

## Hot Idea

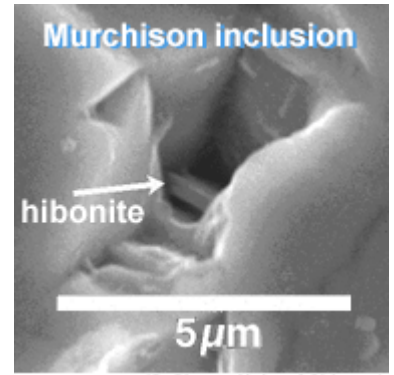
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# The First Rock in the Solar System

--- An aggregate of corundum, hibonite, and perovskite may be among the first rocks to form in the Solar System.

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My colleagues Andrew Davis, Lawrence Grossman (both of University of Chicago), Kevin McKeegan (UCLA), and I have discovered an exceptionally [refractory inclusion](#) in the Murchison carbonaceous [chondrite](#). It is an aggregate of corundum, hibonite, and perovskite, the three minerals expected to condense first in a hot, cooling gas of solar composition. This inclusion was one of the first rocks to form in the solar system 4.5 billion years ago. It was preserved by being sequestered rapidly from the gas and enclosed in a growing carbonaceous chondrite asteroid.

### Reference:

Simon, S. B., A. M. Davis, L. Grossman, and K. D. McKeegan (2002) A hibonite-corundum inclusion from Murchison: A first-generation condensate from the solar nebula. *Meteoritics and Planetary Science*, v. 37, p. 533-548.

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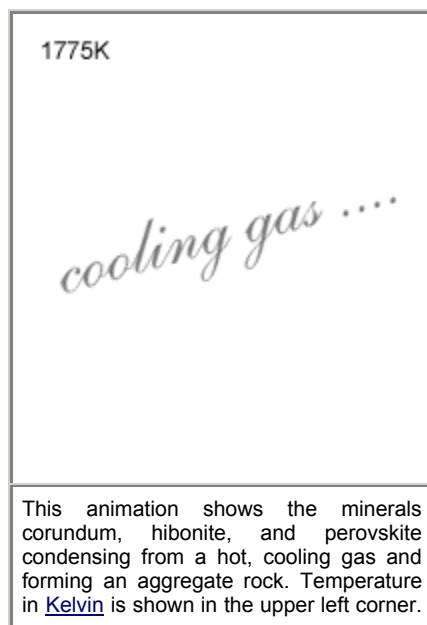
## Samples From the Developing Solar System

A major area of interest in planetary science is the origin and early history of the solar system. We know a great deal about the solar system, but we continue to strive to learn more details, such as the early temperature and pressure conditions. We know that the solar system formed from a large cloud of gas and dust known as the [solar nebula](#). The sun contains 99.9% of the mass of the solar system and we know the composition of the sun from spectroscopic analysis of the light it emits; therefore we basically know the composition of the solar nebula. We can use known physical properties and stabilities of minerals to calculate what minerals will form from a gas of this composition as it cools, and derive a theoretical, equilibrium condensation sequence of minerals that formed as the solar nebula cooled. Finding the predicted minerals and studying them would support the condensation model and improve our understanding of the early solar system.

For detailed study of materials from the early solar system, we need to have samples. The Earth is too active a planet to provide the necessary samples, as its rocks are weathered, eroded, folded, and remelted. We therefore look to meteorites for a record of the early solar system. Specifically, we study carbonaceous chondrites, which have never been melted or changed much at all since the formation of the solar system. In these meteorites can be found many of the very same minerals predicted to form from a gas of solar composition. They occur in small (approx. 5-10 mm across) assemblages, known as refractory inclusions because of the relatively high formation temperature of the minerals in them. They can be thought of as small, individual rocks that formed in space and became enclosed in a later-formed matrix. They probably spent billions of years on a small asteroid, escaping the weathering, erosion, and plate tectonics that destroy rocks on Earth, before being ejected into space and eventually captured by Earth.

## Condensation

According to calculations, pressures that would be reasonable for the solar nebula are between one-thousandth and one-millionth of the atmospheric pressure at the Earth's surface. At such pressures, minerals condense at temperatures that are below their melting points, so they condense as solids, much like solid H<sub>2</sub>O (frost) may condense from the air on a cold winter night. In a solar gas at 1/1000 atmosphere, corundum (Al<sub>2</sub>O<sub>3</sub>) is the first major mineral to form. It condenses at 1770 Kelvin (**K**), or 1497°C (water boils at 373 K or 100°C). The next mineral to form is hibonite, CaAl<sub>12</sub>O<sub>19</sub>, at 1743 K, followed by perovskite, CaTiO<sub>3</sub>, at 1688 K.



