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# Large-Scale Thermal Events in the Solar Nebula: Evidence from Fe,Ni Metal Grains in Primitive Meteorites

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**Chemical zoning patterns in some iron, nickel metal grains from CH carbonaceous chondrites imply formation at temperatures from 1370 to 1270 kelvin by condensation from a solar nebular gas cooling at a rate of ~0.2 kelvin per hour. This cooling rate requires a large-scale thermal event in the nebula, in contrast to the localized, transient heating events inferred for chondrule formation. In our model, mass accretion through the protoplanetary disk caused large-scale evaporation of precursor dust near its midplane inside of a few astronomical units. Gas convectively moved from the midplane to cooler regions above it, and the metal grains condensed in these parcels of rising gas.**

Chondrules and Ca,Al-rich inclusions (CAIs) in primitive meteorites (chondrites) offer insights into events that took place in the solar nebula during the earliest stages of planetary formation ~4.56 billion years ago. Chondrules are millimeter-sized silicate spherules that formed by melting of solids during localized, transient, and repetitive heating events with peak temperatures in the range of 1800 to 2100 K [e.g., (*1*)]. Dynamic crystallization experiments reproduce chondrule textures similar to those of the most abundant porphyritic chondrules only when the cooling rate is ~100 to 1000 K hour$^{-1}$ (*2*, *3*). The CAIs consist of refractory silicate and oxide minerals that are inferred to condense out of a cooling gas of solar composition [e.g., (*4*)]. However, most CAIs have experienced subsequent thermal processing resulting in melting and evaporation [e.g., (*5*)]. Comparison with dynamic crystallization experiments constrains the cooling rates of CAIs that crystallized from melts (type B) to 2 to 50 K hour$^{-1}$ at temperatures around 1700 to 1800 K (*6*). In this way, chondrules and CAIs offer important constraints on the thermal evolution of the solar nebula during processing of preexisting solids. However, constraints on the thermal evolution of the nebula gas during formation of the first solids by gas-solid condensation are lacking.

Recently, Fe,Ni metal grains with chemical zoning patterns in Fe, Ni, Co, and Cr resulting from gas-solid condensation (*7–12*) were described in CH, CR, and Bencubbin-like chondrites (*13–15*). Some metal grains in CH chondrites, amounting to a fraction ($10^{-4}$ to $10^{-2}$) of all metal grains, appear to have condensed from a gas of solar composition at a total gas pressure of $\sim10^{-4}$ bar at temperatures from 1370 to 1270 K (*13*). During this process, the metal grains must have grown sufficiently fast and the gas must have cooled sufficiently fast to avoid homogenization of the zoned patterns by solid-state diffusion. Here we estimate the growth rate of the zoned metal grains, obtain a cooling rate for the region of the nebula from which they condensed, and discuss a possible astrophysical setting of this event.

We model gas-solid condensation of metal grains from a cooling gas of solar composition at a total pressure of $10^{-4}$ bar. For simplicity, we assume that the growing metal grains are spherical in shape and consist of Fe atoms [zoned metal grains contain <10 weight % (wt %) Ni, Co, and Cr] and that the metal grains grow by Fe atoms continuously colliding with and sticking to the surface of the growing grain with a sticking coefficient of 1 (*16*, *17*). The number of hits of Fe atoms per second on a sphere of radius $a$ is $Z = \pi a^2 n_g(\mathrm{Fe}) V_{avg}(\mathrm{Fe})$, where $n_g(\mathrm{Fe})$ is the number density of Fe atoms in the gas and $V_{avg}(\mathrm{Fe}) = (8kT/\pi m_{\mathrm{Fe}})^{1/2}$ is the mean speed of Fe atoms in the gas (Maxwell distribution) [where $k$ is the Boltzmann constant, $T$ is the temperature (in K), and $m_{\mathrm{Fe}}$ is the atomic weight of the Fe atom]. The number density of Fe atoms in solid Fe metal is $n_s(\mathrm{Fe})$, and the growth rate of the sphere is $n_s(\mathrm{Fe})4\pi a^2 da = Zdt \Rightarrow da/dt = n_g(\mathrm{Fe})V_{avg}(\mathrm{Fe})/4n_s(\mathrm{Fe})$, where $t$ is time. In gas of solar composition (*18*) at 1320 K and $10^{-4}$ bar, $n_g(\mathrm{Fe}) = 3 \times 10^{16}$ m$^{-3}$ and $V_{avg}(\mathrm{Fe}) = 705$ m s$^{-1}$. The

