FORMATION OF CHONDRULES AND CAI'S FROM INTERSTELLAR GRAINS ACCRETING TO THE SOLAR NEBULA

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Abstract: The solar system is understood to have formed by the continued infall of interstellar gas and dust to an accretion disk (=the solar nebula). The interstellar material would encounter the nebula at nearly the free-fall velocity, and would have very great kinetic energy. Dust particles falling through the nebula would dissipate their mechanical energy as heat, as they experienced aerodynamic drag in the nebular gases. Heating and deceleration are calculated for a simple infall model. It is found that 1-mm dust aggregations falling into the present zone of the terrestrial planets would be melted, and would cool at ~350 K/hr. Dynamic crystallization experiments have shown that the crystalline textures of meteoritic chondrules were produced during cooling at a similar rate.

1. Introduction

Both Ca, Al-rich inclusions (CAI's) and chondrules appear to have been formed by high-temperature processing of precondensed material in the solar nebula (*e.g.*, WOOD, 1981; TAYLOR *et al.*, 1982). Several possible sources of heat in the nebula have been suggested: shear friction caused by differential rotation of materials at different radial distances in a turbulent nebula (CAMERON, 1978; CAMERON and FEGLEY, 1982); compression by shock waves generated in the body of the nebula (HAYASHI, 1981); and lightning discharges due to charge separation between differentially rotating layers in the nebula (RASMUSSEN and WASSON, 1982). The nature of the heat source is still very uncertain, but the abundance of CAI's and especially chondrules in chondritic meteorites suggests that a major, pervasive stage or aspect of nebular evolution was at work.

All the heating mechanisms just mentioned depend upon the differential motions of gases within a fully-developed nebula. Another possibility, which this paper explores, is that the heat which processed chondrules and CAI's was developed when plointer stellar material was decelerated as it first joined the nebula.

2. Shock Heating of Infalling Gases

Stars generally and the sun in particular are understood to have formed by the self-gravitative collapse of volumes of interstellar gas and dust. Mathematical modeling of the process has shown that it occurs non-homologously: *i.e.*, at first the central portion of the volume of interstellar material falls together, forming a very small protostar (LARSON, 1969). In the case of our own star, the initial protosun may have been about as massive as the present planet Jupiter. Subsequently, over a period of $\sim 10^6$ yr, additional material from farther out in interstellar space would have continued to fall onto the protosun. At the surface of the protosun, infalling material would have been decelerated from nearly free-fall velocity to almost zero velocity in a standing shock front. There the kinetic energy of infalling material was converted to heat (T as much as 8000 K), most of which was promptly radiated away. Thus newly-arriving material went through a rapid heating-cooling cycle.

Material of the interstellar medium has a certain amount of angular momentum, as a result of galactic rotation and interstellar turbulence. Because of its angular momentum content, an element of interstellar material could not have fallen directly toward the protosun. Instead it would have attempted to describe a near-parabolic orbit around the protosun (CASSEN and MOOSMAN, 1981). Near the protosun infalling materials from many directions collided; their motion was averaged into that of an *accretion disk*, rotating at Keplerian velocities about the net angular momentum vector of the mass of collapsing interstellar material. The "solar nebula" of cosmochemistry is equivalent to the "accretion disk" of astrophysics.

The nebula would also have been bounded by an accretion shock front, where material falling onto it was abruptly decelerated. Peak temperatures in the shocked zone would have varied inversely with increasing distances (r) from the protosun, however, since the free-fall velocity (v) and hence the kinetic energy of infalling material vary as $v^2 \cong 2GM/r$, where G is the universal gravitational constant and M is the mass of the protosun and inner nebula. LARSON (1972) suggested that interstellar dust falling through sufficiently close-in, hot zones of the nebular accretion shock would have been vaporized, recondensing to form CAI's.

I have set up a simple collapse model and calculated the approximate peak temperatures that would be developed in the shock front bounding a nebula as interstellar material continued to fall onto it. (Limitations of space prevent me from describing the computation in this paper. It will be discussed in WOOD, 1984.) The temperature profile obtained varies with the model parameters, and with the stage of infall that has been attained. Figure 1 shows the results of a run with plausible input parameters.

In this figure, the shaded band marks the temperature range where we would expect chondrules and CAI's to be thermally processed. Although the computational run plotted developed higher shock temperatures than did other runs (involving different assumptions of the cloud mass and angular momentum), these are still not very high; the temperature profile crosses the shaded band at $\sim 3 \times 10^{11}$ cm, only about four times the present radius of the sun. This is not a promising place in which to create the chondrules and CAI's: it is a very small zone far from the presumed immediate source of the meteorites (the asteroid belt), and material in it is likely to be captured by the sun (CAMERON, 1987).

