**CHONDRULE FORMATION IN NEBULAR SHOCK WAVES GENERATED BY PLANETESIMALS PASSING THROUGH JOVIAN RESONANCES: RELATIVE IMPORTANCE OF BOW SHOCKS AND IMPACT SHOCKS.** L. L. Hood[1], F. J. Ciesla[2], N. A. Artemieva[3,4], F. Marzari[5], and S. J. Weidenschilling[4], [1]Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, Arizona 85721, lon@lpl.arizona.edu, [2]Dept. of Geophysical Sciences, Univ. of Chicago, Chicago, Illinois 60637, [3]Institute for Dynamics of Geospheres, Russian Academy of Sciences, Moscow, [4]Planetary Science Institute, Tucson, AZ 85719, [5]Dept. of Physics, Univ. of Padova, Italy.

**Introduction.** Gas dynamic shock waves in a low-temperature nebula are currently considered to be a plausible mechanism for providing the repetititve transient heating events that were apparently responsible for chondrule formation [1]. However, the sources of the proposed chondrule-forming shocks have not been clearly identified. In this paper, we investigate the relative importance for chondrule formation of two types of shock waves generated by planetesimals passing through jovian resonances [2,3,4]. Using a simplified planetesimal population, we also investigate whether these shock waves were numerous and widespread enough to explain the observed abundance of chondrules in chondrites.

**Resonant Planetesimal Shock Generation.** The primordial asteroid belt contained at least several hundred and as many as 10,000 bodies with diameters of 1000 km or larger. This follows from minimum-mass nebula models which show that the asteroid belt has lost more than 99.9% of its solid mass since the time when the planets formed, equivalent to 3-5 Earth masses. The original large bodies in the primordial belt were later removed through mutual gravitational perturbations into unstable resonances with the giant planets, especially Jupiter [5,6]. For comparison, the largest remaining body in the asteroid belt is 1 Ceres (913 km in diameter).

Following the formation of Jupiter, nebular gas drag combined with passage of primordial belt bodies through jovian resonances produced high eccentricities ($e = 0.3 - 0.5$), low inclinations ($i < 0.5^o$), and, therefore, high velocities (3-10 km/s) for ``resonant''bodies relative to both nebular gas and non-resonant planetesimals [7]. These high velocities would have produced shock waves in the nebular gas through two mechanisms. First, bow shocks would be produced by supersonic motion of resonant bodies relative to the nebula [2]. Second, high-velocity collisions of resonant bodies with non-resonant bodies would have generated impact vapor plume shocks near the collision sites [4]. Both types of shocks would be sufficient to melt chondrule precursors in the nebula.

For a given resonant planetesimal orbit history ($a(t)$, $e(t)$, $i(t)$), the relative velocity between the body and nebular gas assumed to corotate at the circular Keplerian rate can be calculated [2]. This relative velocity is also approximately equal to the collision velocity between the same body in an eccentric orbit and another in a prograde circular orbit. Carrying out the necessary calculations using the orbit simulation results of [7], one concludes [4] that the most probable range of relative velocities *during midplane passages* where both bow shocks and impact vapor plume shocks may have most efficiently formed chondrules is ~ 6.5 – 7.1 km/s.

Several first-order analytic approaches can be applied for estimating the probability of a collision between a non-resonant planetesimal in a circular midplane orbit and a single resonant planetesimal during one orbit [4]. If most of the mass of the primordial belt (~ 3 Earth masses) was in the form of bodies with diameters > 500 km (mean ~ 1000 km), then ~ $10^4$ such bodies would have existed. Based on the simulations of [7], the number of planetesimals that entered the major 2:1 and 3:2 resonances per unit time can be estimated. The net collision frequency of major impacts is then estimated as ~ one per 2400 years [4]. This estimate is uncertain by at least an order of magnitude.

**Chondrule Production in Impact Shocks.** A major impact in the primordial asteroid belt would have produced a shock wave in the nebula as the heated melt and vapor expanded away from the impact point. We have carried out numerical simulations to estimate the approximate local nebular volume that is processed by impact shocks sufficiently strong to melt chondrule precursors as a function of impactor size and velocity [8]. For example, an impact of two 1000 km bodies at 6.5-7.1 km/s would process a volume of ~ $10^{31}$ $cm^3$. If the number density of chondrule precursors in the solar nebula in the near vicinities of colliding planetesimals was ~ 1 $m^{-3}$ and if the shock velocity was marginally high enough to bring all of these precursors to melting temperatures, then ~ $10^{25}$ chondrules would be produced in a single such impact. For a major collision rate of ~ 1 per 2400 years, ~ 830 high-velocity impacts would occur over a 2 Myr interval during which chondrule formation may have been most common. Taking the mean mass of a chondrule as 0.001 g, the total mass of chondrules that could be produced would be ~ $10^{25}$ g.

