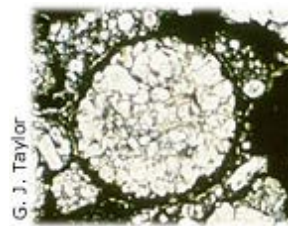


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Headline Article

April 17, 2017

Chondrules: Important, but Possibly Unfathomable



--- Studies of chondrules in meteorites have revealed much about them, except how they formed and if they played a role in forming planets.

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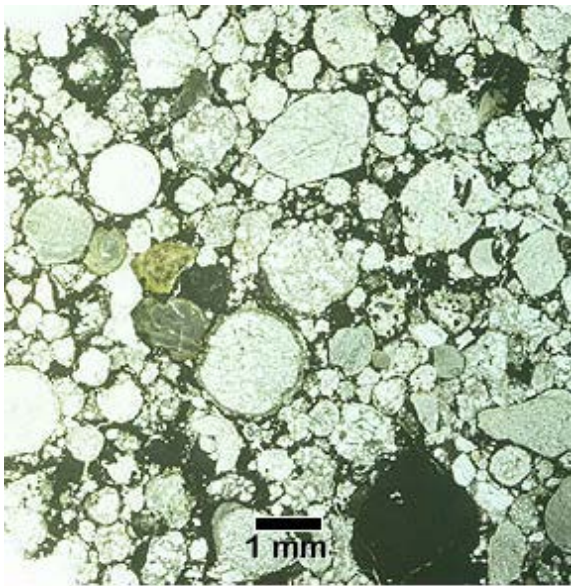
Chondrules are mysterious little droplets of formerly molten silicate found in chondrite meteorites. Harold C. Connolly Jr. (Rowan University, New Jersey) and Rhian H. Jones (University of Manchester, UK) have written a concise review of the properties of chondrules and ideas for their origin. Over a century of chondrule studies have revealed much about their heating and cooling histories, mineralogy, textures (mineral sizes and how the crystals are intergrown), chemical and isotopic compositions, and ages (old—they formed during the first few million years of Solar System history). Nevertheless, cosmochemists are still uncertain how chondrules formed and whether they inform us of conditions and processes in the protoplanetary disk (also called the solar nebula) or are mere by-products of planet formation.

Reference:

- Connolly, H. C., Jr. and Jones, R. H. (2016) Chondrules: The Canonical and Noncanonical Views, *Journal of Geophysical Research: Planets*, v. 121(10), p. 1885-1899, doi: 10.1002/2016JE005113. [[abstract](#)]
- **PSRDpresents:** Chondrules: Important, but Possibly Unfathomable -- [Short Slide Summary](#) (with accompanying notes).

Enigmatic and Important

Chondrules are millimeter-sized, originally molten, rapidly cooled, roundish objects in **chondrites**, a type of primitive, meteorite that contains chondrules. Considering that chondrites are abundant and the oldest rocks in our museums, chondrules must be important. But as Harold Connolly and Rhian Jones point out, from an astrophysical, astronomical, planetary science, or geological perspective, nobody would predict that planetary materials would be processed into tiny molten droplets before accumulating into **planetesimals**. Once they were identified, inventive ideas blossomed to explain how they formed, with ideas coming from astrophysics and cosmochemistry.



(photomicrograph by G. J. Taylor)

Photomicrograph of the [chondrite Semarkona](#) [[Data Link](#) from the Meteoritical Bulletin Database], showing that it is mostly a pile of [chondrules](#). In this sample, most chondrules are about 1 millimeter in diameter.

The existence of chondrules forced us to invent processes operating in the [solar nebula](#) and to test if they fit into our models of [protoplanetary disk](#) formation and evolution. Others skipped that stage and examined processes that operated during and after formation of planetesimals. Connolly and Jones raise the important question of whether chondrules are the keys to understanding previously unknown processes in the protoplanetary disk or are the by-products of planet formation. Whichever it turns out to be, chondrules tell a story of our early Solar System, and even in other protoplanetary disks and planetary systems surrounding other stars.

The first step is to use the properties of chondrules (compositions, mineralogy, sizes) to determine thermal histories (how hot and for how long?), the environments in which they formed, how they acquired their chemical compositions, and when did it happen?

