WHY DO SOME CHONDRULES HAVE HIGH PRIMARY **FeO** CONTENTS? **Alfred Kracher**,
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Introduction: There is mounting evidence that chondrules formed by melting of solid precursors in the solar nebula **(1)**. Since reactions at liquidus temperatures are rapid, it is likely that chondrules preserve some record of their environment during melting. Type 3 ordinary and carbonaceous chondrites contain two distinct populations of porphyritic chondrules: type I, which grades from porphyritic olivine (**type IA**) and olivine-pyroxene to poikilitic pyroxene (**type IB**), and **type II**, which usually contains little or no pyroxene **(2,3)**. In the absence of metamorphic Fe-Mg exchange, ferromagnesian minerals have very low Fe/(Fe+Mg) ratios in type I, and Fe/(Fe+Mg) > 0.2 in type II.

Can melt droplets of chondrule composition survive in the reducing environment of an unfractionated solar gas phase? Conceivably type I chondrules originated by incomplete equilibration of molten oxidized material with nebular gas; chondrule types which cooled more rapidly may have remained further removed from equilibrium and thus may be more oxidized. Neither argument can be made for type II. Constraints on their formational environment can be derived from known chondrule properties and experimental data: **A1**. The temperature range for olivine growth. **A2**. The cooling rate. Together, A1 and A2 give the time during which a chondrule was hot enough to react with gas. **A3**. Within this time-temperature regime, no reduction of olivine occurred. **A4**. No Na was lost during heating.

In evaluating these constraints, I will assume that similar formation conditions apply to all type II chondrules regardless of the meteorite in which they occur. This is reasonable considering their similarity **(3)**, but should not be accepted uncritically. Some authors regard type II objects in ordinary chondrites as rounded rock fragments **(4,5)**, which would imply origin on a parent body. However, coating by opaque rims which are presumably accretionary **(1,3,6)**, spherical shape (which is developed to various degrees in different meteorites), and the existence of intact type I inside type II chondrules **(3)** suggest that they were molten droplets in the solar nebula.

Time-temperature regime: Since type II chondrules are olivine-dominated, the temperature range during which the chondrules were (partially) liquid can be estimated fairly accurately from olivine-liquid equilibria **(7)**. Bulk and mesostasis compositions of large type II chondrules from Manych **(5)** indicate liquidus temperatures of 1520±20°C. If the chondrules were not totally molten, but only to 90 %, the maximum temperature would be only 20° lower (1500°C). Olivine crystallization spans a temperature range of 340±60°C. Olivine morphologies **(8)** and artificially produced olivine-rich chondrules **(9)** indicate a typical cooling rate of < 20°/hour. Even assuming 50°/hour, chondrules must have been liquid for > 7 hours, and perhaps for as long as 50. A 100 μm olivine crystal would grow at a rate of < 7 μm/hour. Faster crystal growth, which would follow from undercooling or high cooling rates **(10)** is unlikely, since it would lead to spinifex-like textures rather than zoned microphenocrysts. In a basalt melt a growth rate of 12 μm/hour leads to the formation of unzoned, skeletal olivines **(11)**. Applying a similar analysis to olivine zoning in type II chondrules would provide better constraints on cooling rates, but the necessary data are not yet available. The long interval during which type II chondrules were partially molten makes it understandable that collisions occasionally implanted foreign material, such as Fe-poor olivines **(12)** or entire type I chondrules **(3)**.

Time-dependent reactions: At 1500°C the oxygen fugacity in the solar nebula is about 10^4 times lower than over olivine(fa20)+iron **(13)**. There is no evidence that melts parental to type II chondrules were metal-saturated, so their $f(O_2)$ may have been higher. Although reduction kinetics are not known, it is unlikely that reduction was kinetically inhibited. Experiments in CO/CO_2 atmospheres (1 bar) lead to reduction and precipitation of metal in olivine within 10 hours at 1300°C **(14)**. Reduction by hydrogen should proceed at least as fast. If the gas was dense enough to be responsible for the slow cooling rate of the chondrules, it must have been much less reducing than unfractionated nebular gas. If on the other hand the gas density was very low, an intrinsic $f(O_2)$ near the metal saturation of the liquid assemblage might have been established, as is the case in many lunar extrusive rocks. However, low gas densities are difficult to reconcile with the apparent absence of volatilization effects.