We have found, in the Murchison carbonaceous chondrite, a refractory inclusion that consists of corundum, hibonite, and perovskite - it is perhaps one of the first rocks to form in the history of the solar system, even older than the Earth, the Moon, and all the planets.

## Freezing and Thawing

Murchison is a CM chondrite, and probably the best way to find inclusions in that type of meteorite is by freeze-thaw disaggregation. We immerse a sample of the meteorite in water, freeze it, let it thaw, then freeze again. The expansion of water when it freezes breaks apart the meteorite, loosening the inclusions from the matrix. The minerals of interest to us are much denser than the matrix, so we put the disaggregated meteorite into a liquid that is denser than the matrix. The lighter material floats and the objects of interest sink. We recover the dense particles, and each one is examined under a microscope.

This photo shows me with Rebecca Elsenheimer at the scanning electron microscope at the University of Chicago. Rebecca was a high school student who worked in our lab through a mentorship program with the Illinois Mathematics and Science Academy. She disaggregated the meteorite and selected the sample for study.

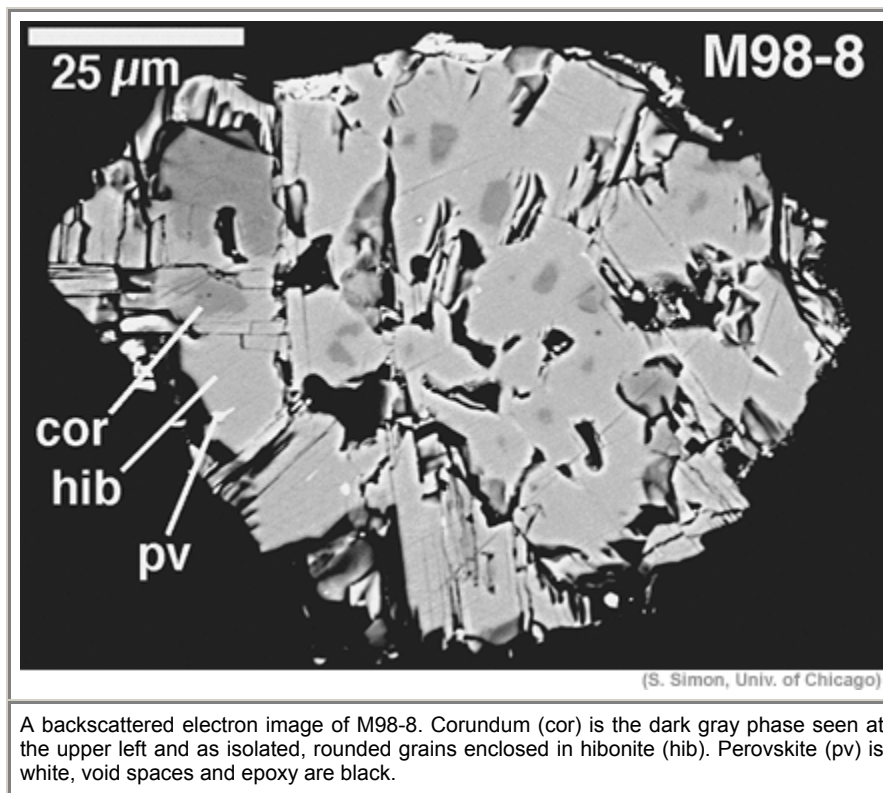


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Murchison hibonite has a sky blue color, so hibonite-rich inclusions can be readily identified. Calculations show that if it were not removed from the nebular gas, corundum would react with the gas to form hibonite. Apparently, most of it did so, because corundum is very rare. Most hibonite-bearing inclusions contain spinel ( $\text{MgAl}_2\text{O}_4$ ), which should condense at 1501 K, rather than corundum.