Chondrites, the Chondrule Storage Facilities

To put chondrules in the right cosmochemical context, Connolly and Jones discuss the critical aspects of chondrites, which we can view as long-term chondrule storage facilities. Chondrites come from [asteroids](#), though we do not know which asteroids. We know that some must come from asteroid 25143 Itokawa (see [PSRD](#) article: [Samples from Asteroid Itokawa](#)). In many ways, chondrites are like sedimentary rocks on Earth: they contain components (mostly chondrules) that formed at different times and in different places, yet end up mingling in a gravitationally-bound pile. Connolly and Jones outline the importance of chondrites, besides being repositories of chondrules.

The top seven reasons why chondrites are important are:

1. The components in chondrites provide a record (even if it is difficult to read) of the processes that operated in the protoplanetary disk before the pieces [accreted](#) into their parent asteroids. A lot of work has been done on the components in chondrites, especially in those that were not heated significantly in their asteroidal homes.
2. Chondrite bulk chemical compositions are similar to the Sun, specifically the solar photosphere, indicating that they are primitive and not excessively reworked like meteorites formed in asteroids that melted.
3. One of the most famous components in chondrites are [refractory inclusions](#) such as those enriched in calcium and aluminum, and nicknamed named [CAIs](#). Many of these are strikingly old and give a solid measure of the age for the first solids to form in the Solar System, 4.567 billion years. See [PSRD](#) article: [Dating the Earliest Solids in Our Solar System](#).

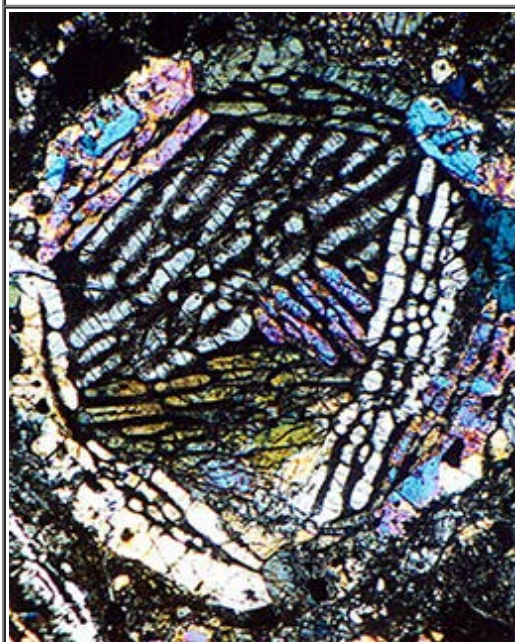
4. Chondrites preserve the record of the timing of chondrule formation, which are mostly (not entirely) younger by up to 3 million years than CAIs. See **PSRD** article: [Dating Transient Heating Events in the Solar Protoplanetary Disk](#).
5. Some chondrites even contain organic compounds, including **amino acids**, which some investigators have taken as evidence that **carbonaceous chondrites** could have seeded the primitive Earth with the ingredients for life. See **PSRD** article: [Wet, Carbonaceous Asteroids: Altering Minerals, Changing Amino Acids](#).
6. Chondrites contain tiny grains that were formed in other stars before the birth of our Solar System. See **PSRD** article: [Silicate Stardust in Meteorites](#).
7. Some chondrites contain a clear record of heating (thermal metamorphism) and alteration by water, both of which occurred early in the histories of their parent asteroids. See **PSRD** article: [Chondritic Meteorites: When Did Aqueous Alteration Happen?](#) To understand the chemical and mineralogical properties of chondrules it is best to avoid heated or altered chondrites, unless it is clear that the chondrules were not affected by these processes in their parent asteroids.

Chondrule Facts and Near-facts

Nobody has questioned the conclusion that Gustav Tschermak made in 1885 that chondrules are little **igneous** rocks. They are rapidly cooled droplets of molten silicate. Central factors about this melting are open questions, such as the highest temperatures to which they were heated (called the peak temperature), how long they were heated, and how fast they cooled. All these factors contain information about the environment where the melting and cooling occurred.

