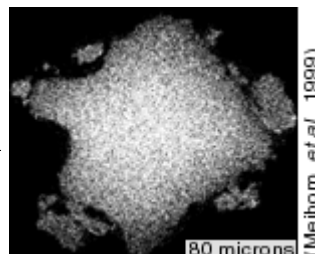


## Hot Idea

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# The Oldest Metal in the Solar System

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Shiny grains of metal in a type of stony meteorite called [CH chondrites](#) contain important information about conditions in the cloud of gas and dust from which the Sun and planets formed. Anders Meibom of the University of Hawai'i (now at Stanford University) and his colleagues at U. Hawai'i, NASA Ames Research Center, and the Harvard-Smithsonian Center for Astrophysics report that many grains of metallic iron-nickel have chemical zoning patterns expected for grains condensing from a cooling gas that has the composition of the Sun. They estimate that the gas was cooling at a rate of about 0.2 °C per hour. This slow cooling implies that the grains formed in a large-scale heating episode in the [nebula](#), not in a localized event. They suggest that heating of the disk surrounding the young Sun caused evaporation of the solid materials. The hot gas rose in clouds over a million kilometers across. The clouds cooled as they rose, causing the metal grains to form. This type of work bridges the gap between the chemical study of meteorites and the astronomical study of young stars.

### References:

Meibom, A., Petaev, M. I., Krot, A. N., Wood, J. A., and Keil, K. (1999) Primitive FeNi metal grains in CH carbonaceous chondrites formed by condensation from a gas of solar composition. *Journal of Geophysical Research*, vol. 104, p. 22,053-22,059.

Meibom, A., Desch, S. J., Krot, A. N., Cuzzi, J. N., Petaev, M. I., Wilson, L., and Keil, K. (2000) Large-scale thermal events in the Solar Nebula: Evidence from Fe,Ni metal grains in primitive meteorites. *Science*, vol. 288, p. 839-841.

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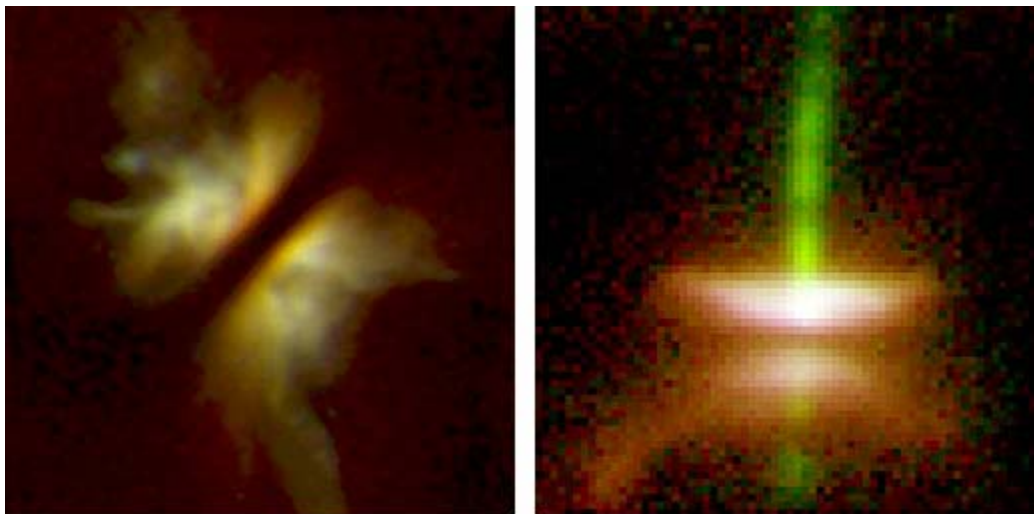
## Astronomers' Views of Star Birth

The Hubble Space Telescope and new ground-based telescopes such as the Keck telescopes on Maunakea, Hawai'i, have given unprecedented views of stars in various stages of formation. Vast regions of gas and dust, such as the Orion nebula shown below, are star factories. Stars form as clouds of interstellar gas and dust collapse, with much of the mass concentrated in the center. The central mass becomes a star, while the surrounding, flattened disk can form planets, asteroids, and comets surrounding the star.



Center of the Orion nebula, as photographed by the Hubble Space Telescope. This mosaic of fifteen separate photographs shows an area 2.5 light-years wide, a small portion of the entire Orion nebula. Over 700 young stars are in this region, and glowing protoplanetary disks surround 153 of them. This natural laboratory for studying star formation is located a mere 1,500 light years from us.

