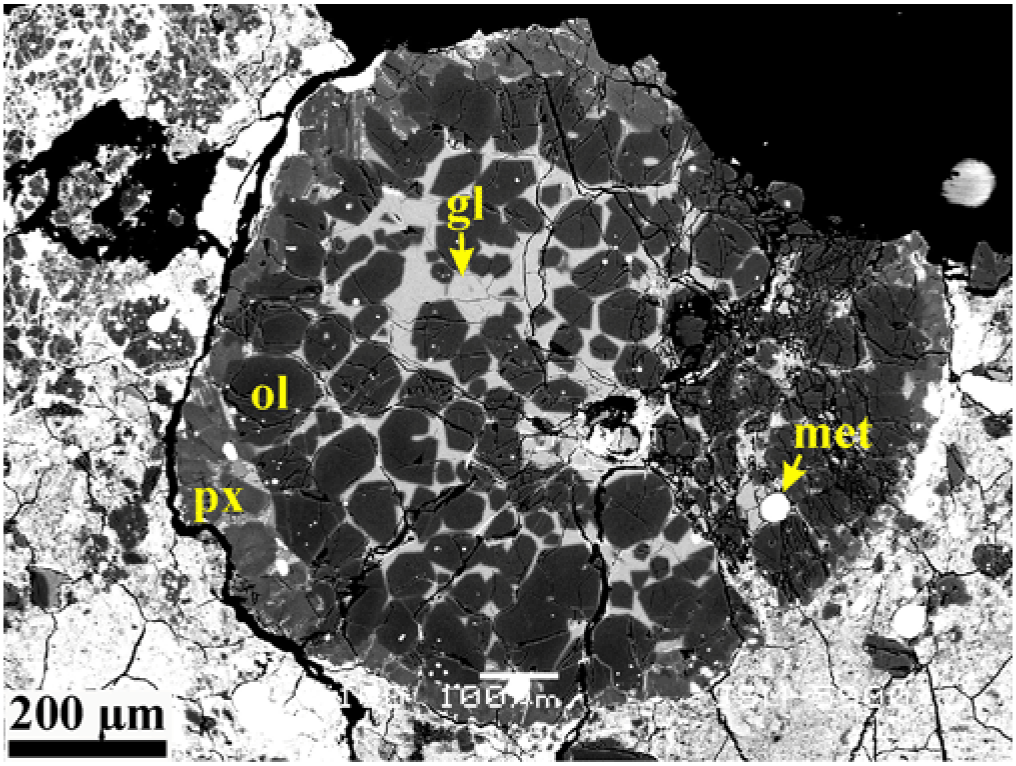
- Krot, Alexander N., Yuri Amelin, Patrick Cassen, and Anders Meibom (2005) Young chondrules in CB chondrites from a giant impact in the early Solar System. *Nature*, vol. 436, p. 989-992.

Normal Chondrules and their Formation

Most meteoriticists think that normal chondrules (if "normal" is the right word to use for millimeter-sized frozen droplets of silicate melts that formed before the planets) formed by flash heating events in the solar nebular, the flattened cloud of gas and dust in which the Sun and planets formed. (See **PSRD** article: Flash Heating.) Numerous ideas for the source of flash heating were devised over the years, but the favorite now is shock waves in the solar nebula. There are, as usual in science, a lot of ideas for the origin of the shock waves.