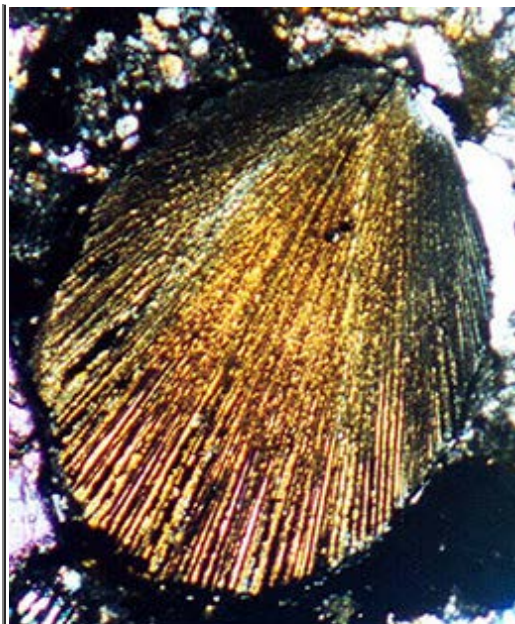
Chondrules vary in their appearance, main minerals, and chemical compositions (especially in the ratio of oxidized iron to magnesium). The table below gives an idea of their variability and of how stunning chondrules are when thin slices are viewed in polarized light under the microscope. Not all chondrule types are listed here. (The term **porphyritic** means that some crystals are much larger than the surrounding areas.)

PHOTOMICROGRAPHS OF CHONDRULES IN POLARIZED LIGHT
Courtesy of Ted E. Bunch ([Northern Arizona Meteorite Laboratory](#)) and Harold C. Connolly Jr. and Rhian H. Jones.



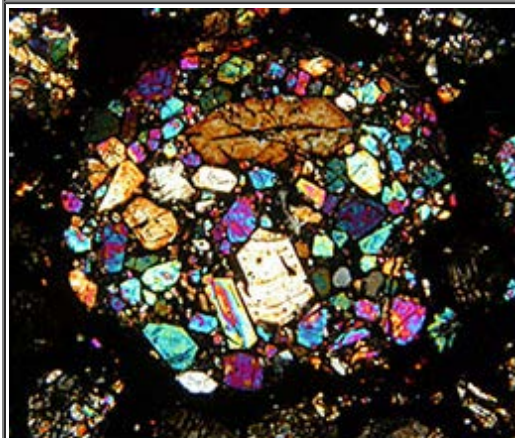
(T. E. Bunch / Northern Arizona Univ. Meteorite Lab)

Barred olivine chondrules have long parallel arms of olivine in a fine-grained to glassy matrix.



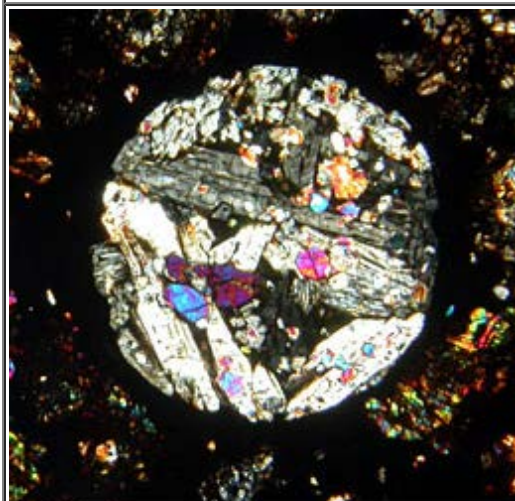
(T. E. Bunch / Northern Arizona Univ. Meteorite Lab)

Radial pyroxene chondrules have thin sheets of low-calcium pyroxene radiating out from a single point where crystal growth started. Same credit.



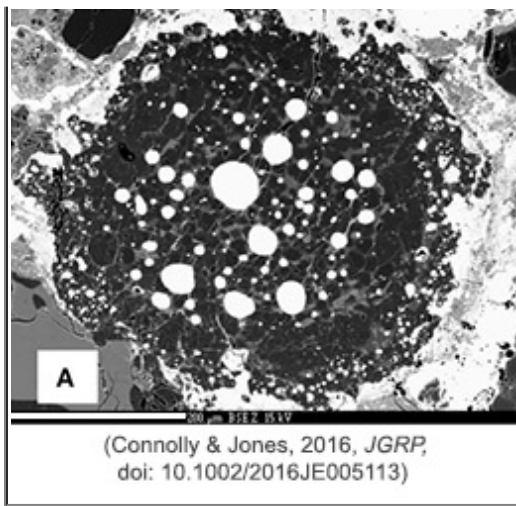
(T. E. Bunch / Northern Arizona Univ. Meteorite Lab)

Porphyritic olivine chondrules have large crystals of olivine surrounded by a fine-grained to glassy matrix.



