NEBULAR SHOCK WAVES GENERATED BY LARGE-SCALE IMPACTS: POSSIBLE SITES FOR CHONDRULE FORMATION. Lon L. Hood[1], Fred J. Ciesla[2], Natalia A. Artemieva[3,4], and Stuart J. Weidenschilling[4]; [1]Lunar and Planetary Lab, University of Arizona, 1629 E. University Blvd., Tucson, Arizona 85721; lon@lpl.arizona.edu; [2]DTM, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, D.C. 20015; fciesla@ciw.edu; [3]Institute for Dynamics of Geospheres, Russian Academy of Sciences, Leninskii Prospect 38/6, 117334 Moscow, Russia; [4]Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, Arizona 85719; artemeva@psi.edu; sjw@psi.edu.

Introduction: Most detailed analyses have inferred that meteoritic chondrules formed in short-duration heating events in a relatively cool (< 650 K) solar nebula environment [1]. Many chondrules have apparently been thermally processed repeatedly and some contain recycled fragments of previous generations of chondrules [2,3]. Multiple heating events are therefore indicated. Chondrule formation regions have been inferred to be large (more than hundreds of km across) but also relatively localized in order to explain the differences in physical, textural, chemical, and paleomagnetic properties of chondrules from different chondrite groups [4,5]. Chondrules coexist in chondrites with products of later parent body processes (e.g., igneous rock fragments), indicating that chondrule formation occurred during or after the accretion of a substantial population of planetesimals [6]. Radiometric age data indicate that chondrule formation began ~1 Myr after the formation of many CAIs and continued for several Myr [7,8].

First suggested by Wood [9], gas dynamic shock waves in a low-temperature nebula are currently considered to be a plausible mechanism for providing the necessary repetitive transient heating events that were responsible for chondrule formation (e.g., [10]). However, an unresolved issue associated with this proposed mechanism is the source of the shocks.

The apparent time delay between the formation of many CAIs and the initiation of chondrule formation suggests that the formation of Jupiter may have been involved in the generation of the chondrule-forming shocks (e.g., [11]). Previously proposed mechanisms in this category include spiral density wave shocks induced in the nebula by proto-Jupiter [12] and bow shocks upstream of planetesimals excited into eccentric orbits through resonant interactions with Jupiter (e.g., [13]). Spiral density wave shocks would have passed through the entire asteroid belt region of the nebula, presumably processing chondrule precursors in a fairly uniform way. They may therefore conflict with the requirement that chondrule formation regions were relatively localized. Planetesimal bow shocks would have scale sizes comparable to the diameters of the scattered planetesimals, which may be smaller than length scales inferred from a recent model to explain the depletion of volatile elements in chondrules [4]. Moreover, it is questionable whether planetesimal bow shocks were numerous and large-scale enough to explain both the high abundance of chondrules in chondrites and evidence that many or most chondrules were heated more than once.

In this paper, we report initial investigations of an additional mechanism for generating repetitive but relatively localized nebular shocks that would have been most numerous after the formation of Jupiter.

Impact-generated Nebular Shocks: According to nebula models, the asteroid belt has lost more than 99.9% of its solid mass since the time when the planets formed. Much of this original mass was probably in the form of Moon- to Mars-sized bodies that were later removed through mutual gravitational perturbations into unstable resonances with the giant planets, especially Jupiter [14]. Jupiter and Saturn, which consist mainly of hydrogen and helium, must have formed prior to the time when the protoplanetary nebula was dissipated. Assuming that the nebula persisted in the asteroid belt region for a period of time after Jupiter formed, numerical simulations demonstrate that gas drag combined with temporary trapping in Jovian resonances would have produced high eccentricities (e = 0.3-0.4) and, therefore, high velocities for perturbed planetesimals relative to those in circular orbits (> 5 km/s) [15]. Their inclinations would have remained low leading to a high probability of close encounters and collisions. In addition to slower-moving solid ejecta, hypervelocity impacts produce a cloud of heated vapor and melt that expands rapidly away from the impact site (e.g., [16]). Consequently, the expanding vapor-melt clouds resulting from the inferred collisions would have produced gas dynamic shock waves in the ambient nebula.

To investigate the scale and duration of nebular shock waves generated by major impacts in the primordial asteroid belt, we use initial conditions based on recent 3D simulations of lunar basin-forming impacts [16]. Figure 1 shows the density distribution of the vapor-melt cloud 620 seconds after impact of a 240 km diameter silicate planetesimal onto a differentiated Moon-sized body at 18 km/s. The impact angle relative to the horizontal was 30^o and the planetesimal impacted from left to right. Density contours are labeled in g cm^{-3}. Temperatures within the vapor-melt cloud range from ~1000 K near the periphery to ~4000 K near the center. The gray color shows projectile and target materials; the green color shows crustal materials. No nebular gas was assumed to be present for this calculation.

