

**CHONDRULE CRYSTALLIZATION EXPERIMENTS.** R. H. Hewins<sup>1</sup>, H. C. Connolly Jr.<sup>2</sup>, G. E. Lofgren<sup>3</sup> and G. Libourel<sup>4</sup>, <sup>1</sup>Geological Sciences, Rutgers University, Piscataway, NJ08816 <sup>2</sup>KBCC-CUNY, New York, <sup>3</sup>ST NASA Johnson Space Center, Houston, TX 77058, <sup>4</sup>CRPG-CNRS, 15 Rue Notre-Dame des Pauvres (BP 20), 54501 Vandoeuvre les Nancy, France.

**Introduction:** Given the great diversity of chondrules, laboratory experiments are invaluable in yielding information on chondrule formation process(es) and for deciphering their initial conditions of formation together with their thermal history. In addition, they provide some critical parameters for astrophysical models of the solar system and of nebular disk evolution in particular (partial pressures, temperature, time, opacity, etc). Most of the experiments simulating chondrules have assumed formation from an aggregate of solid grains, with total pressure of no importance and with virtually no gain or loss of elements from or to the ambient environment. They used pressed pellets attached to wires and suffered from some losses of alkalis and Fe.

**Conventional Experiments:** The hierarchy of chondrule textures has been well established. Skeletal crystals found in barred olivine and some porphyritic olivine (PO) chondrules require rapid growth rates (but not necessarily rapid cooling rates), and hence formation by undercooling of a completely melted liquid. Equant crystals found in most PO chondrules indicate formation from a liquid with abundant nuclei and/or, depending on the amount of relict grains, a partially melted precursor. The textures of some porphyritic chondrules in ordinary chondrites can be duplicated by low degrees of melting of chondritic material. Partial melting of very fine-grained starting material produces dominantly very fine-grained porphyritic chondrules. Production of normal porphyritic chondrules from such a precursor would require multiple remelting events to coarsen them.

The olivine phenocrysts of type II (ferroan) chondrules show normal Fe-Mg zonation which has been simulated with cooling rates of a few to a few hundred degrees per hour. The size of pyroxene exsolution features in charges constrains cooling rates around 1200°C to less than 45°/hr. Reverse zoning on relict grains can be shown from diffusion experiments to require many minutes for the dissolution process. Large olivine grains introduced as seeds into finely ground mixture showed barred overgrowths when the mixture

was totally melted, but no overgrowths in the case of incomplete melting where new growth was on nuclei surviving in the melt. Thus overgrowths must be used with caution as indicators of chondrule thermal history. Element partitioning experiments yield information about approach to equilibrium and cooling rate.

Heating times are much more difficult to constrain than cooling times, because longer times and higher temperatures have similar effects. However, extremely short heating times coupled with high cooling rates are inappropriate for chondrules: they produce mixtures of relict grains and skeletal crystals unlike the natural case.

**Complex experiments:** Totally glassy spheres can easily be made by total melting, though similar chondrules are rare. If crystalline dust is injected into a cooling totally molten droplet, crystallization ensues forming normal chondrule textures. In some experiments, the starting material was a powder blown into the furnace, instead of a pellet pressed on a wire. Chondrule-like droplets charged with crystals were accreted; the textures were heterogeneous and aggregational, resembling particularly some chondrules in CR chondrites. Igneous rims on chondrules might have formed by accretion of such a mist, though formation by melting of solid dust mantles has also been demonstrated to be feasible. Partially melted charges that incorporated C in a form such as graphite contain olivine grains in which much of the FeO was reduced to Fe metal. These crystals resemble the dusty olivine relict grains found in many chondrules. Forsteritic olivine and pyroxene have also been made in graphite crucibles.

**Condensation/Evaporation experiments:** Relatively few experiments have been designed to study evaporation or condensation of silicate melt. Condensation of a chondritic vapor at high temperature results in the sequence of phases seen in CAI. High partial pressures of K and SiO in the ambient gas have been shown to result in condensation into silicate melt droplets. The resulting zonation in silica-rich phases resembles what is seen in some layered chondrules. When chon-

driftic or IIA chondrule compositions are heated at 1580°C with a  $p_{H_2}$  of  $10^{-5}$ , sequential evaporative losses are seen, with S lost first and then all alkalis in less than one hour. With loss of FeO to the vapor, type IAB compositions are approached, and as loss of Si also becomes important, type IA compositions with Ca-rich forsteritic olivine are reached. Loss of FeO by evaporation takes 18 hours for 4mm charges. Silica-rich IIB and IB compositions cannot be reached by evaporation from these precursors. Experimental residues with IA compositions have porphyritic textures and show strong isotopic mass fractionations. Heating in graphite crucibles in evacuated silica tubes produces forsteritic olivine by reduction of FeO to Fe metal and migration of metal blebs out of the silicate sphere. The loss of FeO is more rapid than by pure evaporation, taking less than 4 hours.

**Constraints on chondrule formation:**

If formed as closed systems, the peak temperatures of chondrules with skeletal crystals would have been relatively close to their liquidus temperatures. These have an enormous range, but because the most Mg-rich were incompletely melted and the most Mg-poor were completely melted, the range of maximum peak temperatures may have been restricted to 1450-1750°C. If chondrules were heated for extremely short durations, the temperatures would be higher than this to achieve the same amount of melting and the same density of nuclei at the onset of crystallization. Within the range of peak temperatures, the liquidus temperature correlates with bulk composition, and there is the apparent problem that each chondrule must be heated to the temperature appropriate to its composition if indeed it were heated to its liquidus temperature. However, if most chondrules were incompletely melted, as were many porphyritic chondrules, or if they were open systems, the temperatures need not be near-liquidus. Experimental evaporation residues have porphyritic textures produced at up to 200°C below the final liquidus temperatures of the residues.

Consideration of textures and mineral features requires cooling rates of several to several hundred degrees per hour. Chondrules were probably self-buffered at oxygen fugacities a few log units below the I-W buffer, and many contained solid carbon. Some type II chondrules contain supra-chondritic alkalis and can have experienced little or no evaporation. Type I could have experienced ~40%, the lack of isotopic mass fractionation being explained by exchange with a gas containing high pressures of the lithophile elements. Similarly an important role for condensation in chondrule formation requires high  $p_{SiO}$ , due to evaporation of locally concentrated dust. Chondrules that are condensates or evaporation residues formed in very restricted volumes. If type I chondrules did form by evaporation of partially melted crystalline precursors, they were heated about three hours, and their alkalis are secondary.

It is likely that different kinds of chondrules formed in different ways. In some, the dominant process may have been condensation, in others evaporation, or accretion of a mist of droplets and dust, or melting of aggregates with little change in composition. If chondrules formed in heterogeneous turbulent clouds, many may have experienced all of these processes to some extent. Therefore, more specific experiments of crystallization, evaporation or condensation, involving the control of complex gas partial pressures, are needed.