(T. E. Bunch / Northern Arizona Univ. Meteorite Lab)

Porphyritic pyroxene chondrules have large crystals of low-calcium pyroxene in a fine-grained to glassy matrix. This one also contains (brightly-colored) olivine crystals.

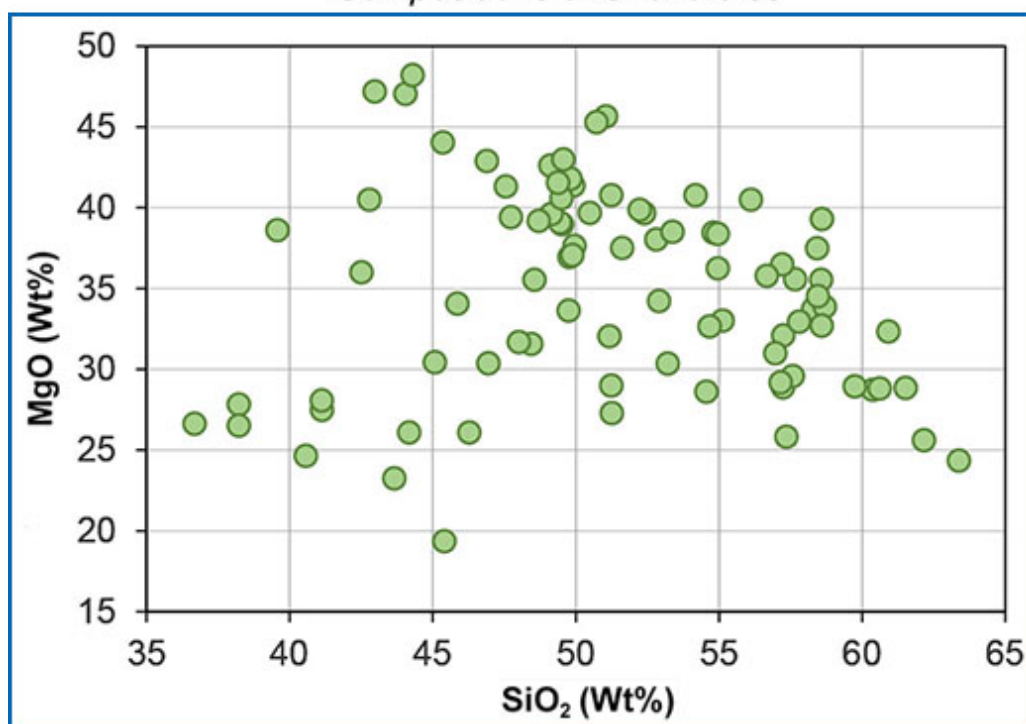


Backscatter electron image of (bright) metallic iron-nickel blobs in porphyritic olivine chondrule. Scale bar is 200 μm .

(Connolly & Jones, 2016, *JGRP*, doi: 10.1002/2016JE005113)

Chondrule compositions vary impressively, an important fact that hypotheses for their origin need to take into account. An example of the large range in the compositions of chondrules is shown in the graph below that has data from four different chondrites. Another important (and amazing) feature is that any given chondrite contains essentially the full range of chondrule compositions shown in the graph. Models for chondrule origin need to explain how this compositional diversity arose.

Compositions of Chondrules



(From Berlin, J., 2009, *Mineralogy and Bulk Chemistry of Chondrules and Matrix in Petrologic Type 3 Chondrites: Implications for Early Solar system Processes*, PhD, University of New Mexico. <http://hdl.handle.net/1928/10275>)

Variation in the concentrations of magnesium oxide (MgO) and silicon dioxide (SiO_2) in chondrules from four different chondrites. Any model for chondrule formation must account for such variations in chemical composition. Data are from the Ph.D. dissertation of Jana Berlin (University of New Mexico) and can be found at <http://hdl.handle.net/1928/10275>. The research was done with Drs. Adrian Brearley and Rhian Jones at the University of New Mexico. (Jana is now at Bruker, Inc. in Berlin, Germany.)