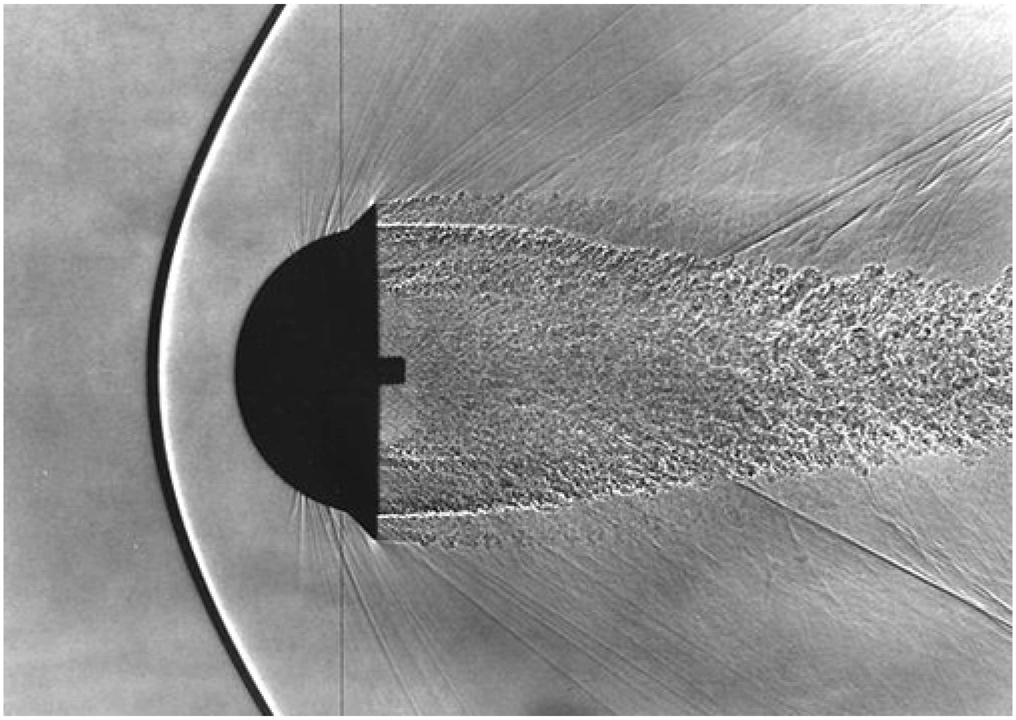
- Accretion shocks, in which energetic waves are set up as dust falls onto the growing accretion disk around the proto-Sun.
- Waves set up by infalling clumps of dust and gas.
- Bow shocks in front of planetesimals moving through the dusty nebula.
- Formation of spiral arms and clumps in the protoplanetary disk.
- Eruption of X-ray flares from the young Sun.

A Normal Chondrule



(Sasha Krot, University of Hawaii)

This backscattered electron image shows a typical normal chondrule in a CR carbonaceous chondrite. Most of the grains are olivine crystals (black, labeled ol). They are surrounded by a glass (grey, labeled gl). Pyroxene (px) and droplets of metallic iron (white, labeled met) are also visible.



(NASA)

The image above shows the shock wave in front of a blunt object (moving from right to left) in a wind tunnel during an experiment at NASA Ames Research Center. This may resemble the shock wave preceding a planetesimal moving through the solar nebula.

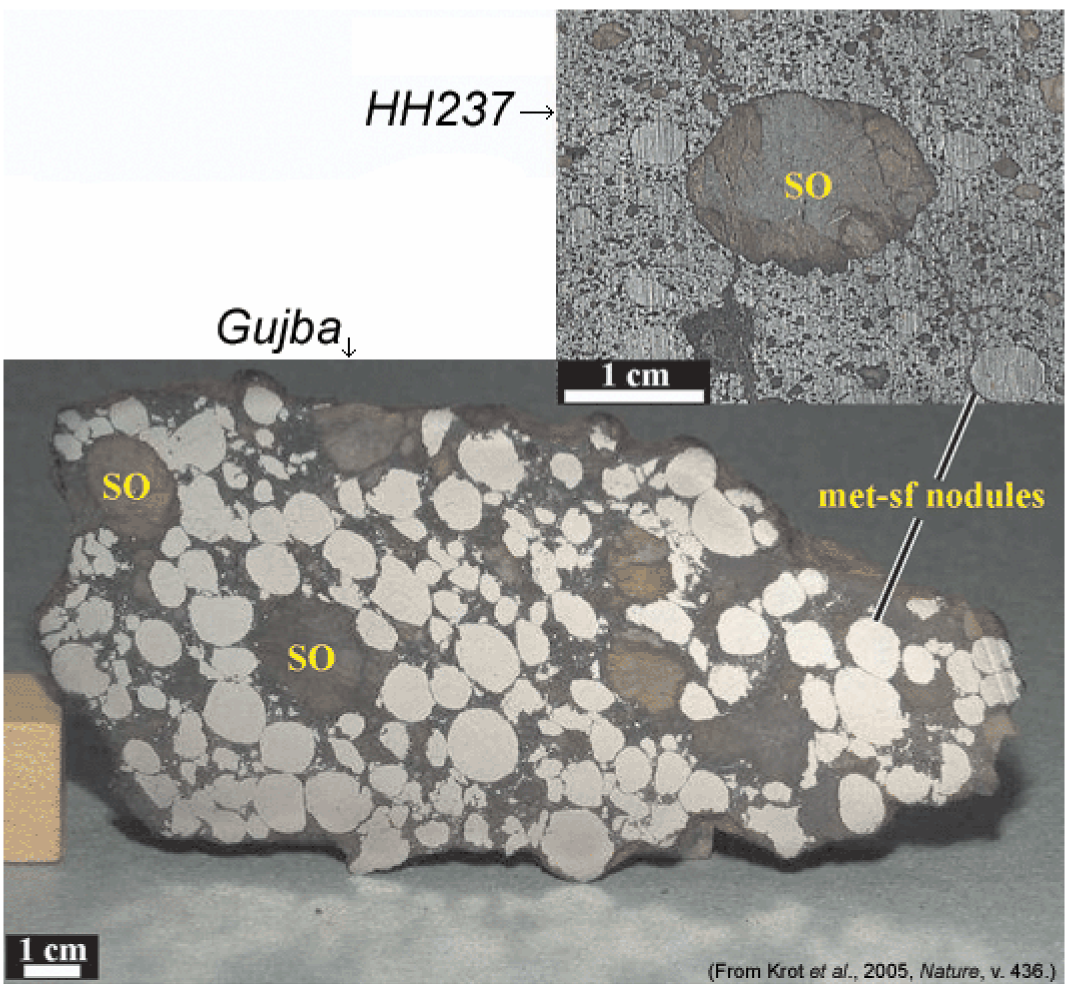
(NavSource Naval History)

