Petrographic Evidence for Rapid Heating and Cooling during Chondrule Formation. J. T. Wasson, Institute of Geophysics and Planetary Physics, University of California, Los Angeles 90095-1567 USA.

Introduction. The chondrule cooling rates used in most chondrule-formation models appear to be too low. Recent petrographic evidence [1] indicates that the amount of crystal (especially olivine) growth that occurred after the last melting event was about 30× smaller than the grain sizes simulated in order to estimate cooling rates. The smaller amount of growth leads to an upwards revision of cooling rates by about a factor of 1000.

Most chondrules are porphyritic. They consist of large and small crystals of olivine and, less commonly, pyroxene immersed in a mesostasis having a plagioclase-rich composition. In the most primitive chondrites the mesostasis is often vitreous.

Because the large majority of chondrules contain FeS, it is clear that the nebula had cooled below the FeS condensation temperature (ca. 650 K) before chondrule formation occurred. The high FeO/(FeO+MgO) ratios of some chondrules require still lower nebular temperatures (<500 K) [2].

The traditional view has been that porphyritic chondrules formed in a single heating/cooling event and many laboratory experiments have been carried out in various kinds of kinds of furnaces to try to simulate the formation of chondrules textures in a single heating/cooling cycle [3, 4]. These furnace experiments have been used to infer the cooling rates of chondrules during the temperature range at which olivine crystallized from the melt. Most of these inferred values are in the range 0.01-1 K s^{-1} [5].

These low cooling rates are problematical because there is no long-term nebular environment that yields such values. In transparent regions chondrules would cool at rates orders of magnitude higher, whereas in an opaque nebular disk the cooling rates would be many orders of magnitude lower. And these latter conditions are not suitable locations for chondrule formation because such high temperatures would cause the complete evaporation of chondrules (which have melting temperatures about 600 K higher than their evaporation temperatures) [2].

During the last several years several kinds of petrographic evidence indicating rapid chondrule cooling have been recognized. These include thin overgrowths on relict grains, clusters of small crystals that grew following the most recent melting event, and fragments preserving shard-like shapes that would have been hidden had several tens of micrometers of new growth occurred following the last melting event. And there are other indications of rapid cooling including the preservation of volatiles such as FeS and one case where the modeling of O-isotopic and FeO/(FeO+MgO) gradients indicated a high cooling rate [6].

Petrographic evidence. Because aqueous alteration can confuse the evidence in chondrites showing appreciable effects (such as such as CR, CM and CV) we have limited our studies to LL3.0 Semarkona, CO3.0 Yamato 81020, and the ungrouped type-3.0 carbonaceous chondrite Acfer 094.

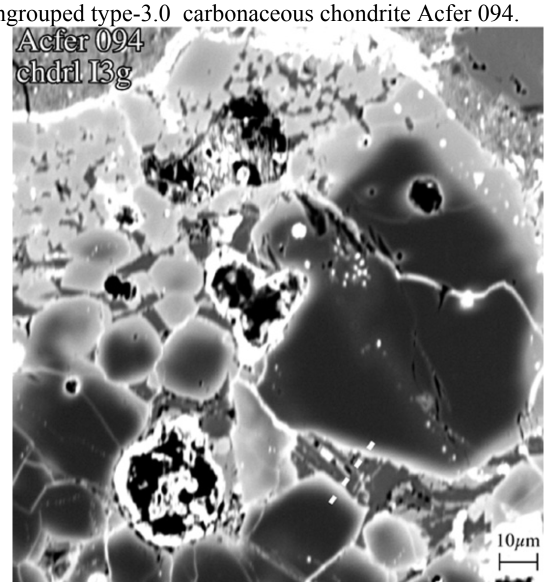

Fig 1. Cluster of relict olivines in Acfer 094 chondrule I3g. At the dashed line overgrowth thickness is ~4 μm.