The temperature profile ("viscous dissipation") developed by shear friction between differentially rotating elements within the nebula, as estimated by CAMERON (1978), is also shown. A rigorous comparison cannot be made with the shock-heating profile shown, as the model parameters differ, but the figure does suggest that shock is

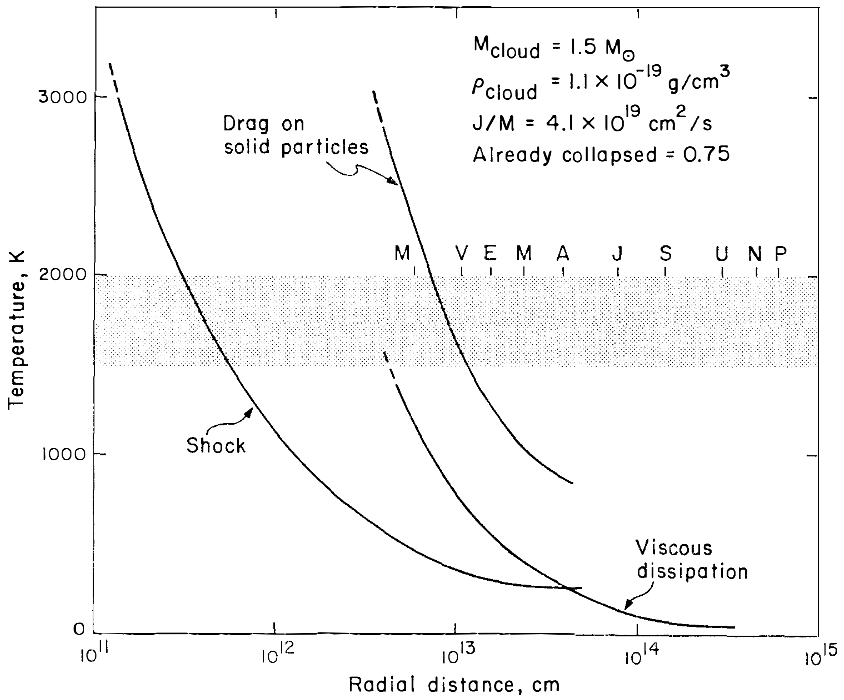

Fig. 1. Temperatures produced by several heating mechanisms in the solar nebula. The "Viscous dissipation" curve is from CAMERON *(1978); the "Shock" and "Drag on solid particles" curves are the subject of this paper. The shaded band is the approximate temperature range in which chondrules and CAI's would be formed. Parameters of the infall model assumed appear at upper right.*

a less potent heating mechanism than others that probably operated. Note, however, that even the viscous dissipation profile crosses the shaded band inside the present orbit of Mercury. Thus it also cannot be considered a very promising mechanism for providing the heat needed to process chondrite components.

3. Drag Heating of Infalling Particles

The inadequacy of shock heating does not rule out the possibility that thermal processing of chondrules and CAI's occurred during the infall of interstellar material. We are primarily concerned with the thermal history of solid grains of interstellar dust as they encounter the nebula; gas temperatures are important only if they are closely coupled to the grain temperatures, and in the present circumstance they are not. (In most astrophysical settings, where radiative heat transport is important, solid grains have a different temperature than surrounding gases.)

Infalling dust grains are not abruptly decelerated at the nebular shock front, as infalling gas is (Fig. 2). They are not substantially decelerated until they have encountered a mass of gas atoms comparable to their own mass. A 1-mm (chondrule-sized) object would have to traverse many thousands of km of nebular gas before this was the case. In the meantime it experiences aerodynamic drag in the thin nebular gas, and is heated by this drag. A quasi-steady state is established between the rate at which drag deposits heat in the particle, and the rate at which the particle loses heat by radia-