Sodium evaporation from chondritic melts has been studied experimentally **(15)**. The decrease in Na concentration with time, given by $-(dC/dt)=3kC/r$, has a rate constant k (in cm/min) of approximately $\log k=8.14-0.265*\log f(O_2)-23396/T$. It is difficult to understand that type II chondrules have apparently not lost any Na **(5)**. To limit Na loss to below 10 % during cooling from 1500° to 1450°C within 1 hour, it is required that $\log k=-3.8$, implying $\log f(O_2)=-4.3$, which is unreasonably high. The experiments **(15)** were performed at 1 bar, but at lower pressures Na should evaporate faster, not slower.

Discussion: Cooling rates of type II porphyritic olivine chondrules are too fast to be controlled by nebula-wide processes, like condensation **(16)**, and too slow for localized, instanteneous processes. Olivine zoning is probably a more sensitive indicator of cooling rate than morphological similarities to experimental charges. However it is necessary to distinguish igneous zoning from mildly reheated relict-overgrowth textures **(12)**, which may sometimes be difficult. Nebular cooling rates would likely have led to metamorphic textures. Fast cooling rates or substantial undercooling entails very fast crystallization rates, which would probably produce unzoned olivine.

Type II chondrules did not form in a gas of solar composition. Partial hydrogen loss does not make the gas sufficiently oxidizing to allow equilibrium with type II parent material. Vaporization of oxidized solid (oxygen >> carbon + sulfur) after gas-dust fractionation is perhaps the most likely source for the gas phase, since it would produce not only an oxidizing but also volatile-enriched gas, which could explain the Na retention. However, it is then hard to understand that vapor phase fractionation seems to have been a relatively unimportant mechanism for generating chemical variation among chondrules **(4,18)**. Gas clouds formed by localized events like impacts cool to < 500°C in a few seconds[17]. The same is probably true of electric discharges, although intermittent activity might be sustained for some time in a confined region of the solar system.

Statistical treatment of chondrule bulk composition data **(18)** indicates that chondrules with high Fe/(Fe+Mg) ratios are chemically different from reduced ones. This complicates inferences about the chondrule forming environment, since it suggests that precursor composition and environment are not independent parameters.

References: **(1)** Taylor et al (1983), in:"Chondrules and Their Origins", 262. **(2)** McSween (1977) GCA 41, 1843; McSween et al. (1983) in: "Chondrules...", 195. **(3)** Scott & Taylor (1983), ProcLPSC14, B275. **(4)** Dodd (1981) "Meteorites". **(5)** Dodd (1978) EPSL39, 52. **(6)** King & King (1981) Icarus 48, 460; Scott et al (1984) GCA 48, 1741. **(7)** Roeder & Emslie (1970), ContrMinPet 29, 275. **(8)** Donaldson (1976) ContrMinPet 57, 187. **(9)** Tsuchiyama et al. (1980) EPSL 48, 155. **(10)** Nagahara (1983) MemNatInstPolarRes 30, 61. **(11)** Donaldson (1975) Lithos 8, 163. **(12)** Kracher et al (1984) ProcLPSC14, B559. **(13)** Williams (1971) AJS270, 334. **(14)** Duba et al (1982) LPSXIII, 188. **(15)** Tsuchiyama et al. (1981) GCA 45, 1357. **(16)** Blander (1983) in:"Chondrules...", 1. **(17)** Kluger et al (1983) in: "Chondrules...", 188. **(18)** Grossman & Wasson (1982) GCA 46, 1081.