AN EXPERIMENTAL INVESTIGATION OF THE PLANETARY EMBRYO BOW SHOCK MODEL AS A CHONDRULE FORMATION MECHANISM. A. M. Perez[1], S. J. Desch[1], D. L. Schrader[1], and C. B. Till[1], [1]*School of Earth and Space Exploration*, Arizona State University, P.O. Box 871404, Tempe, AZ 85287-1404, alexandra.m.perez@asu.edu

Introduction: Chondrules are sub-mm to mm-sized igneous inclusions that can comprise up to ~80% of the primitive meteorites called chondrites, and provide us with snapshots of the solar nebula. They are the key to understanding the early history of the Solar System and the formation of terrestrial planets. Chondrules formed in the first few million years (Myr) of the Solar System's history [e.g., 1], during its protoplanetary disk phase, so understanding the energetic event(s) that melted chondrules is key to using meteoritic data to constrain astrophysical models of the disk.

Chondrules display an array of igneous textures that are the result of melting and crystallization. Textures refer to the overall appearance (e.g., size, shape, orientation) of phenocrysts (melt-grown crystals) within a fine grain matrix or mesostasis. The three most common chondrule textures, in the order of their abundance, are (1) porphyritic, (2) radial, and (3) barred [2]. Once these igneous objects were recognized in chondrites, astrophysical models of their melting have been sought, to understand disk conditions and planet formation [3].

Nebular shock models. The community has not settled on any astrophysical model, making it difficult to use the rich and detailed data from chondrules (i.e., petrology, chemical composition, isotopic fractionation, compound chondrule frequency) to constrain conditions and processes in the protoplanetary disk. Nebular shock models are currently the most favored, meeting both the thermal and petrographic constraints to form chondrules. Models include large-scale shocks driven by gravitational instabilities [4,5,6] and bow shocks driven by planetary embryos [7,8]. The bow shock model is highly motivated by the evidence that planet building had already taken place before chondrule formation. Mars accreted approximately 50% of its mass $1.8^{+0.9}_{-1.0}$ Myr after the formation of CAIs [9,10], iron meteorite parent bodies are modeled to have formed in < 0.5 Myr after CAI formation [11], and it is inferred that Jupiter's core grew to about 20 Earth masses in < 1 Myr after CAI formation [12].

We investigate the validity of the planetary embryo bow shock model by conducting dynamic crystallization experiments to see if the cooling rates predicted by this model are consistent with the most dominant chondrule texture type, porphyritic.

Methods: Crystallization experiments were conducted inside a 1-atmosphere vertical gas-mixing furnace located at the *School of Earth and Space Exploration's* Experimental Petrology and Igneous processes Center (EPIC). Natural chondrule analogs with bulk compositions similar to FeO-poor chondrules were created using a mixture of San Carlos Olivine, Amelia Albite, and Dog Lake Diopside in proportions similar to those used in [13]. Cooling rates of 300, 600, 1000, 3000, and 5000 K/hr were investigated as well as heating durations of 1, 5, and 10 minutes, and peak temperatures at the liquidus and 50 K below and above the liquidus. To investigate the role of seed nuclei, we used two different grain size fractions. One chondrule analog consisted of 63-90 µm starting materials and the other also consisted of 63-90 µm starting materials, but the olivine had a grain size fraction of 212-250 µm.

Back-scattered electron (BSE) images of the samples were acquired along with semi-quantitative, standardless energy-dispersive spectrometry (EDS) analysis using the JXA-8530F Electron Probe Microanalyzer located at Arizona State University.

Results: Our results show that porphyritic textures are most consistent with cooling rates < 1000 K/hr (Figure 1). The results are not sensitive to other parameters. If grain size, peak temperature, or heating duration are individually varied, similar textures are produced.

