THE PLANETESIMAL BOW SHOCK MODEL FOR CHONDRULE FORMATION: SIZES OF HIGHLY ECCENTRIC PLANETESIMALS AND INITIAL SIMULATIONS FOR A RADIALLY MIGRATING JUPITER. Lon L. Hood[1] and Stuart J. Weidenschilling,[2] [1]Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721; lon@lpl.arizona.edu; [2]Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, Arizona 85719; sjw@psi.edu.

Introduction: As reviewed in a companion abstract [1], the near absence in meteorites of chondrule-like objects that formed in regions of low particle density is most easily understood if the primary setting for chondrule formation was a dense layer of precursor particles near the nebular midplane [2]. A number of studies have shown that shock waves in the nebula are a plausible transient heating mechanism for melting chondrule precursors [3,4,5]. However, chondrule-forming shocks did not maximize at the time of solar system formation but apparently reached a peak 1-2 Myr after CAIs [6]. One shock mechanism that satisfies the latter constraint is the planetesimal bow shock model, which requires the prior formation of Jupiter to inject planetesimals into eccentric orbits during passage through Jovian resonances [7,8,9]. One problem with the bow shock model is that furnace experiments indicate relatively slow chondrule cooling rates near the solidus [10]. The latter can be matched only if the planetesimals producing the bow shocks were large — Moon- to Mars-sized. Also, it remains uncertain whether bow shocks were numerous and strong enough to explain the abundance of chondrules in chondrites. To address both of these issues, we report here improved simulations of planetesimal orbital evolution in the presence of Jovian resonances.

Planetesimal Orbit Simulations: The numerical code integrates orbits of accreting planetary embryos perturbed by Jupiter. The nominal case assumes Jupiter is at its present distance of 5.2 AU, and initially includes 240 embryos with sizes 500-5000 km, with a total mass of 1 Earth mass between 2 and 4 AU. They interact collisionally with a comparable mass of asteroid-sized (1-350 km diameter) bodies. The small bodies can be accreted by embryos, but for simplicity do not collide with each other. All bodies are subject to Jovian perturbations and nebular gas drag. The embryos undergo mutual collisions and scattering in close encounters. Embryos in commensurability resonances with Jupiter can attain high eccentricities. Velocities relative to the local Keplerian circular velocity are evaluated at their nodes (the nebular midplane). The area swept by an embryo of radius R in an orbit with inclination i during a nodal passage is $\pi R^2/\sin i$. The absolute minimum shock velocity for partial melting of silicate precursors is ~ 5 km/s while complete melting of mm-sized precursors may require shock velocities of ~ 8 km/s [5]. We therefore track the cumulative midplane area swept at V > 5 and > 8 km/s as a function of time, and normalized to the area of the disk between 2 and 4 AU; to first order this is also the fractional volume of a midplane layer of arbitrary thickness. Thus, we track the fraction of the disk exposed to shock waves able to produce chondrules.

Figure 1:

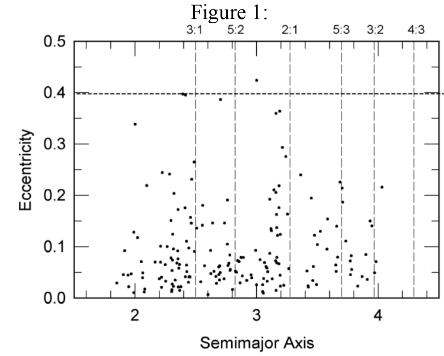
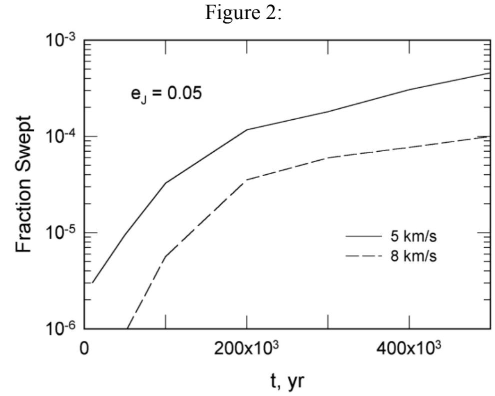


Figure 2:



Results for the Nominal Case: Our standard case assumes that Jupiter's eccentricity is 0.05, near its present value. After 0.5 Myr, 179 embryos survive; those that became Jupiter-crossing have been removed. Figure 1 shows eccentricities vs. semimajor axis and denotes the locations of the strongest resonances; a few embryos have e > 0.4. Figure 2 shows the fractional area swept vs. time at 0.5 Myr. Note that this calculation uses only the geometrical cross-section. The actual obstacle size may be increased by impact-generated dust and debris clouds around resonant planetesimals. Also, the bow shock area is several times larger than the area of the effective obstacle. But even accounting for these factors, it seems unlikely that the fractional area swept by potentially chondrule-forming shocks would exceed 1% in 2 Myr. The swept fraction depends on Jupiter's eccentricity and is lower by about an order of magnitude for e = 0.01.

