EXPERIMENTAL AND THEORETICAL PROGRESS ON THE FLYBY MODEL FOR CHONDRULE AND CHONDRITE FORMATION

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Introduction: The Flyby model for chondrule and chondrite formation [1, 2] is a proposal that chondrules and chondrites formed simultaneously during brief heating events caused by the close encounter of small (m-scale to km-scale) porous planetesimals (SPP) with larger (>100 km) differentiated planetesimals (LDP) having lava on their surfaces. Surface lava may be a product of volcanism, crust-breaching impactors, crustal foundering, or impact melting. Multiple heating events are possible as the SPP may orbit the LDP prior to accretion. An LDP with undifferentiated chondritic exterior has been proposed previously as a model for chondritic parent bodies [3]. The Flyby model can account for most chondrule properties, including the difficult ones of nucleosynthetic complementarity [4] and unidirectional magnetization [5]. It also accounts for the fact that chondrules are ubiquitous within chondrites.

Experimental Methodology: Using published heating and cooling curves for the Flyby model [1], we have been able to make a reasonable set of Type I and II chondrules. We use a Deltech furnace with gaseous mixtures of CO and CO_2 to control fO_2 to either IW+1 or IW-1. Temperature is monitored with external thermocouples to track the heating and cooling of the middle curve of Fig. 2 of [1]. Recently, we have focused our experimental program on synthesizing pyroxene mantles on olivine/glass cores of typical Type I chondrules. We have been adding quartz rims to our chondrule precursor analogs (a mixture of Globe peridotite, Miyake anorthite, and graphite) to assess if pyroxene mantles in Type I chondrules are a result of silica rims on chondrule precursors [6] or the result of enhanced SiO vapor [7].

Experimental Results: We have found it extremely difficult to make pyroxene mantles on olivine/glass chondrule cores during a reasonable flyby. Using one thermal trajectory, and varying the size of the quartz rim, we synthesized barred olivine and barred pyroxene chondrules. We have thus far been unable to make a pyroxene rim on a olivine/glass core. This is surprising, as the quartz rim should lead to a locally more silica-rich melt near the chondrule exteriors during melting. We are finding instead that the experimental charges are apparently equilibrating and reacting to the compositional divide in the forsterite-anorthite-silica ternary phase diagram [8]. As the thermal conditions of the flyby model are similar to published constraints on chondrule thermal histories, our results would likely be relevant to most chondrule formation scenarios. These preliminary results suggest that chondrule formation occurs in areas of enhanced SiO vapor [7] to explain the common Type I chondrule texture of an olivine/glassy core with a pyroxene mantle.

Theory: We have developed an improved model of the thermal history of the SPP during a flyby based on the gray plane parallel solution to the equation of radiative transfer described in Chapter 11 of [9]. It allows for heating by the directly incident infrared radiation from the lava, as well as re-radiation from the SPP matter itself, as it heats up. If the SPP has a closed pore structure, at least in some parts, it can achieve temperature and pressure conditions not only sufficient for chondrule formation but also for lithification by Hot Isostatic Pressing (HIP) [10]. The ubiquity of chondrules within most chondrites is, therefore, predicted, as is their absence in CI's, the least-well-lithified group. Simultaneous chondrule formation and chondrite lithification in a closed system also accounts for complementarity and for cluster chondrites [11]. These events happen within the magnetic field generated by the LDP. Metamorphosis occurs on the LDP, post-accretion, as proposed by [3]. Aqueous alteration may occur during lithification.

Summary: The Flyby model is unique among chondrule formation theories in not only meeting the demands of experimental petrology on thermal histories but also addressing the broader suite of constraints that has proven challenging to canonical nebular and planetary models. We argue that chondrules were never widespread in the solar system but only exist within chondrites, as a by-product of their lithification. The Flyby model provides a framework for addressing many aspects of chondrites and chondrules often seen as puzzling, including: thermal histories, epoch of formation, vapor pressure of Na and O_2 in formation zone, nucleosynthetic complementarity, compound chondrites, cluster chondrites, size sorting of chondrules within chondrites, chondrites without chondrules (CI's), metamorphic types, aqueous alteration, and remnant magnetism.

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