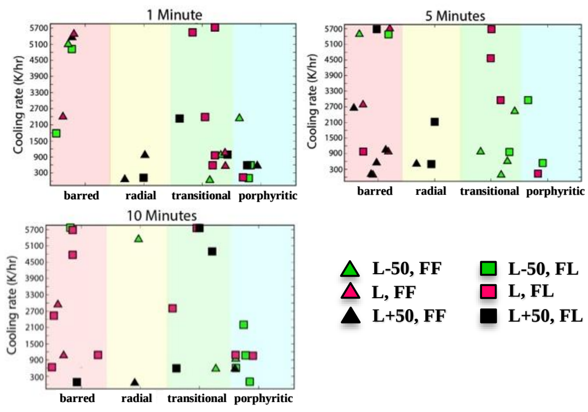

Figure 1. Cooling rates relative to texture type at different heating durations. *L: liquidus = 1608 °C; FF: 63-90 µm (olivine, albite, diopside); FL: 63-90 µm (albite, diopside) and 212-250 µm (olivine)*

The results demonstrate the primary importance of cooling rate in dictating which chondrule texture will be produced. Grain size, heating duration, and peak temperature are secondary parameters.

We also show that there is a continuum of textures at various cooling rates and there is no clear boundary defining each textural type. In fact, the majority of our experimentally reproduced porphyritic textures contain skeletal grains and not just the classic subhedral to euhedral grains present in characteristic porphyritic textures. To compare the experimental textures with natural chondrules, we took BSE images of chondrules from Queen Alexandra Range (QUE) 97008, a L3.05 chondrite. We find that QUE 97008 contains a few porphyritic chondrules with skeletal textures, implying that not all porphyritic chondrules are comprised solely of subhedral to euhedral grains, and making our experimentally reproduced textures consistent with textures of actual chondrules (Figure 2).

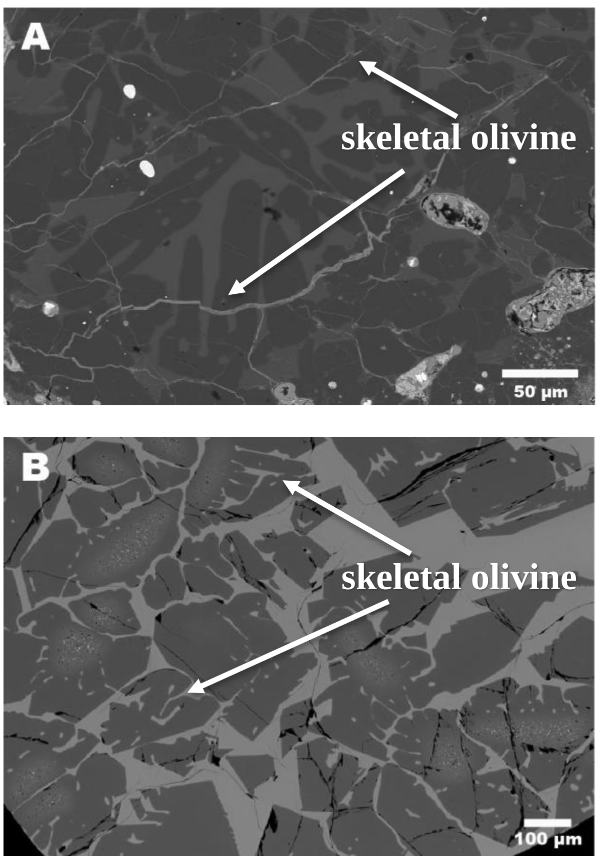

Figure 2. BSE images showing similar skeletal grains present in both meteoritic (A) and experimentally (B) produced textures using a 600 K/hr cooling rate.

Conclusion: Cooling timescales predicted by current planetary embryo bow shock models, using Mars-sized embryos, are as low as 600 K/hr [14]. Our experimental results show that the most dominant chondrule texture, porphyritic, requires cooling rates < 1000 K/hr to form. The planetary embryo bow shock model therefore is a viable chondrule mechanism for the formation of *most* chondrules, although lower cooling rates would be preferred. Cooling rates in the bow shock model are inversely proportional to planet size [14], suggesting that the bow shock around a planetary embryo larger than Mars may better produce porphyritic textures. Our results imply that large planetary embryos were present and on eccentric orbits during the first few million years of the Solar System's history.

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