Closer views of individual stars in the early stages of their formation show that disks composed of dust and gas surround many of the fledgling stars. These often obscure a young star, but it can still illuminate regions of in-falling dust above the disk. Many stars shoot out powerful jets of gas. These jets originate as dust and gas move in towards the star and are deflected by the magnetic fields of the star and the surrounding disk. The star formation process is very dynamic, as shown dramatically by recent [time-lapse images](#) of young stars located only about 450 light years from Earth.



(Space Telescope Science Institute)

These Hubble Space Telescope images show stars surrounded by dusty disks. You cannot see the star in either photograph, though their light illuminates the surrounding nebula. **Left:** Image of a star called IRAS 04302+2247. The dark band is the dark disk surrounding it, which we see edge-on. The diameter of the disk is 50 billion kilometers. The wispy regions above the disk are gas and dust still falling into the disk. **Right:** This shows a young star surrounded by a thin disk. Though relatively thin, the disk is 25 billion kilometers across. Powerful jets spew out of the star.

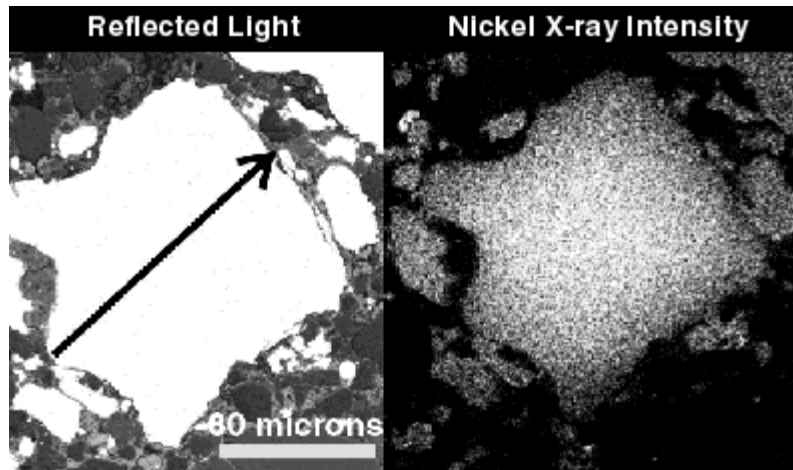
## Cosmochemists' View of the Sun's Birth

In spite of the numerous examples of stars and disks, and the excellent theoretical studies of the process of star formation, we have limited observations of what happens inside the disks. Fortunately, we have materials preserved from the disk of one star, the Sun. These materials are the components in primitive chondritic meteorites.

For decades, meteorite specialists have considered chondrites to be unaltered containers for materials formed in the dust-gas cloud (the solar nebula) surrounding the gestating Sun. In particular, chondrites contain calcium-aluminum-rich inclusions (CAIs) and

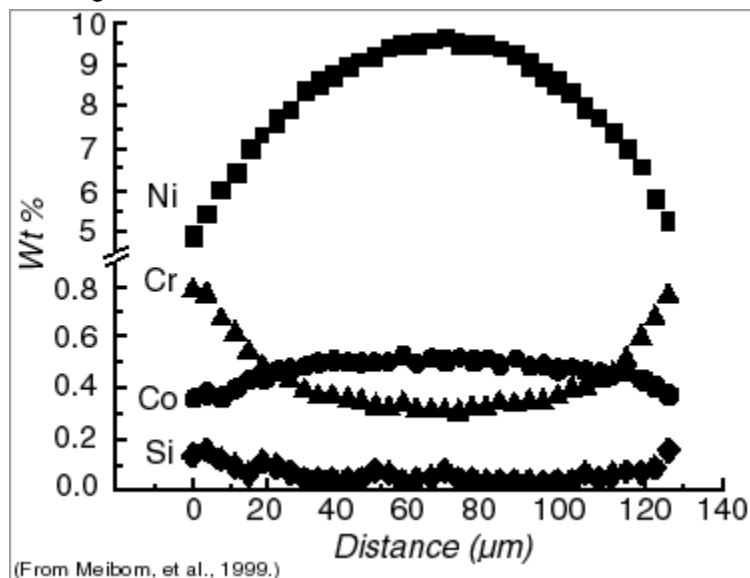
chondrules, both roughly millimeter-sized objects that experienced melting. Crystallization experiments indicate that CAIs cooled at rates of about 2 to 50 °C per hour. Most chondrules cooled faster, about 100-1000 °C per hour. The experiments also suggest that chondrules and CAIs formed from pre-existing solids, and chondrules were probably recycled through the melting process several times. Thus, these components record the effects of localized heating events in the solar nebula and do not directly reflect large-scale processes in it.