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parameter $n_s$(Fe) = $8.4 \times 10^{28}$ m$^{-3}$. Thus, we get $da/dt \approx 6 \times 10^{-11}$ m s$^{-1}$, which can be integrated to obtain the time, $t_{growth}$, required to grow a grain of radius $a$. For a grain with radius $a \approx 100$ μm (typical size of zoned metal grains), we obtain $t_{growth} \approx 19$ days.

This $t_{growth}$ needs to be compared with the time scale on which solid-state diffusion of Ni, Co, and Cr would cause homogenization of the zoning pattern ($t_{diff}$). In order for solid-state diffusion of Ni to cause substantial homogenization of a zoned metal grain with radius $a$ = 100 μm, a minimum average diffusion length of ~25 μm is required. The time scale for diffusion over a length scale, $d$, is $t_{diff} = d^2/D_{Ni}$, $D_{Ni}$ being the diffusion coefficient of Ni (~$10^{-12}$ cm$^2$ s$^{-1}$ at $T$ = 1400 K). Accounting for the decrease in $D_{Ni}$ with decreasing temperature (*19*, *20*), $t_{diff} = 10^{(-9.74\ +\ 15250/T)}d$. At $T$ = 1300 K and $d$ = 25 μm, homogenization takes $t_{diff}$ = 100 days. At $T$ = 1000 K, homogenization takes $t_{diff}$ = 1000 years. Because $t_{diff} \gg t_{growth}$, we infer that the zoned metal grains condensed fast enough to avoid being homogenized by solid-state diffusion.

Because the temperature interval during condensation of the zoned metal grains is $\Delta T \approx$ 100 K, the cooling rate of the nebula gas (and the solids entrained in it) is $\Delta T/t_{growth} \approx 0.2$ K hour$^{-1}$. This cooling rate is substantially slower than those inferred for chondrule or CAI melts (*2*).

Consider the thermal adjustment time ($t_{rad}$), i.e., the time scale on which a parcel of gas of size $d$ achieves thermal equilibrium with its surroundings by exchange of radiation (*21*):

$$t_{rad} = \rho^2 \kappa c_p d^2 / 64\sigma T^3 \qquad (1)$$

where $c_p = 1.25 \times 10^8$ erg g$^{-1}$ K$^{-1}$ is the heat capacity of the gas, $\rho = 2.1 \times 10^{-9}$ g cm$^{-3}$ is its density, and $\sigma$ is the Stefan-Boltzmann constant. The Rosseland mean opacity of the gas, $\kappa$, is dominated by silicates, which largely condense out of the gas before the Fe,Ni metal; we therefore assume that $\kappa \approx 3$ cm g$^{-1}$ (*22*). At $T$ = 1320 K, even as large a region as $d$ = $3.6 \times 10^5$ km (such as considered below) will reach thermal equilibrium in only about 3 days. For a transiently heated region of the nebula to cool on longer time scales, such as those relevant to zoned metal grain condensation ($t_{cool}$ = $t_{growth}$ = 19 days), the region would have to be millions of kilometers across, comparable to the scale height of the protoplanetary disk and much larger than inferred for chondrule formation (e.g., shock waves). Although shock waves from infalling planetesimals (*23*, *24*) could possibly heat gas on these large length scales, the heating occurs high above the midplane of the disk, where the density of the gas is substantially lower ($\rho \ll 10^{-9}$ g cm$^{-3}$) than that inferred for metal condensation. We propose instead that the zoned Fe,Ni metal grains condensed in a very large parcel of nebula gas as it convectively ascended from the hot nebula midplane into the cold, dusty regions above it.