## The First Rock

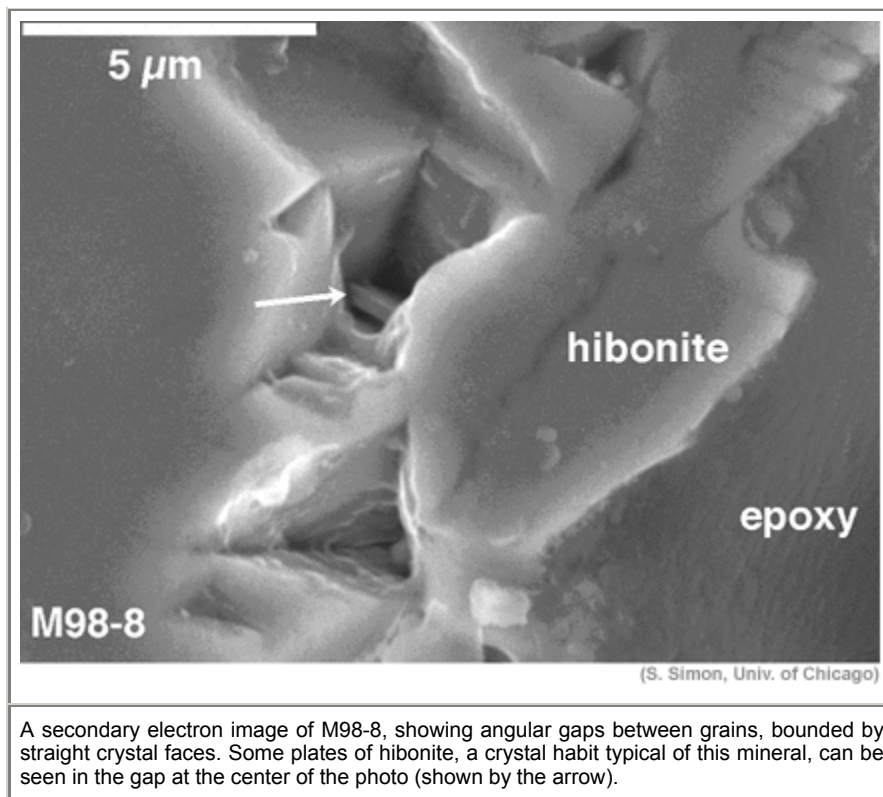
It's exciting to find a corundum-hibonite-perovskite inclusion, because there are conditions under which these would be the first three minerals to condense from the solar nebula, but we need to study the inclusion closely to find evidence of whether it is indeed a condensate or whether it is something that was heated and melted before it was trapped within the meteorite and preserved. The inclusion, numbered M98-8, was mounted in epoxy and polished, yielding a smooth, flat surface, which is needed for microscopic study. We viewed the sample with a scanning electron microscope. A backscattered electron image is shown below. The higher the average atomic weight of a mineral, the more efficiently it reflects electrons to the detector, and the lighter it looks in the image. Thus, the epoxy is black, corundum is dark gray, hibonite is light gray, and perovskite is white.



A backscattered electron image of M98-8. Corundum (cor) is the dark gray phase seen at the upper left and as isolated, rounded grains enclosed in hibonite (hib). Perovskite (pv) is white, void spaces and epoxy are black.

This image shows two important features. First, we note that there are gaps between many of the hibonite grains, as might be expected for an aggregate of individually formed condensate grains. If the inclusion had solidified from a molten droplet, we would expect to find tightly intergrown crystals, with the shapes of late crystals conforming to the shapes of early crystals. Second, from the gaps we can see or infer grain boundaries, and it appears that many of the hibonite crystals enclose rounded corundum grains. This is consistent with the corundum having formed first, and becoming rounded as it reacted to form hibonite, but the reaction stopped before all of the corundum was consumed. If this object had crystallized from a melt having the composition of the inclusion, we might expect corundum, the first phase to crystallize, to mainly be found around the edge of the inclusion, and hibonite, the second phase, to mainly occur in the core, assuming it would have cooled (and crystallized) from the outside in. This is not observed.

A closer look (below), with a secondary electron (surficial) image, shows that the voids are angular, their triangular or trapezoidal shapes determined by hibonite crystal faces.



Some of the voids contain plates of hibonite, below the polished surface. This further suggests that crystals were individually formed and brought together, rather than grown together. It turns out that there are problems with any model for the formation of M98-8 that includes a liquid stage. It would require very high temperatures to melt, which would make evaporation likely, and we know from isotopic analysis that the inclusion did not experience significant degrees of evaporation. In addition, conditions required to keep a liquid from evaporating at those temperatures, such as high pressures, are thought to be unrealistic. From our observations and analyses, we conclude that M98-8 did not crystallize from liquid, and that it is a primary condensate that has remained virtually unchanged since its formation in the early solar nebula over 4.5 billion years ago.

## Additional Resources

Simon, S. B., A. M. Davis, L. Grossman, and K. D. McKeegan (2002) A hibonite-corundum inclusion from Murchison: A first-generation condensate from the solar nebula. *Meteoritics and Planetary Science*, v. 37, p. 533-548.

University of Chicago news release: [Geophysical sciences scholars mentor high school student in meteorite study](#).



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