However, it is unlikely that precursors were uniformly distributed throughout the volume that was processed by impact shocks. Although non-resonant planetesimals would be in nearly circular orbits with low inclinations, mutual perturbations among these bodies would ensure inclinations of at least several tenths of a degree. Collisions would therefore occur over a substantial vertical range (~5,000,000 km). Assuming a mass for each precursor of 0.001 g, a number density of 1 $m^{-3}$ would imply a surface mass density of ~ 500 g $cm^{-2}$. If this mass density extended over a radial range of 1 AU, the total mass would be about 350 Earth masses, much greater than the likely mass of the primordial asteroid belt. We therefore assume here that precursors were either concentrated in a thin zone near the midplane or were concentrated in ``clumps'' near the midplane and that their total mass was a small fraction of the mass of the primordial asteroid belt, taken here to be 3-5 Earth masses. For a total mass of 1 Earth mass, a precursor number density in these midplane concentrations of ~ 1 $m^{-3}$ and a mass for each precursor of 0.001 g would require that precursors occupied no more than 1/350 of the total volume processed by the impact shocks. The total mass of chondrules that could potentially be produced in impact shocks would then be ~ $3 \times 10^{22}$ g.

**Chondrule Production in Bow Shocks.** Numerical simulations of bow shocks ahead of resonant planetesimals (e.g., [8]) allow estimates of the effective ``melting cross sections'', i.e., the area of nebular gas that would be processed to produce chondrules. For a relative velocity of ~ 6.5 – 7.1 km/s, appropriate for midplane passages, the melting cross section has a radius of ~ 4 planetesimal radii. A resonant planetesimal with a mean diameter of 1000 km would then sweep a total volume of ~ $3.6 \times 10^{31}$ $cm^3$ during one orbit at ~ 3 AU. However, it is again unlikely that precursors were distributed uniformly throughout the volume processed by bow shocks. By the same arguments given above, for a precursor number density of 1 $m^{-3}$, a mass for each precursor of 0.001 g, and a total precursor mass of 1 Earth mass, the total mass of chondrules that could potentially be produced in a single orbit would be ~ $10^{20}$ g.

According to the simulations of [7], a resonant planetesimal passing through the 3:2 resonance spends about 23,000 years or about 4600 orbits with e > 0.3. Such a planetesimal, if it had a diameter of 1000 km, would therefore produce ~ $5 \times 10^{23}$ g of chondrules if the total mass of precursors was 1 Earth mass. Again assuming a population of $10^4$ planetesimals in the asteroid belt region, the gas drag simulation results of [9] imply that ~ 0.1 planetesimals per year would have entered jovian resonances. Over a 2 Myr assumed chondrule formation time interval, about 200,000 planetesimals would have entered resonances. However, only 10,000 planetesimals would have existed in the belt at any given time (assuming a steady supply of planetesimals at the outer edge of the belt and a steady rate of planetesimal losses due to collisions and resonant ejection). The total mass of chondrules that could have been produced over this time period would therefore have been ~ $9 \times 10^{28}$ g.

**Conclusions and Discussion.** Although a number of simplifying assumptions were made in the above analysis, the results indicate that impact-generated shocks would be capable of producing a much smaller total quantity of chondrule mass (~ $3 \times 10^{22}$ g) than would bow shocks (~ $9 \times 10^{28}$ g). These numerical estimates are upper limits for several reasons. First, not all precursors that pass through shock waves will produce chondrules (some will be vaporized, for example). Second, it is generally accepted that most chondrules were heated to melting temperatures more than once; hence, most chondrules may have been processed by more than one shock. Third, the assumption that the total precursor mass at any given time in the primordial belt during chondrule formation was ~ 1 Earth mass is probably an upper limit; a total mass of ~ 0.1 Earth mass is also plausible. Consequently, the above numerical estimates should be revised downward by at least an order of magnitude.

The minimum total mass of chondrules in the primordial asteroid belt can be estimated as roughly $10^{24}$ – $10^{25}$ g [4]. The lower limit of this range is still a factor of ~ 30 larger than the maximum chondrule mass production estimated above for impact-generated shock waves. However, the maximum chondrule mass production in bow shocks is several orders of magnitude larger than the upper limit of this range. It therefore appears possible that the resonant planetesimal shock mechanism (and bow shocks in particular) can be consistent with the observed abundance of chondrules in chondrites.

**References:** [1] Desch S. J. et al. (2005) In *Chondrites & the Protoplanetary Disk,* A. N. Krot et al. (eds) *Astron. Soc. Pacific Series 341,* pp. 849-872. [2] Hood L. L. (1998) *Meteoritics & Planet. Sci., 33,* 97-107. [3] Weidenschilling S. J. et al. (1998) *Science, 279,* 681-684. [4] Hood L. L. et al. (2009) *Meteoritics & Planet. Sci.,* in press. [5] Chambers J. E. & Wetherill G. W. (2001) *Meteoritics & Planet. Sci., 36,* 381-399. [6] O'Brien D. P. et al. (2007) *Icarus, 191, 434-452.* [7] Marzari F. & Weidenschilling S. J. (2002) *Celestial Mech. Dynamical Astron., 82,* 225-242. [8] Ciesla F. J. et al. (2004) *Meteoritics & Planet. Sci., 39,* 1809-1821.