SOME IMPLICATIONS OF METEORITIC CONSTRAINTS FOR CHONDRULE FORMATION MODELS INCLUDING THE BOW SHOCK MODEL. Stuart J. Weidenschilling[1] and Lon L. Hood,[2] [1]Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, Arizona 85719; sjw@psi.edu; [2]Lunar and Planetary Laboratory, University of Arizona , 1629 E. University Blvd., Tucson, AZ 85721; lon@lpl.arizona.edu.

Introduction: Chemical, petrologic, and isotopic analyses place a number of constraints on the processes by which chondrules formed and their environment in the solar nebula. Chondrules formed 1-3 Myr after CAIs [1]. It is generally inferred that they were free-floating droplets melted by transient heating events before incorporation into asteroidal parent bodies [2]. Cooling rates estimated from furnace experiments and the lack of loss or isotopic fractionation of Na, K, and Mg imply that melting occurred in regions of high particle density with sizes of at least hundreds of km [3].

Chondrule Formation Mechanisms: Transient heating events associated with the formation of the solar nebula (e.g., infall shocks, shocks in spiral density waves) or activity of the early Sun (x-ray flares, X-wind, FU Ori events) would have been more frequent / intense at early times, declining with time thereafter. Multiple heating events could reset chondrule ages, erasing the earliest record of such activity and yielding a younger median age for the survivors. However, CAIs would also have had ages reset by such events. Therefore, whatever the true heating mechanism was, it did not decline monotonically from the formation of the Sun and the protoplanetary disk, but reached a peak ~ 1-2 Myr after that time. One mechanism that can satisfy the latter constraint is the planetesimal shock mechanism, which involves planetesimals injected into eccentric orbits in Jovian resonances following the formation of Jupiter, assumed to have occurred about 1 Myr after CAIs [4,5]. Chondrules are hypothesized to have been melted in either bow shocks upstream of the eccentric planetesimals or in localized shocks caused by collisions between resonant and non-resonant bodies. However, order-of-magnitude calculations indicate that bow shocks would have been the dominant process [6].

Setting of Chondrule Formation: Turbulent concentration could produce clumps of chondrules or precursors with sizes and densities sufficient to prevent volatile depletion and isotopic fractionation [7,8]. However, such clumps are transient, and comprise only a small fraction of the particles at any time, i.e., any given particle would find itself in such a clump only rarely. If the heating mechanism was spatially widespread, most chondrules would have been produced in a low-density environment. The lack of chondrules that are fractionated and rapidly cooled implies that if they were concentrated by turbulence, heating events occurred only within the dense clumps. The mechanism for such events and their energy source is problematic. Also, if such heating was coincident with clumping that resulted in gravitational collapse to form planetesimals, multiple heating events would be impossible, and all chondrules in a given parent body should have identical ages. If on the other hand heating events were not restricted to regions of high particle density, then essentially all chondrule precursors had to be in regions of high density to avoid production of chondrules that were depleted in volatile elements and isotopically fractionated. The most plausible scenario for that condition to be met would be if all chondrule-sized solid particles had settled into a dense layer, leaving no significant amount of precursor materials in low-density regions far from the nebular midplane.

A setting for chondrule formation close to the nebular midplane is allowed in the context of the planetesimal bow shock model since the maximum gas-planetesimal relative velocities, and the strongest bow shocks, occur during midplane passage [e.g., 5].

The Chondrule Cooling Rate Constraint and the Sizes of Eccentric Planetesimals: Cooling rates for freshly formed chondrules inferred from furnace experiments are of the order of 100-1000 K/hr at temperatures near the solidus [9]. Accepting these furnace simulations as valid, if chondrules were melted by passage through bow shocks of planetesimals moving supersonically through the nebula on eccentric orbits, the size of the heated region is comparable to the planetesimal size. Cooling times would be comparable to the duration of an encounter. These considerations imply that planetesimals producing the bow shocks had to be more than ~ 1000 km in diameter [10]. However, individual planetesimals as small as ~ 50 km can become trapped in Jovian resonances and could, in principle, have attained eccentricities large enough to produce strong shocks [11]. If chondrules were produced by bow shocks, the lack of very short cooling times implies that the eccentric population was dominated by a small number of large (Moon- to Mars-sized) planetary embryos rather than by asteroid-sized bodies. Collisional damping and/or impact disruption may have prevented the latter from attaining supersonic velocities. Planetesimal orbit simulations to investigate the latter possibility are in progress [12].

Conclusions: A number of suggested mechanisms are capable in principle of producing igneous objects with the properties of chondrules. However, most of these would have yielded a significant fraction of additional objects with ages or chemical/isotopic/petrologic properties that are not found in meteorites. A viable mechanism for chondrule formation must avoid producing such objects. In particular, the lack of chondrule-like objects formed in regions of low particle density argues against turbulent concentration of chondrule precursors.

Presently accepted meteoritic constraints are most easily explained if the primary setting for chondrule formation was a dense layer of precursor particles near the nebular midplane [13]. The transient heating events that melted the precursors must have reached a peak 1-2 Myr after CAIs. The planetesimal bow shock model, which requires the prior formation of Jupiter, can naturally satisfy this constraint. However, chondrule cooling rates near solidus temperatures estimated from furnace experiments are consistent with the bow shock model only if the flux of bodies in highly eccentric orbits due to Jovian resonance passages was dominated by large (Moon to Mars-sized) bodies.

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