To understand the environment in which chondrules formed, scientists have performed numerous melting experiments on concoctions with the same chemical compositions as chondrules, paying close attention to reproducing the crystal shapes and intergrowths seen in natural chondrules. This work was valuable in assessing

the rates at which chondrules cooled and in demonstrating that many were not completely melted when they formed. (See **PSRD** article: **Dry Droplets of Fiery Rain**.) The experiments indicate that some chondrules, such as barred olivine chondrules, were heated to a temperature at which the entire droplet is molten (1750 to 2200 °C, depending on composition). In contrast, experiments show that porphyritic chondrules were heated to only 1550 °C, which implies that some unmelted debris remained from the heating phase before cooling started. Porphyritic textures are matched by experimental cooling at rates between 0.5 and 100 °C/hour.

Non-porphyritic chondrules probably cooled much faster, but there is a complex interplay between peak temperature and cooling rate: the non-porphyritic chondrules might have been heated hot enough to remove all traces of crystal nuclei (the building blocks for crystal formation), yet cooled slowly. In other words, non-porphyritic chondrules might not have had any leftover solids after the heating phase of their formation was done; but porphyritic chondrules did have dusty grains left over. In fact, studies of natural chondrules show that some porphyritic chondrules contain relict olivine grains the size of the porphyritic olivine crystals. This indicates some recycling of pre-existing chondrules during chondrule manufacture. An additional type of chondrule is characterized by being very fine-grained and depleted in volatile elements such as sodium and sulfur. These appear to have been heated to high temperatures and cooled on the order of a few tenths of a degree C/hour. See **PSRD** article: **Relicts from the Birth of the Solar System**.

Diverse and Numerous Ideas for How Chondrules Formed

There is no shortage of hypotheses for chondrule formation. Connolly and Jones summarize the ideas and their variants. I will give a brief overview of the main types of ideas, many of which have been discussed in **PSRD** articles before.

Early active Sun:

The Sun is hot, so logically if material drifts close to it, it ought to be heated. More important, the young Sun was actively spewing out material that in principle could interact with the dust in the solar nebula, or at least transfer heated products to further out in the solar nebula. These ideas are good, but none has detailed how the mechanism reproduces chondrule thermal histories that include rapid heating and somewhat slow cooling.

Impacts between planetesimals:

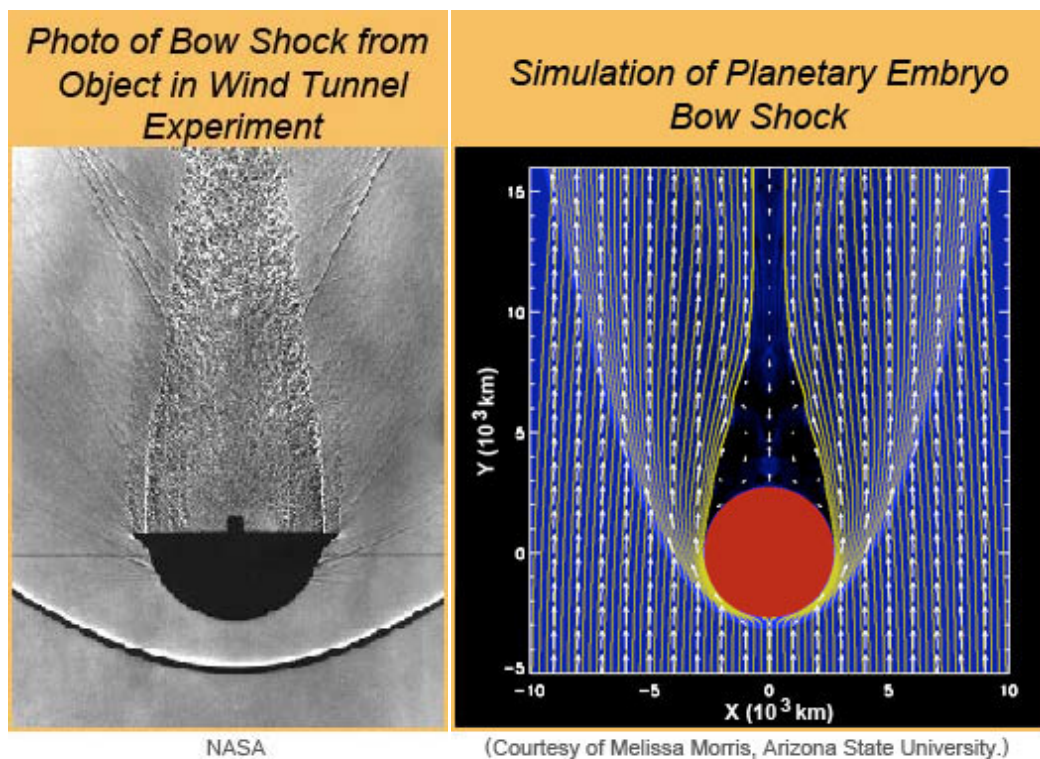
You don't build planets without collisions, and some might be fast enough to cause melting. In 2011 Erik Asphaug (then at the University of California, Santa Cruz and now at Arizona State University) and colleagues proposed that chondrules formed by collisions between molten or partially molten planetesimals. Ian Sanders (Trinity College, Dublin) and my colleague Ed Scott (University of Hawai'i) also have proposed this idea. None of the models so far appears to have the right thermal history for chondrules or explains the compositional diversity.