Anders Meibom and his colleagues may have discovered some pristine metallic iron grains in an uncommon group of chondrites, the CH carbonaceous chondrites. CH chondrites consist of about 70% metallic iron-nickel and 30% chondrules, CAIs, and other rocky components. Some of the metallic grains are chemically zoned, with higher nickel and cobalt in the centers and lower nickel and cobalt near the edges. Chromium and silicon are zoned in the opposite sense, lower in the centers and higher at the edges of the grains.



(From Meibom, et al., 1999.)

A typical zoned metal grain in a CH chondrite (in this case PAT 91546, found in Antarctica). The photo on the **left** was taken in reflected light in a microscope. Bright white areas are metallic iron-nickel; dark areas are silicate minerals. The image on the **right**, made with an electron microprobe, shows the intensity of nickel x-rays, hence reflects the amount of nickel present. Note that it is brighter in the central regions, hence higher in nickel, than closer to the edge of the grain. The arrow in the left photograph shows the direction of a compositional traverse, shown below. Note the zoning in nickel, cobalt, chromium, and silicon.

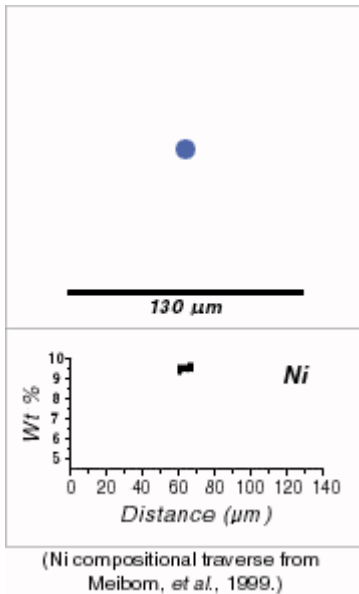


(From Meibom, et al., 1999.)

Meibom and his colleagues suspected that the distinctive compositions of the metallic grains formed by condensation from the nebula. They calculated the composition expected for metal grains forming from a hot cloud, and found that the zoning pattern matched that in the metal grains in CH chondrites. Their calculations suggest that the metal grains grew by condensation from a gas between about 1100 °C and 1000 °C, assuming a pressure of 0.0001 atmospheres.

## Growing Metal Grains

Meibom and his coworkers wanted to use their data and calculations to understand conditions in the solar nebula. The first step was to estimate how long it would take to form the typical zoned metal grain. By knowing the temperature, pressure, and abundance of iron in the nebula, they could calculate how long it took to grow a grain by random collisions of atoms. They assumed that all the atoms stuck to the growing grains if they hit it. They found that the typical grain would take 19 days to grow from a microscopic seed to 100 micrometers across.



Meibom and coworkers modeled the growth of metal grains in a cooling gas. A grain grows by iron and nickel atoms randomly hitting it. As the temperature decreases, the amount of nickel (Ni) in it decreases, as shown by the graph on the bottom.

The temperature range over which the growth occurred is about 100 °C, so Meibom was able to calculate a cooling rate for the portion of the nebula in which the metal grains grew. By dividing the temperature interval (100 °C) by the growth time (19 days, or 456 hours), he found a cooling rate of 0.2 °C per hour. This is substantially slower than the cooling rates of CAIs and chondrules (with a few exceptions). Meibom and coworkers then applied some astrophysical theory and found that a parcel of gas cooling at that rate must be at least a few million kilometers across.

The large size inferred for the portion of the nebula in which metal grains in CH chondrites formed suggested to Meibom that it was a large-scale process, not a localized heating event. He and his colleagues propose that as the disk heated up, great clouds of gas rose from the mid-plane. As a cloud ascended, it cooled, leading to growth of the metal grains. They calculate that a rising cloud would take 12 to 44 days to cool the required 100 °C, which agrees reasonably well with their estimate of 19 days for a growth time.