Spherical shock waves generated by the firing of the huge guns of the USS Iowa are clearly visible on the ocean surface. While not exactly a simulation of a shock wave in the early solar system, the photograph gives a good view of the shock wave generated by the explosion.

Not everyone agrees with an origin by shock waves in the solar nebula, of course. Some meteoriticists think chondrules originated during impacts between solid or molten small bodies. Everyone agrees, however, that chondrules made their appearance early in the history of the solar system. Isotopic dating of chondrules shows that they formed within three million years of the formation of calcium-aluminum-rich inclusions (CAIs), the first solids to be produced in the solar nebula. This was a busy period. Most meteoriticists and astrophysicists believe that not only did shock waves create CAIs and normal chondrules from fluffy balls of dust, but chondrules and dust accreted into asteroid-sized planetesimals, some of which were melted by short-lived isotopes (mostly ^{26}Al), forming metallic cores, mantles, and basaltic crusts. Other planetesimals were just heated a bit. All this in a period lasting only 3 million years. (Only geologists and astronomers attach the adjective "only" to 3 million years. But 3 million years is *only* 0.07% of the age of the Solar System.)

CB Chondrites and Their Unusual Chondrules

There is an unusual group of five chondrites, named CB chondrites (for Bencubbin-like, one of their members). Their most notable feature is that they are loaded with round chunks of metallic iron-nickel. Many of the metal particles in two members of the group, HH 237 and QUE 94411, are chemically zoned in a way that indicates formation from a hot, but cooling, gas (see **PSRD** article: The Oldest Metal in the Solar System). Besides big, abundant metal particles, the CB chondrites have distinctive chondrules in them. Instead of chondrules that contain abundant large crystals in a fine-grained matrix, those in CB chondrites are much more uniform in grain size. One type of chondrule is called "cryptocrystalline," which means that the crystals are too small to be seen even in a microscope. A second type contains olivine crystals shaped like a small, skinny skeleton, called "skeletal" (e.g. see insert figure below).



Photograph of a polished slab of Gujba, with insert of closer view of another CB chondrite, Hammadah al Hamra 237. Note the large abundance of metallic iron (bright). The chondrule in HH 237 is a skeletal olivine (SO) chondrule; it is surrounded by metallic iron.

A striking chemical feature of CB chondrules is that they are very depleted in volatile elements. Even moderately volatile elements such as sodium and potassium are very low in abundance. In contrast, refractory elements (these condense from a gas at a high temperature and include calcium, titanium, aluminum, and the rare earth elements) are all in the same relative abundance as in average solar system materials (given by CI carbonaceous chondrites and measurements of the Sun), but their abundance varies from 4 times higher than CI to only 1% of CI.