The low chondrule formation efficiency for the present simulations contrasts with earlier estimates [4,5] which assumed (a) a lower shock velocity for chondrule formation (4-5 km/s) and (b) that planetesimals were small (~ 100 km) and were brought into resonances slowly by orbital decay due to gas drag; such evolution gives a high probability of resonance capture. The present simulations account for the existence of bodies that are too large to be moved by gas drag and are instead transported radially by orbital diffusion due to collisions and gravitational scattering. Only a small fraction of embryos spend enough time in resonances to attain shock velocities exceeding 8 km/s.

Results for a Larger Population of Test Bodies: The nominal case showed a slight positive dependence of eccentricity on planetesimal mass (size). This may be a consequence of collisional damping and impact disruption, which would preferentially reduce eccentricities for smaller bodies. To test further this possibility, a separate simulation was performed assuming an initial population of 1000 bodies with diameters between 70 and 4000 km and a total mass of 2 Earth masses randomly distributed between 2 and 4 AU. Other parameters in the model were left unchanged.

Figure 3:

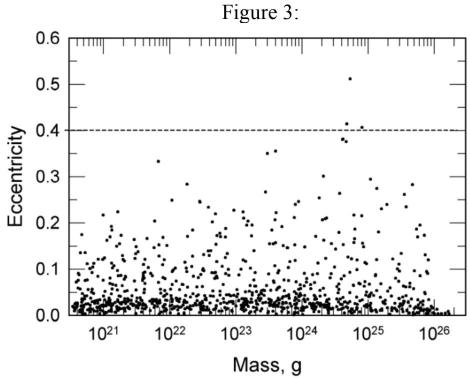


Figure 3 plots the eccentricities of remaining test bodies vs. mass after a simulation time of 10^5 years. A tendency for more massive bodies to have higher eccentricities is more clearly seen in this simulation. Specifically, only three bodies have eccentricities exceeding 0.4 and they all have masses approaching 10^{25} g and diameters approaching 2000 km, i.e., they are more than half as large as the Moon. If only these bodies are able to produce shocks strong enough to form chondrules, then the cooling rates may be compatible with those inferred from furnace experiments.

Consideration of a Radially Migrating Jupiter: Current models for planet formation and orbital evolution predict a substantial early radial migration of the giant planets owing to tidal interactions with the nebular disk. As an extreme example, one recent simulation has proto-Jupiter migrating inward to 1.5 AU over a 10^5 year period followed by outward migration to its present orbital radius over the next 0.5 Myr [11]. The associated radial sweeping of resonance locations would increase the number of embryos that are scattered into eccentric orbits at a given time. To provide an initial estimate of the consequences for the bow shock model, a simulation is currently in progress with Jupiter migrating from 6 to 5.2 AU over a 1 Myr period. The resulting increase in chondrule formation efficiency will be reported at the conference.

Discussion: The latest simulations with the improved numerical code indicate that only bodies of substantial size (~ Moon-sized) may attain eccentricities (> 0.4) sufficient to melt mm-sized chondrule precursors. The resulting cooling rates may therefore be compatible with furnace experiment results. However, the fraction of the asteroid belt region that is swept by these bow shocks is small (< 1%) for the nominal (fixed Jupiter) case. Allowing for a radially migrating Jupiter may increase this efficiency. On the other hand, even at 1% efficiency, if an Earth mass of chondrule precursors was available, then the mass of chondrules produced could exceed the present mass of the asteroid belt. The later dynamical depletion of asteroids may have been only about one order of magnitude by number, if most of the mass was in large embryos [12]. As only a small fraction of the precursor material would have been converted to chondrules, they would have had to be preferentially accreted by asteroid-sized parent bodies, perhaps by aerodynamic sorting. Embryos would make repeated nodal passages through the same region of the disk on successive orbits, raising the probability of multiple heating events. Production of chondrules by bow shocks may therefore be at least marginally possible from a quantitative standpoint even for the standard (fixed Jupiter) case.

Acknowledgment: Supported by the NASA Origins program under Grant No. NNX09AF70G.

References: [1] Weidenschilling S. J. & Hood L. L. (2012) LPSC XLIII, this volume. [2] Weidenschilling S. J. (2010) *MAPS*, *45*, 276. [3] Ciesla F. J. & Hood L. L. (2002) *Icarus, 158,* 281. [4] Desch S. J. & Connolly H. C. Jr. (2002) *MAPS, 37,* 183. [5] Morris M. A. & Desch S. J. [2010] *Astrophys. J., 722,* 1474. [6] Connelly J., Y. et al. (2008) *Astrophys. J.., 675,* L121. [7] Hood L. L. (1998) *MAPS, 33,* 97. [8] Weidenschilling S. J. et al. (1998) *Science, 279,* 681. [9] Hood L. L. et al. (2009) *MAPS, 44,* 327. [10] Hewins R. et al. (2005) In *Chondrites and the Protoplanetary Disk,*(Krot A. N. et al., eds.) Astron. Soc. Pacific Conf. Series, v. 341, p. 286. [11] Walsh K. J. et al. (2011) *Nature, 475,* 206. [12] Weidenschilling S. J. (2011) *Icarus, 214,* 671.