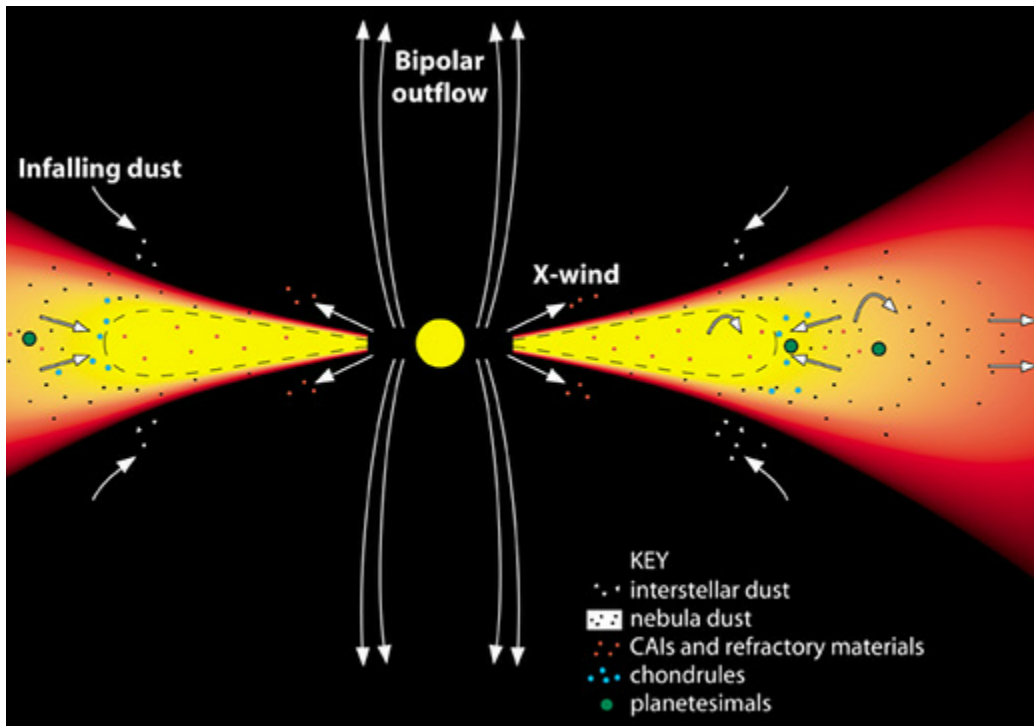
After the metal grains they formed they must have moved to cooler regions of the nebula. If they had not, they would not have preserved the chemical zoning observed. How did they move? Meibom suggests that the up and down convection in clouds would have resulted in a migration of some of the grains to cooler parts of the nebula. Alternatively, the strong stellar winds blowing from the early, active Sun could have blown the metal grains to cooler regions of the nebula. In either case, the key point is that metal grains formed in one region of the nebula and were transported to outer, cooler regions. Transport of materials has also been suggested for preservation of CAIs. Unpublished work by Meibom and Krot indicates that the same holds for chondrules in CH chondrites.

CH chondrites are not the only type to contain condensed metal grains. CB and CR chondrites also contain them (in fact, the zoned metal grains are more abundant in CB chondrites than in CH chondrites). All three types of chondrites are very rich in metallic nickel-iron, but nobody yet understands how they become enriched.

## The Solar Nebula

Putting astronomical observations and astrophysical theory together with their observations and calculations, Meibom and colleagues come up with a complicated picture of the solar nebula. There is a hot central disk, which may be uniform in temperature near the Sun. The temperature is lower farther from the Sun. In-falling interstellar material becomes heated as it accretes to the disk. Convection causes clouds to rise near the inner, hottest part of the disk; this is where the metal grains may have formed. Powerful jets (or bipolar outflow) and strong solar winds called the "x-wind" transport hot gas and dust away from the Sun. In some regions, transient, localized

heating events recycle materials. Eventually, planetesimals and then planets begin to form from the dust.



(PSRD graphic by Nancy Hurbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

Synthesis of ideas depicting processes in the nebular disk surrounding a young star.

## Rocky Astronomy

The work described by Anders Meibom and his team is a good example of the value of meteoriticists and astrophysicists working together. Astronomers with their impressive new telescopes are making fascinating observations of stars in the process of forming, but cannot see inside the disks surrounding the stars nor can they observe all the chemical processes at work. Meteoriticists have the products of only one star's nebula, but they have very detailed information about it. They even have pieces of nebular products. Thus, astronomy and studies of primitive components in meteorites complement each other. This also holds for astronomy and studies of pre-solar grains (stardust) in meteorites. [See PSRD article: [Moving Stars and Shifting Sands of Presolar History](#).] The tradition of distinct fields for astronomy and meteoritics is outdated. Scientists wishing to understand star formation or interstellar dust must learn about both astronomy and meteorites.

## Additional Resources

Meibom, A., Petaev, M. I., Krot, A. N., Wood, J. A., and Keil, K. (1999) Primitive FeNi metal grains in CH carbonaceous chondrites formed by condensation from a gas of solar composition. *Journal of Geophysical Research*, vol. 104, p. 22,053-22,059.

Meibom, A., Desch, S. J., Krot, A. N., Cuzzi, J. N., Petaev, M. I., Wilson, L., and Keil, K. (2000) Large-scale thermal events in the Solar Nebula: Evidence from Fe,Ni metal grains in primitive meteorites. *Science*, vol. 288, p. 839-841.

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