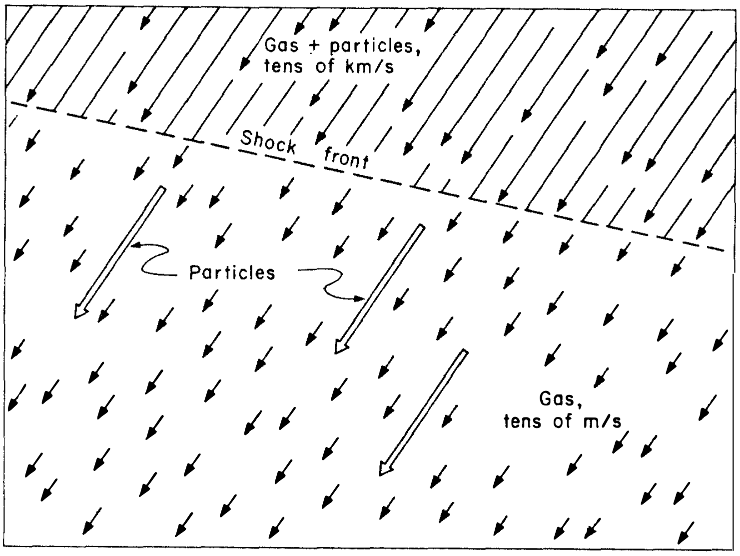

Fig. 2. Infalling interstellar gas is abruptly decelerated at the accretion shock front, but particles penetrate the nebular gases at high velocities until aerodynamic drag decelerates them.

tion to its surroundings. The steady state heat content of the particle determines its temperature. As the particle is gradually decelerated this steady state heat content, and therefore the particle temperature, decline. The process is closely analogous to the heating of small meteoroids as they enter the earth's atmosphere.

The particle temperature (T_p) in such a situation can be calculated approximately by use of the relationship

$$mC_s\left(\frac{\mathrm{d}T_p}{\mathrm{d}t}\right)=\frac{\alpha}{2}A\rho V^3-\beta B\sigma(T_p^4-T_0^4)\,,$$

from WHIPPLE's (1950) classic paper on the survival of micrometeorites in the upper atmosphere. (Here m is the particle mass; C_s, its specific heat; t, time; α, the accommodation coefficient of the particle surface, $\cong 1$; A, the particle cross-sectional area; ρ, the gas density behind the shock front; V, the particle velocity; β, the emissivity coefficient of the particle material, $\cong 1$; B, the surface area of the particle; σ, the Stefan-Boltzmann constant; and T_0, the radiation temperature of the environment "seen" by the particle.) The rate of deceleration of the particle can be estimated from the relationship (ÖPIK, 1974)

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=\frac{-0.75C_d\rho V^2}{r\rho_p}\,,$$

(where x is distance traversed; C_d, the drag coefficient, $\cong 0.5$; r, the particle radius; and ρ_p, the particle density).

I have numerically integrated these equations to follow the thermal history of infalling particles under a variety of circumstances. Gas densities determined in the course of the shock-heating calculations of Section 2 were used for $\rho(=\rho_{\mathrm{gas}}$ of Fig. 3), and T_0 was taken to be 10 K: that is, the nebular gas was assumed to be transparent to radiation, so the particle radiated to the 10 K background of a typical interstellar cloud.

A representative thermal history is shown in Fig. 3. The quasi-steady state temperature is established very rapidly (~ 10 s), after which this temperature falls over a period of several hours as the particle is slowly decelerated. The peak temperature is, to a first order, independent of the particle diameter. It does depend on the particle's infall velocity (kinetic energy) and the local gas density, and both of these quantities decrease with increasing radial distance in the nebula. A profile of peak drag temperatures appears in Fig. 1. This was calculated for the same infall model that produced the shock-heating profile of Fig. 1.