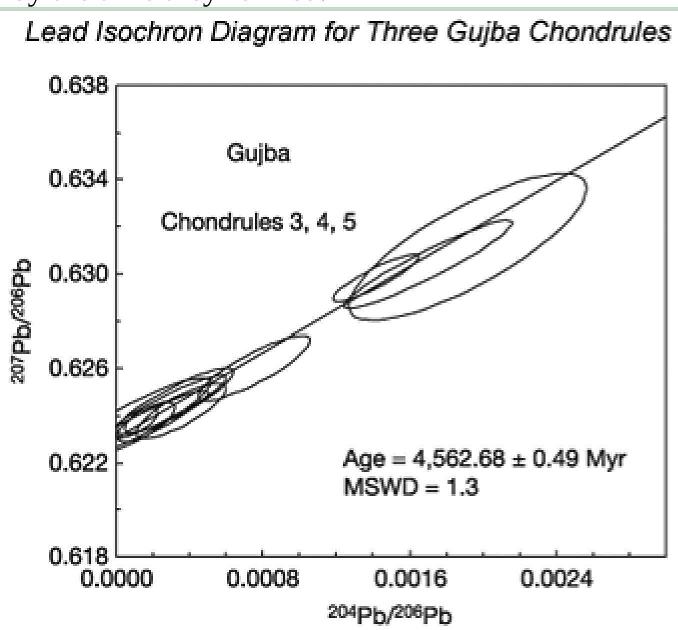
Meteoriticists do not agree on how these unusual chondrites formed. Some suggest energetic events in the solar nebula; others suggest impacts between asteroids. Nebula models require that the chondrules in CB chondrites be old, while the nebula was still around. On the basis of observations of disks around other stars and theoretical calculations, astronomers say that the solar nebula lasted only about 3 million years. Thus, CB chondrules ought to have formed within 3 million years of the origin of the solar system. Normal chondrules are no more than 3 million years younger than calcium-aluminum-rich inclusions (CAIs), the first solid objects formed when the Solar System formed. Krot and his colleagues wanted to determine the ages of the unusual chondrules in CB chondrites.

The Young Ages of CB Chondrules

Krot separated chondrules from two CB chondrites, Gujba and HH 237. He characterized these carefully using scanning electron microscopy and electron microprobe analysis, then passed them on to Yuri Amelin for lead-lead age dating. These are painstaking analyses to make, especially on such small samples. It requires a special clean room (to isolate the samples from lead all around us) and ultra-clean chemicals.

Lead-lead dating uses the fact that ^{207}Pb-^{206}Pb are produced at different rates from their parent isotopes, ^{235}U and ^{238}U, respectively. By also measuring ^{204}Pb, which is not produced by radioactive decay, cosmochemists can make a diagram called an isochron. The samples, if all have the same age, lie on a line whose slope defines the age. It takes a bit of math and knowledge of the decay rates of uranium isotopes.

The results for Gujba and HH 237 are shown in the isochron diagram below. The chrondrule and chondrules fragments from each sample fall on well-defined lines that indicate the same age within analytical uncertainty, 4,562.7 (plus/minus 0.5) million years for Gujba, and 4,562.8 (plus/minus 0.9) million years for HH 237. This indicates that they formed at essential the same time. More important, their age is 5 million years younger than the age of CAIs, 4,567.2 (plus/minus 0.7) million years. CB chondrules are not only younger than CAIs, they are so much younger that solar nebula processes should have shut off by the time they formed.