An interesting variant of the impact model was proposed in 2015 by Brandon Johnson (then at MIT and currently at Brown University) and coworkers. They propose that molten material jets out from the point of impact between two fast-moving planetesimals. See **PSRD** article: **Ancient Jets of Fiery Rain**. The mechanism produces reasonable thermal histories for the droplets produced and for the abundance of chondrules. Johnson and coworkers suggest that chondrules are a "byproduct of [planetary] accretion," an important feature of all impact models in that it makes chondrules secondary, not primary solar nebula products. The model does not explain quantitatively the range in chondrule compositions.

Shock waves in the solar nebula:

Chondrule formation has been proposed by lightning discharges in the solar nebula or shock waves generated by materials accreting to the protoplanetary disk or motions of planetesimals and planet-sized objects. An interesting variant of nebula shocks is compression of the gas-dust cloud in front of a fast-moving planetary embryo. Such

bodies are Moon- to Mars-sized objects formed rapidly early in Solar System history. The idea is that they eventually accrete to form the inner planets. Their orbits are not circular, which gives them high relative velocities compared to the nebular gas. As a planetary embryo plows through the gas, it creates a shock in front of it (called a "bow shock"), compressing and heating the dust and gas, possibly leading to the formation of chondrules. Melissa Morris (Arizona State University and The State University of New York, Cortland) and colleagues modeled the bow shock surrounding a Mars-sized object as it plowed through the nascent Solar System (see illustration below). They point out that **isotopic** analysis by Nicolas Dauphas (University of Chicago) and colleagues strongly suggests that Mars formed in 2–4 million years, while the nebular gas was still present.



[Left] This photo shows the shock wave in front of a blunt object (moving from top to bottom) 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. **[Right]** Computer simulation by Melissa Morris and colleagues of a Mars-size embryo moving through the dusty solar nebula.

The Need to Know

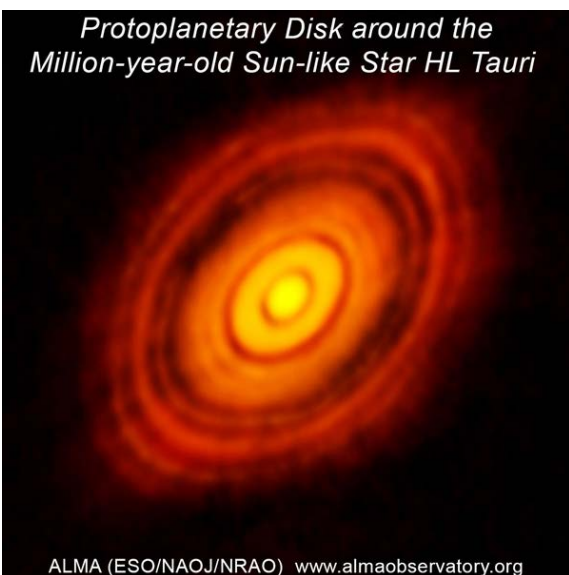
Chondrules formed somehow, but how? Which of the ideas will win the origin-of-chondrules challenge? Connolly and Jones give a long list of things we need to know. These include:

- Whether chondrules formed in open systems, freely exchanging elements and isotopes between melt and surrounding gas. This would provide important information about the physical setting of chondrule formation.
- What conditions led to molten chondrules being stable in the solar nebula. At the typical pressure in this gas-dust disk around the young Sun, molten rocky droplets would evaporate. Perhaps the gas pressure was higher (at least locally) than simple disk models call for, which favors some models over others.
- Why are chondrules so chemically diverse? Why are all the types of chondrules and all the compositional types present in almost all chondrite groups?
- Why do chondrule sizes vary from one chondrite group to another? Why are there no big chondrules (the largest are only a couple of centimeters across)? Do the sizes reflect their formation conditions or subsequent sorting?