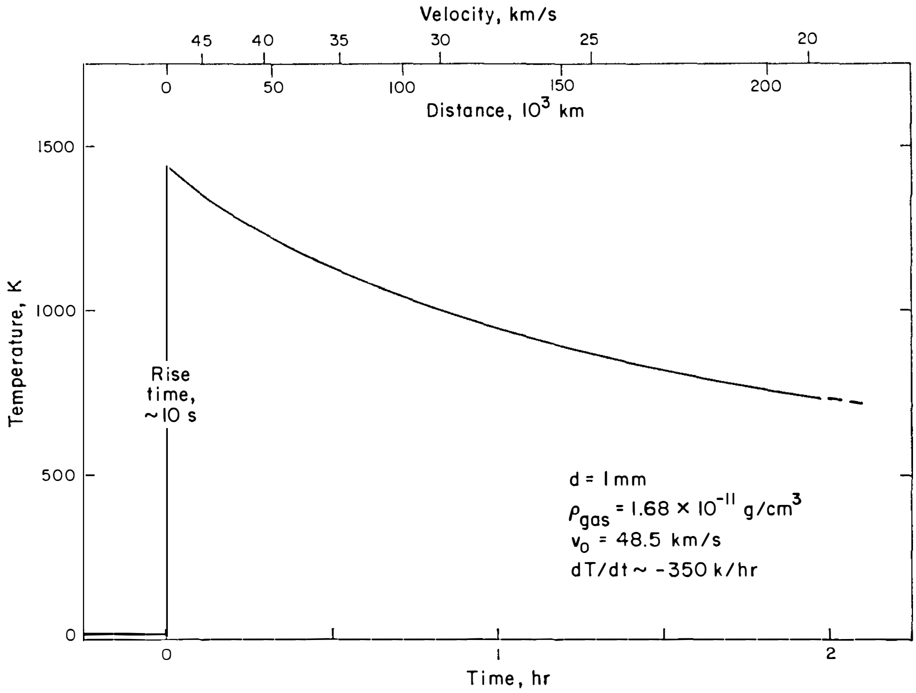

Fig. 3. Temperature evolution of a 1-mm particle penetrating the solar nebula at a radial distance of 1.17×10^{13} cm (0.78 AU) in the infall model of Fig. 1. Deceleration of the particle, and distance penetrated, are shown at the top of the figure.

We see that drag heating produces much higher temperatures for a given radius than shock heating does, or viscous dissipation. The drag-heating curve crosses the shaded band in the region of the terrestrial planets. For purposes of rationalizing the properties of chondrites, one could wish it crossed this critical band at the asteroid belt; but the result obtained is more encouraging than are the heating effects produced by the other astrophysical processes tested. It is possible that further refinement of the infall model will move the temperature profile outward under some circumstances. It is also the case that viscous dissipation in the nebula has the effect of redistributing its substance (Lynden-Bell and Pringle, 1974; Cameron, 1978), and under some circumstances material that fell into the nebula at ~ 0.5 AU might be spun out to 3 AU before the particles in it began to accrete.

This discussion has ignored the possible effects of ablation on the speeding droplets. An analysis of the dynamic pressure of gas on the leading face of the droplet shows that it is quite small, only $\sim 10^4$ dynes/cm^2 (WOOD, 1984). The surface tension of the silicate liquid is great enough to resist this stress, which would otherwise disrupt (ablate) the droplet.

4. The Cooling Rate of Drag-Heated Particles

To a first order, the cooling rates of drag-heated particles that fall into the nebula are inversely proportional to their diameters. Submicron dust particles heat and cool very rapidly, in a few seconds. Chondrule-sized objects falling through the nebula, however, cool much more slowly, ~ 350 K/hr (Fig. 3).

This is of interest because dynamic crystallization experiments on molten droplets of chondrule composition have shown that the crystalline textures preserved in chondrules place limits on the rate at which they could have cooled from the molten state, and a comparison with the theoretically derived cooling rates of this work is possible. The laboratory work on cooling rates is summarized in Table 1.

Table 1. Constraints on cooling rates at which textures and other properties of chondrule types (and CAI's) are produced in laboratory experiments.

Textural type	Cooling rates K/hr	Reference
Barred olivine	<10000	TSUCHIYAMA and NAGAHARA (1981) NAGAHARA (1983)
Olivine porphyry	<~3000	
Radiating pyroxene	1–200	
Radiating pyroxene	50–3000	HEWINS *et al.* (1981)
Olivine porphyry	300–4000*	PLANNER and KEIL (1982)
Igneous CAI	<20	STOLPER *et al.* (1983)

* During the first of three stages of cooling inferred by these authors.

The ~ 350 K/hr cooling rate of Fig. 3 falls comfortably within the ranges of cooling rates in Table 1. The agreement might not seem very striking, since the cooling-rate ranges of Table 1 span three or four orders of magnitude. However it must be recognized that, broad as their range is, the laboratory cooling rates fall in a peculiar kinetic regime that is very difficult to reconcile with traditional models of chondrule formation. Chondrules formed by suggested impulsive events such as collisions in space or lightning blasts in the nebula could be expected to cool by radiation very much more rapidly than the upper end of the range of laboratory cooling rates. And chondrules melted by ambient nebular temperatures (*e.g.*, temperature developed by viscous dissipation) could not cool until they were moved a substantial fraction of the distance to the surface of the nebula. The scale of the nebula is so large that this could not be done in less than $\sim 10^6$ hr, even if the motion occurred at sonic velocity. Some of the laboratory work of Table 1 appears to exclude such very slow cooling rates. A very special mechanism is required to cool droplets at the intermediate rate of 100–1000 K/hr, and the gradual loss of kinetic energy (and thus temperature) of drag-heated particles penetrating the thin gas of the solar nebula is exactly such a mechanism.

