FORMATION OF CHONDRULES BY DRAG HEATING IN DUST-ENRICHED ENVIRONMENTS

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At the XIV Lunar and Planetary Science Conference, I proposed that meteoritic chondrules were formed when interstellar dust aggregations, falling into the solar nebula during the collapse process that formed the solar system, were decelerated by aerodynamic drag in the nebula and were heated and melted in the process. I examined the process quantitatively, making the assumption that drag heating occurred in an optically transparent environment in which the hot droplets could lose heat by radiation to the cold ($\sim$ 10 K) interstellar background (1).

This model has many attractive qualities: for example, drag-heated droplets lose heat and cool at the same relatively slow rates that meteoritic chondrules did (2). However, it has several major problems.

a. High infall velocities ($>\sim$50 km/sec) are needed to melt chondrules in the transparent environment assumed, since heat is lost so easily by radiation. A very massive protosolar system (>2 solar masses) is required to accelerate infalling material to this velocity at a radial distance equivalent to the asteroid belt. Since it is currently understood that protostars lose only 10-20% of their mass by T Tauri emission, this extra mass is an embarrassment.

b. Compound chondrules cannot be accounted for. Chondrules are molten only during the early, high-velocity phase of their trajectories, and at this time relative velocities are so large (tens of km/sec; because objects decelerate at different rates, inversely proportional to their radii) that encounters between droplets would be destructive.

c. Interstellar grains must have already clumped into chondrule-sized masses before they fall into the nebula, because primary interstellar grains ($\sim$0.1 μm) would heat and cool too rapidly when they encountered the nebula to be able to accumulate into 1-mm chondrules while they were molten. Cameron (3,4) and Morfill *et al.* (5) conclude that grain aggregation would in fact occur during infall, yet one is uneasy about this aspect of the model.

In addition, this mechanism of chondrule formation shares two problems with other models that make chondrules in the solar nebula:

d. All chondrules, even those in enstatite chondrites, contain mafic minerals with a higher Fe^{2+} content than would be at equilibrium with gases having the cosmic O/H ratio at the melting temperature of mafic silicates.

e. The partial pressures of condensable species at the surface of the nebula would have been orders of magnitude less than the saturation values; molten chondrules in such a system should evaporate.

Solution of problem d. requires some form of O/H fractionation. In the drag-heating model, gas/dust fractionation in the presolar interstellar medium would effect the needed O/H fractionations, since most of the interstellar oxygen resides in dust grains, either as refractory oxide cores or icy mantles. Fe^{2+}-rich chondrules could be formed where dust-rich parcels of interstellar material fell into the nebula. Gas/dust fractionation undoubtedly occurs in the interstellar medium (6,7); whether the local dust enrichment factors needed to explain chondrule compositions (>1000x) are attained is not known.

If an increase in the dust content of local systems is contemplated, however, this makes a radical difference in the underlying premise of the drag-heating model: the process now occurs in an optically opaque rather than a transparent environment. (Even a system containing gas and dust in the cosmic proportions is only marginally transparent.) This, it turns out, alleviates most of the problems outlined above.

a. Since objects drag-heating in an opaque environment could not lose their heat, smaller infall velocities (∿10 km/sec) are needed to heat protochondrules to the melting temperature. A protosolar system of <1 solar mass can accelerate infalling material to this degree.

b. Chondrules could remain hot and molten even after they decelerated to very small absolute and relative velocities, since they are temporarily insulated from heat loss by their environment. Constructive collisions can occur at low velocities, forming compound chondrules.

c. Similarly, chondrules can be built up by the coalescence of smaller primary droplets. They cannot be built up all the way from melted primary 0.1 μm interstellar grains (the latter would lose their kinetic energy before they penetrated deeply enough into the nebula to be shielded from radiative heat losses), but presolar aggregations in the 10-100 μm size range might melt and coalesce into chondrules. This lessens the required degree of presolar aggregation.

d. Dust (and ice) fractionation would increase the local O/H ratio, accounting for the relatively large Fe^{2+} content of chondrules.

e. A dust/gas enrichment of (say) 1000x still leaves the partial pressures of condensable components in the gas 4-5 orders of magnitude below the saturation values. The chondrules' survival in the nebula must be attributable to the finite rate of vaporization of silicate liquids, and a relatively short time during which the chondrules were molten.

The postulated opaque environments would soon be dispersed by shear and turbulence in the nebular gases, and their contained chondrules would cool. The cooling rate would be highly model-dependent, making a detailed comparison with the observed cooling rates of meteoritic chondrules unprofitable.

References

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