THERMAL HISTORIES OF CHONDRULES: PETROLOGIC OBSERVATIONS AND EXPERIMENTAL CONSTRAINTS.
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Introduction: Petrology is fundamental to understanding chondrules. Knowing what minerals are present, their chemical compositions, and how those minerals are arranged, allows us to interpret important chemical and physical characteristics of the chondrule formation process. Chondrules show diverse compositions and textures that indicate variation in chondrule precursors, heating and cooling rates, interactions with local gas, chondrule density in the formation region, relationships with refractory inclusions, and many other parameters. In addition, experimental studies of chondrule analogues provide important insights into the conditions controlling chondrule melting and crystallization. Here we focus on the observations and experiments that specifically place constraints on chondrule thermal histories, which are fundamental to discriminating between chondrule formation models.

Observations of natural chondrules: Petrologic properties of chondrules are the most direct way of determining their thermal histories. Chondrule textures are described as either porphyritic or non-porphyritic, with the dominant silicate mineralogy consisting of crystalline olivine and pyroxene, and an interstitial feldspathic mesostasis [1]. Different textures represent differing degrees of nucleation as the chondrule cools: incomplete melting results in a high density of nucleation sites, which leads to a porphyritic texture, whereas complete melting results in destruction of nucleation sites and a non-porphyritic texture [2,3].

Several other petrologic indicators can also constrain cooling rates. Both olivine and pyroxene show growth zoning, especially in more FeO-rich chondrules: diffusion modeling of this zoning can put quantitative constraints on cooling rates [4]. The presence of relict grains that persisted through the melting event puts limits on thermal histories, from considerations of dissolution rates and from chemical and isotopic diffusion modeling of relict / overgrowth zoning profiles [1,3]. The presence of clinoenstatite, and glass with quench microcrystallites, both indicate rapid cooling. Pyroxene and metal microstructures give information about lower-temperature thermal histories at sub-liquidus temperatures [5,6].

Chondrule analogue experiments: Dynamic crystallization experiments on chondrule analogue compositions have provided the most important quantitative constraints on chondrule thermal histories [2,3,9]. In general, chondrules were heated to peak temperatures in the range 1500 to 2000 °C and cooled at rates of 10 to 1000 °C/hr, with ambient temperature <400 °C.

More recent work adds further insights. For example, [10] showed that in order for plagioclase to nucleate and grow in type I chondrule analogues, very slow cooling rates are necessary in the temperature range close to the solidus. [11] showed that it is possible to produce type II chondrules from type I chondrules by oxidation, although this requires thermal histories that are not typically considered. [12] has shown that olivine dissolution in chondrule-like melts is fast, with rates of about ten $\mu m.min^{-1}$, suggesting that cooling rates as high as 1000–8000 °C/hr are required to preserve relict olivines in type IA chondrules.

Discussion: We know a lot about the petrology of chondrules, and we have a good general understanding of thermal constraints. These observations and experiments provide essential parameters for thermal histories in chondrule formation models. However, there are still some important questions to answer such as: 1) What is the thermal history prior to the (last recorded) rapid heating event, and also close to and below the solidus? 2) Relationships between composition and texture should be investigated further. Specifically, kinetic effects in open system experiments should be explored. 3) More modelling of chemical and isotopic zoning would be useful to determine thermal histories specific to individual chondrules. 4) The role of metals has not been fully investigated. Does the thermal history recorded by metal in chondrules match the silicate one? How do metals segregate from molten chondrules, and does this place time and / or physical constraints on melting?

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