5. The Dimensions of Pre-Nebular Solid Particles

Operation of the chondrule-forming process discussed above is crucially dependent on the sizes of the solid objects that fell into the solar nebula. The mechanism appears to work well for $\sim$1-mm particles. However, interstellar dust grains are, to the best of our knowledge, much smaller than this. The spectral properties of starlight that has traversed dusty regions of space on the way to Earth are consistent with a dominant particle size of $\sim 0.1\ \mu m$. As noted earlier, such small particles would heat and cool in a few seconds after they encountered the nebular shock front. The space density of infalling particles is too small by many orders of magnitude for them to collide and agglomerate into chondrule-sized droplets during such a brief melting interval.

Thus chondrules can have formed by drag heating in the nebula only if there was a pronounced tendency for interstellar dust grains to have aggregated into coherent clumps of millimeter scale or larger before they fell into the nebula. This may seem improbable in view of the inconceivable emptiness of interstellar space, but FLANNERY and KROOK (1978) and JURA (1980) have suggested that clumping of dust might tend to occur in regions of high dust density in interstellar clouds. (The spectral signature of dust in such regions would still be dominated by the remaining fine dust component.) Further, CAMERON (1975) and MORFILL *et al.* (1978) have argued that particle collisions during infall to the protosolar system would have permitted the growth of aggregations (up to 1–10 mm, in CAMERON's analysis), if particles tended to stick when they collided. A photochemical process of organic molecule synthesis on particle surfaces studied by GREENBERG *et al.* (1980) may have made the infalling dust particles sticky enough to adhere on contact, and given the aggregation enough strength to resist the stresses of drag deceleration until it melted.

6. A Proposed Model of Formation of Chondrite Components

The drag-heating profile of Fig. 1 is in the critical shaded temperature range only over a limited range of radial distances in the solar nebula. Inside this range infalling dust presumably would be totally vaporized; outside it, the dust would not be melted.

Figure 4, a schematic enlargement of a portion of Fig. 1, identifies four different thermal regimes. This paper proposes that chondrules were formed in the temperature range where infalling dust aggregations were melted but not significantly vaporized. CAI's were formed in a range of higher temperatures, where substantial vaporization of the more volatile elements occurred (distillation; WOOD, 1981). Vapors from this regime and from interstellar dust that was totally vaporized at smaller radial distances is presumed to have recondensed, on cooling, to a fine amorphous dust. This dust probably forms a component of the matrices of carbonaceous chondrites, along with dust that accreted to the nebula at large radial distances, which was not melted or severely thermally processed at all.

It is hoped that other puzzling properties of the chondrites and CAI's, in addition to their apparent cooling rates, can be understood as arising from the drag-heating mechanism.

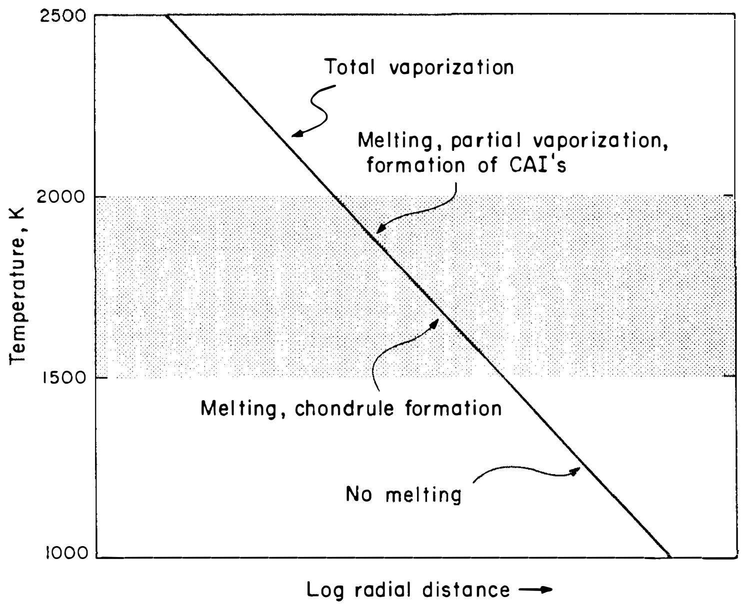

Fig. 4. Thermal processing of infalling interstellar dust particles and aggregations, at different positions on the drag-heating curve of Fig. 1; schematic.

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