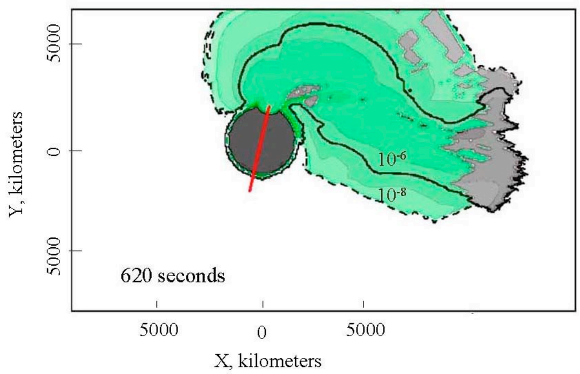

Figure 1

As the impact-generated vapor-melt cloud expands thermally into the ambient protoplanetary nebula, a shock front propagates ahead of the expanding cloud followed by shocked nebular gas. For the purpose of an initial simulation, we have employed a 2D hydrocode in which the piecewise parabolic method (PPM) is used to interpolate the upwind variables consistently (17). The hydrocode grid consists of 200 cells in the vertical and 300 in the horizontal. Each cell has a size of 2000 km by 1800 km. The ambient nebula is initially assumed to be in hydrostatic equilibrium with a midplane mass density at 3 AU of 10^{-9} g cm^{-3} and a temperature of 346 K. Density and temperature fall off radially as $1/r^2$ and $1/r^{1/2}$, respectively. The initial distribution of vapor-melt mass density, temperature, and velocity is approximated by assigning values to 13 cells centered at 3.002 AU. The presence of the impacted body is neglected in this initial simulation.

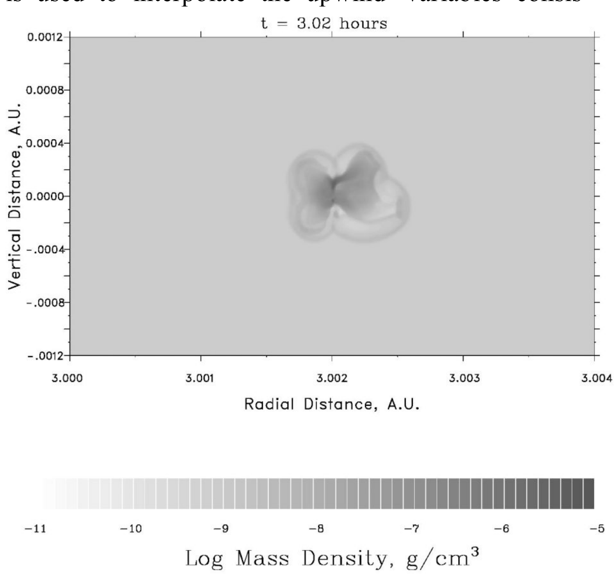

Figure 2

Figure 2 shows the mass density distribution after 3.02 hours of thermal expansion. The darker region near the center is the expanding vapor-melt cloud. The nebular shock front is the thin dark region that encircles the expanding cloud. The shock front has a mean velocity of up to 10 km/s and the shocked gas velocity behind the shock front is as much as ~9 km/s. Such a shock would easily melt chondrule-sized precursor particles in the ambient nebula. Due to their short stopping distances in the shocked gas, they would then be swept ahead of the expanding vapor-melt cloud and reside in the nebula again as the shock dissipates. The same particles would be subject to repeated thermal processing by later impact-generated shock waves.

Further work using the 3D hydrocode is needed to determine the fate of melt in the vapor cloud and the extent to which solid ejecta fragments would escape the impacted body. In addition, the frequency of impacts necessary to explain the abundance of chondrules in chondrites needs more detailed study. Nevertheless, further investigation seems warranted of whether impact-generated nebular shock waves combined with contemporaneous planetesimal bow shocks could have played a significant role in chondrule formation.

References: [1] Hewins, R. (1997) *Ann. Rev. Earth Planet. Sci.,, 25,* 61-84. [2] Alexander C. M. O'D. (1994) *LPS XXV,* 7-8. [3] Rubin, A.E., and A. N. Krot (1996) In *Chondrules and the Protoplanetary Disk* (eds. R. Hewins et al.), pp. 173-180, [4] Cuzzi, J. N., and C. Alexander (2006) *Nature, 441*, 483-485. [5] Ebel, D. (2007), 70th Meteorit. Soc. Meeting, Abstract #5326. [6] Hutchinson, R. et al. (2005) In *Chondrites and the Protoplanetary Disk* (eds. A. N. Krot et al.), pp. 933-948. [7] Kita, N. T. et al. (2005) ibid, pp. 558-583. [8] Krot, A. N. et al. (2005) LPS XXXVI, Abstract #1482. [9] Wood, J. A. (1963*) Scientif. Amer., 10*, 65-82. [10] Desch, S. M. et al. (2005) In *Chondrites and the Protoplanetary Disk* (eds. A. N. Krot et al.), pp. 849-872. [11] Weidenschilling, S. J. et al. (1998) Science, 279, 681-684. [12] Boss, A. P. & R. Durisen (2005) In *Chondrites and the Protoplanetary Disk* (eds. A. N. Krot et al.), pp. 821-838. [13] Hood, L. L. et al. (2005) ibid, pp. 873-882. [14] Chambers, J. E., & G. W. Wetherill (2001) Meteorit. Planet. Sci., 36, 381-399. [15] Marzari, F., & S. Weidenschilling (2002) *Celest. Mech. Dynam. Astron., 82*, 225-242. [16] Hood, L. L. & N. Artemieva (2008) Icarus, doi:10.1016/ j.icarus.2007.08.023, in press. [17] Colella, P., & Woodward, P. R. (1984) J. Comp. Phys., 54, 174-201.