Inward radial evolution of matter through the protoplanetary disk liberates gravitational potential energy that heats the disk (*25*). Early in the disk's evolution, the mass accretion rate may be on the order of $dM/dt = 10^{-6}$ solar masses ($M_\odot$) year$^{-1}$, during which the midplane temperature in the innermost several astronomical units (AU) exceeded ~1400 K (*26*), enough to vaporize most solids (*27*). Under such circumstances, the midplane region becomes optically thin with essentially the same temperature throughout. Thermal energy is transported from the midplane region to the dusty surface regions mostly by radiative diffusion. However, if heat is transported to the disk surface by radiation alone, the resultant temperature gradient in the dusty regions becomes superadiabatic and protoplanetary disks are therefore predicted to be convective as well (*26*) (Fig. 1). The velocities ($v_{conv}$) associated with convection in the dusty layers of the disk can be estimated (*21*) from

$$F_{conv} \approx 4\rho c_p T v_{conv}^3 / g l_m \qquad (2)$$

where $F_{conv}$ is the heat flux through the disk carried by convection, $l_m$ is the mixing length of convection, and $g = \Omega^2 z$ is the gravitational acceleration [where $\Omega$ is the orbital frequency and $z \approx 2H$; $H$ is the scale height of the disk, about $10^7$ km at 1 AU (*26*)]. The major uncertainty in the convection velocity is the mixing length $l_m$, an upper limit for which we estimate as $2H$. The smallest $l_m$ consistent with this model is roughly 0.04 $H$, the vertical distance between the $T$ = 1370 K and the $T$ = 1270 K levels, as shown below. It is assumed that convection in the dusty layers above the midplane carries about 10% of the total heat flux ($F$) through the disk: $F = (3/8\pi)\Omega^2 dM/dt$ (*26*). Using these parameters and assuming the pressure at $z$ = 2H is about 0.1 times the pressure at the midplane, the range of convective velocities based on the uncertain mixing length is $9.4 \times 10^3$ to $3.5 \times 10^4$ cm s$^{-1}$ = 0.04 to 0.16$c$, where $c$ is the sound speed at the midplane (~2.2 km s$^{-1}$). Such convective velocities are realistic for the solar nebula and perhaps even required for convection to overcome the radial inward drift of gas at velocities of ~0.01 km s$^{-1}$ (*28*).

The length of time taken for rising gas to cool from 1370 to 1270 K can be estimated if the temperature gradient in the condensation zone is known. We assume a radiative temperature gradient (*21*) in this temperature interval:

$$dT/dz = 3F\rho\kappa/16\sigma T^3 \qquad (3)$$

With the same parameters and heat flux as above, the temperature drop from 1370 to 1270 K is achieved over a distance of $3.6 \times 10^5$ km, which is a small fraction of $H$. With the range of convective velocities derived above, the rising gas takes from 12 to 44 days to cross this region, which is in good agreement with the time it takes to grow a zoned Fe,Ni metal grain by condensation (19 days). Because the thermal adjustment time (Eq. 1) for the rising gas is about 3 days, this gas is in good thermal equilibrium with its surroundings and cannot be considered to be adiabatic until higher into the dusty region, justifying the use of the radiative temperature gradient.

After their formation, some of the metal grains in CH chondrites escaped within a few years (at $T$ = 1200 K, $t_{diff}$ ~ 2.5 years) to regions of the solar nebula with midplane temperatures low enough ($T$ < 1000 K) to make homogenization by solid-state diffusion ineffective ($t_{diff} > 10^3$ years). These regions are about 0.3 AU farther from the sun than regions with midplane temperatures $T$ > 1300 K, where metal condensed (*26*). Convective updrafts alternate with adjacent downdrafts in the protoplanetary disk (*29*) (Fig. 1). When Fe,Ni metal grains in a convective updraft reach their maximum height above the midplane, about 50% enter the downdraft closer to the sun and about 50% enter the downdraft farther away from the sun. However, the convective cells will be turbulent (*30*), and turbulent diffusion can trans-