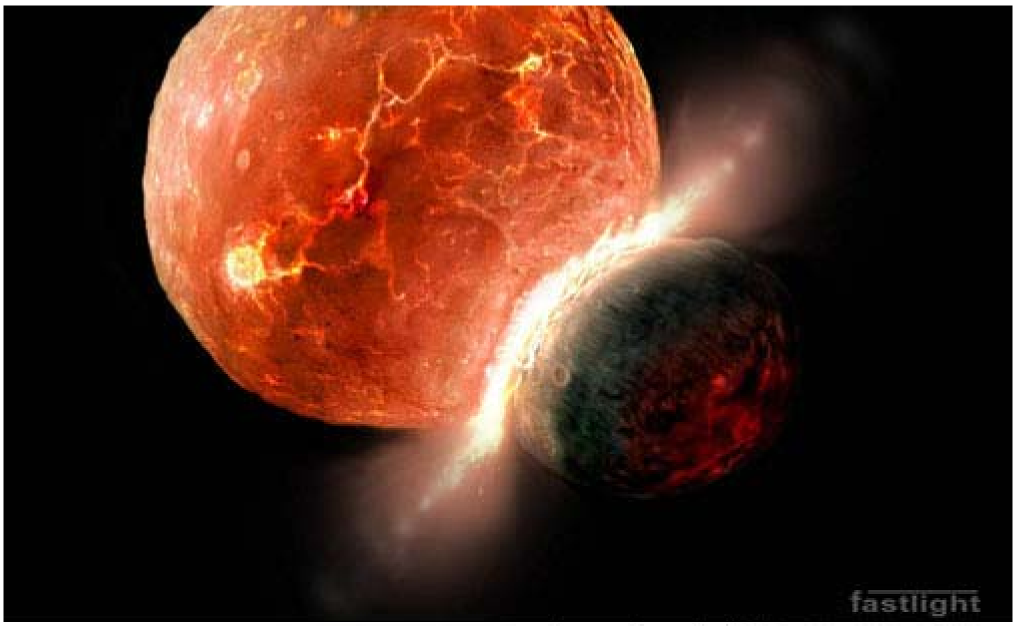


(From Krot *et al.*, 2005, *Nature*, v. 436, p.991.)

^{204}Pb /^{206}Pb vs ^{207}Pb /^{206}Pb diagram for chondrules separated from Gujba. The ellipses show two-standard-deviations uncertainty around each data point. The data lie on a well-defined line that indicates and age of 4,562.68 million years. This age is about 5 million years younger than the oldest materials in the Solar System.

Chondrule Formation by Impact?

So, the CB chondrites (at least Gujba and HH 237) formed after the solar nebula had finished being energetic. Yet their formation indicates an energetic process was involved. The metal was melted and some seems to have formed from a vapor. Chondrules were totally molten droplets that contained no pre-existing debris and cooled rapidly. All these features point a cosmic finger at formation during an impact event. In a collision between large objects, there is a lot of vaporization and melting. These hot conditions provide settings in which metal nodules and skeletal olivine chondrules form by melting, and cryptocrystlline chondrules (which are smaller) are made by condensation from a vapor. There are no unmelted remnants of the original materials left in these meteorites. This is consistent with their formation by impact between two objects the size of Earth's Moon. Such a monumental collision would separate melt and vapor from unmelted materials.



James Garry, Fastlight Used with permission.

Collision between two Moon-sized (or larger) objects in the early Solar System would have produced vast amounts of melt and vapor, from which the components in CB chondrites could have formed. Such impacts may have been common for a few million years early in the evolution of the Solar System.

Crash, Bam, Whack, Slam: The Early Solar System

Astrophysical models of the very early Solar System suggest that the asteroid belt (where CB chondrites come from) contains only 0.1% as much material as was present initially. Within a few million years of formation of the solar nebula most of that mass was in the form of Moon to Mars-sized planetary embryos. How fast they were depleted by mutual collisions (a critical part of the planet-forming process) depended on exactly when Jupiter and Saturn formed because gravitational interactions between the embryos and the giant planets caused mixing throughout the asteroid belt. Collisions among these big rocky balls would have been extremely energetic, producing the conditions necessary to form CB chondrites.

Sasha Krot and his colleagues tell an interesting story. An appealing aspect of it is that it fits in with the current paradigm for planet formation. This involves impacts between planetary embryos until they either formed the inner planets or were scattered to the far reaches of the Solar System, never to return. Some of the large objects in the asteroid belt must have collided with each other. Perhaps there are other products in other types of chondrite that we ought to examine. In fact, perhaps non-chondrites, which we think formed by melting inside asteroids, formed as the result of giant impacts.

Most planetary scientists think that the Moon formed as the result of an impact between a Mars-sized planetary embryo with the young Earth. Like CB chondrites, the Moon is depleted in volatile elements and enriched in refractory elements. Perhaps the CB impact event (if there was one, of course) is a small example of the Moon-forming giant impact.

The early Solar System was a violent place! Carlé Pieters' (Brown University) poem about the Moon, published in **Origin of the Moon**, has a particularly appropriate line that reads, *"Moon holds secrets of ages past when planets dueled for space."* Apparently CB chondrites also hold some secrets about an epoch when planets dueled for space.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Fastlight Artwork for aerospace and spacecraft projects.
- Krot, Alexander N., Yuri Amelin, Patrick Cassen, and Anders Meibom (2005) Young chondrules in CB chondrites from a giant impact in the early Solar System. *Nature*, vol. 436, p. 989-992.
- **Origin of the Moon** (1986) W. K. Hartmann, R. J. Phillips, G. J. Taylor (eds.), Lunar and Planetary Institute, 781 p.
- Taylor, G.J. (2000) Flash Heating. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Mar00/flashHeating.html
- Taylor, G.J. (2000) The Oldest Metal in the Solar System. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Sept00/primitiveFeNi.html

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