The presence of relict grains in chondrules indicate recycling. How many times were chondrules recycled?

- Although all types of chondrules occur in most chondrite groups, why does each group have its own set of properties such as mean chondrule size or isotopic compositions?
- What is the relationship between chondrules and CAIs? CAIs formed earlier by 2–3 million years, suggesting a progression from melting refractory materials first, then the more abundant materials that make up chondrules. Was this progression due to the process that did the melting or to the environment in which the melting took place?
- What properties of chondrules were controlled exclusively by the process that formed them, and which are due to the environment in which they formed?
- What is the cosmic importance of chondrules, if any? Will study of solar systems forming around other stars reveal the role chondrules play in planet formation?

These are important questions, and some are way harder than others to answer. Perhaps the overriding issue to settle is whether chondrules formed by a fundamental process in the solar nebula, hence provide information about planet formation, or they formed as by-products of the planet formation. Being a by-product would disappoint many cosmochemists, although even by-products have important information about the manufacturing process that produced them.



Chondrules might have broader cosmic significance beyond helping us understand formation of our Solar System. Astronomers have identified other solar systems that contain Earth-like planetary bodies. Did chondrule formation play a role in the formation of those far-off planets? Or could we observe the record of chondrule formation that might indicate their secondary origin as planets swept through dusty disks? As Connolly and Jones point out, such observations could be impossible, at least for now, but observing chondrule formation in action would provide a look back to the time when the protoplanetary disk around the Sun was evolving and planets were growing. Studies of chondrules and ideas for their origin give astronomers something concrete to search for in those distant places.

Protoplanetary disk image produced by the international astronomy facility known as ALMA — The Atacama Large Millimeter/submillimeter Array. This image was acquired during the ALMA Long Baseline Campaign. The dark rings in the disk may mark regions where planets are accreting. (ALMA, C. Brogan, B. Saxton.) Read more about it in this [PSRD CosmoSpark](#).

Over a century of research on these fascinating little spheroids and yet we still haven't found what we are looking for, yet cosmochemists continue their quixotic search for answers.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Chondrules: Important, but Possibly Unfathomable --[Short Slide Summary](#) (with accompanying notes).
- Asphaug, E., Jutzi, M., and Movshovitz, N. (2011) Chondrule Formation During Planetesimal Accretion, *Earth and Planetary Science Letters*, v. 308, p. 369-379, doi: 10.1016/j.epsl.2011.06.007. [[abstract](#)]

- Chondrules and the Origin of Meteorites, from [Northern Arizona Meteorite Laboratory](#)
- Connolly, H. C., Jr. and Jones, R. H. (2016) Chondrules: The Canonical and Noncanonical Views, *Journal of Geophysical Research: Planets*, v. 121(10), p. 1885-1899, doi: 10.1002/2016JE005113. [[abstract](#)]
- Dauphas, N. and Pourmand, A. (2011) Hf-W-Th Evidence for Rapid Growth of Mars and its Status as a Planetary Embryo, *Nature*, v. 473, p. 489-492, doi: 10.1038/nature10077. [[abstract](#)]
- Doyle, P. M. (June, 2015) Chondritic Asteroids—When Did Aqueous Alteration Happen? *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/June15/Mn-Cr-fayalites.html>.
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- Martel, L. M. V. (November, 2014) Extraordinary View of a Star and its Protoplanetary Disk, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/CosmoSparks/Nov14/HL-Tauri-protoplanetarydisk.html>.
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- Taylor, G. J. (March, 2001) Relicts from the Birth of the Solar System, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/Mar01/relicts.html>.
- Taylor, G. J. (June, 2004) Silicate Stardust in Meteorites, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/June04/silicatesMeteorites.html>.
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- Taylor, G. J. (November, 2012) Dating Transient Heating Events in the Solar Protoplanetary Disk, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/Nov12/ages-CAIs-chondrules.html>.
- Taylor, G. J. (April, 2015) Ancient Jets of Fiery Rain, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/April15/impact-jetting.html>.

Taylor, G. J. and Martel, L. M. V. (August, 2011) Samples from Asteroid Itokawa, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/Aug11/Itokawa-particles.html>.



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