The most telling evidence for rapid cooling consists of overgrowths on relict grains; these form in melting events in which the mesostasis melts and phenocrysts remain as largely intact substrates for the overgrowths. Wasson and Rubin (2003) surveyed and discussed high-FeO overgrowths on low-FeO olivine grains in Y81020 and observed that more than 90% of the high-FeO (type-I structured) chondrules contain low-FeO relicts with thin overgrowths adjacent to mesostasis (necessary to allow unimpeded growth during cooling). The apparent thickness of overgrowths oblique to the plane of the section are too high; after allowance for this it appears that all overgrowth thicknesses are in the range 4-5 μm. This is the property that needs to be reproduced. The high-FeO chondrules in Acfer 094 show similar features; in Fig. 1 the dashed line marks a position where low-FeO olivine grains on opposite sides of a patch of mesostasis each show high-FeO overgrowths about 4 μm thick. Similar overgrowth thicknesses are observed on phenocrysts in ordinary-chondrite chondrules. Fig. 2 shows a shard-like low-FeO fragment from Semarkona with an FeO-rich overgrowth that is about 4 μm thick in the narrowest regions. In some high-FeO pyroxene-rich chondrules in Semarkona up to four successive 4-5 μm growth layers are observed; these are preserved because cation diffusion is much slower in pyroxene compared to olivine. we interpret these to reflect successive melting events in which the melt fraction was largely confined to the mesostasis. Although it is more difficult to recognize overgrowths on phenocrysts in low-FeO chondrules, they are visible on the surfaces of olivine grains that contain clouds of dusty metal in their interiors, where they are observed to have the canonical thickness of 5-10 μm [7]. Olivine precipitates at higher temperatures in low-FeO chondrules, thus overgrowths are expected to be slightly thicker .

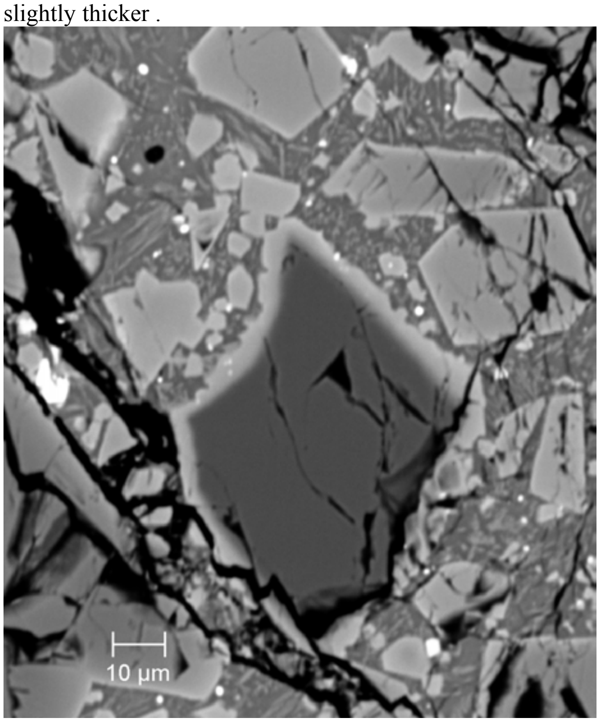

Fig. 2 Semarkona chondrule Q8b. The high-FeO overgrowth on this olivine shard is about 4 μm thick.

Constraints on chondrule formation models. Thus 4-5 μm overgrowths are the feature that needs to be reproduced in laboratory simulations, not the gross porphyritic structures of the chondrules. The impact these thin growth layers have on inferred cooling rates can be readily modeled.. Olivine has higher Fe and Mg and lower Si contents than the mesostasis melt. A reasonable assumption is that olivine growth requires the diffusion through the melt of Fe and Mg towards and Si away from the growing surface, and that growth stops when the temperature drops to a value below which negligible additional growth occurs. This "blocking" temperature will depend on the cooling rate but, because diffusion coefficients vary exponentially with temperature, the actual values will probably differ by only a few tens of degrees. We will define Δt to be the interval between the maximum temperature reached by the melt and the blocking temperature. Because most growth occurs in the high portion of this range, the difference in blocking temperature is negligible for the purposes of this approximation. It thus follows that where D, the mean diffusion coefficient during the growth period, should be independent of the cooling rate.

If the growth rate is limited by the diffusion of constituents through the mesostasis melt, the thickness X of the overgrowth is given by:

$$X = \left(D \cdot \Delta t\right)^{0.5}$$

We will assume that the 4-5 μm overgrowth thickness is 30× smaller than the half-thickness of the phenocrysts that led to an estimated cooling rate of 1 K/s in published furnace simulations. It then follows that the correct cooling rate is about 10^3 K/s. This cooling rate applies at the olivine liquidus temperature for the individual chondrule, probably generally in the range 1600-1800 K.

A cooling rate of 10^3 K/s is an order-magnitude lower tha cooling rates estimated for chondrules cooling in a transparent nebula in which allowance is made for latent heat of crystallization (Wasson, 1996). Although this difference is probably not outside errors of estimation, it is important to keep in mind that chondrule formation occurred in the dusty and thus somewhat opaque midplane, and cooling models need to include allowance for the slower rates of heat transport away from the small (1-10 m^3) scale regions associated with chondrule melting events.

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