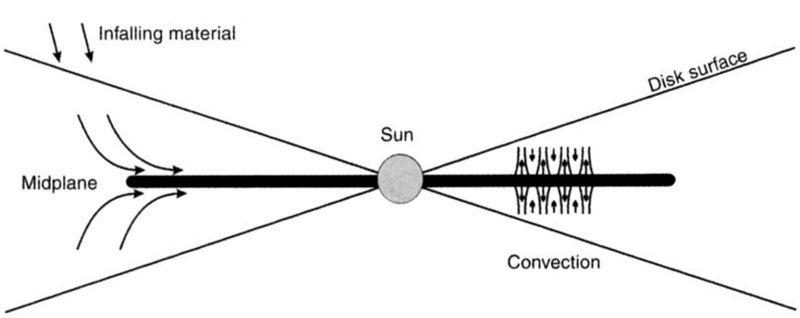


**Fig. 1.** Schematic representation of a cross section through the protoplanetary disk of the sun. Matter falls on the disk and accretes into the sun through the midplane of the disk. Inward of 1 AU from the sun, the midplane temperature becomes high enough to evaporate dust. Convection carries heat from the midplane to the surface of the disk, and the zoned Fe,Ni metal grains condense as the gas rises and cools through the 1370 to 1270 K temperature interval.

port some metal grains out of a convective downdraft (into an updraft) before they are brought down to the midplane. The diffusivity of a particle in a convective eddy is $k \approx l_m v_{conv}$, and the turnover time of the eddy is comparable to $l_m/v_{conv}$, so that particles can diffuse about one mixing length. Let $\Delta r$ be the radial width of the convection cell. The fraction of particles in a downdraft that diffuses outward and into an adjacent updraft before falling halfway to the midplane is $0.5x[1 - \mathrm{erf}(0.28\Delta r/l_m)]$. If $\Delta r = l_m$, this fraction is about one-third (0.345). Of this fraction of particles that diffuses into the neighboring updraft, ~50% will be transported to a downdraft even farther away, and the process can repeat. The width of a convection cell is likely to be about one mixing length (*29*), and we assume that $\Delta r = l_m = H$ (yielding $t_{growth} = 15$ days). In this case, particles must migrate outward through about three updrafts and three downdrafts (~0.3 AU) before escaping safely to cooler regions. The fraction that does so is $(0.5)^3(0.345)^3 = 5 \times 10^{-3}$. Thus, turbulence induced by convection can transport some Fe,Ni metal grains outward from the sun without sweeping them all the way to the midplane. These particles would not experience temperatures high enough to be vaporized or become homogenized by solid-state diffusion. The fraction of Fe,Ni metal grains that in this way retain their zoning is consistent with the observed relative abundance of zoned metal grains in CH chondrites ($10^{-4}$ to $10^{-2}$).

The high temperatures and the high heat flux implied in our model require a high mass flux ($dM/dt = 10^{-6}$ $M_\odot$ year$^{-1}$), formation close to the sun ($r \leq 1$ AU), or both.

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# Age of Neoproterozoic Bilatarian Body and Trace Fossils, White Sea, Russia: Implications for Metazoan Evolution


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**A uranium-lead zircon age for a volcanic ash interstratified with fossil-bearing, shallow marine siliciclastic rocks in the Zimnie Gory section of the White Sea region indicates that a diverse assemblage of body and trace fossils occurred before 555.3 ± 0.3 million years ago. This age is a minimum for the oldest well-documented triploblastic bilaterian *Kimberella*. It also makes co-occurring trace fossils the oldest that are reliably dated. This determination of age implies that there is no simple relation between Ediacaran diversity and the carbon isotopic composition of Neoproterozoic seawater.**


The terminal Neoproterozoic interval is characterized by a period of supercontinent amalgamation and dispersal (*1*, *2*), low-latitude glaciations (*3*, *4*), chemical perturbations of seawater (*5*–*7*), and the first appearance and subsequent diversification of metazoans. Construction of a terminal Neoproterozoic biostratigraphy has been hampered by preserva-