THE PLANETESIMAL SHOCK MODEL FOR CHONDRULE FORMATION: IMPROVED ORBITAL SIMULATIONS AND EXTENDED SHOCK FRONTS. 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: Most detailed analyses have inferred that meteoritic chondrules formed in short-duration heating events in a relatively cool (< 650 K) solar nebula environment (e.g., 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. 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 (e.g., 4). In addition, chondrule formation regions have been inferred to be large (more than several hundred km across) but also relatively localized in order to explain observed differences in physical, textural, and chemical properties of chondrules from different chondrite groups (e.g., 5). Finally, although the relative timing of chondrule and CAI formation is not fully understood, many isotopic studies have concluded that formation of most chondrules began 1-1.5 Myr after CAIs and continued for several Myr (6, 7).

Planetesimal Shock Model: Gas dynamic shock waves in the nebula are currently considered to be a plausible mechanism for providing the transient heating events that were responsible for chondrule formation (e.g., 8). One class of nebular shocks that can potentially satisfy current constraints on chondrule formation is shocks generated by planetesimals passing through Jovian resonances (9,10). Included are both planetesimal bow shocks produced by bodies perturbed into eccentric orbits and impact vapor plume shocks produced by high-velocity collisions between planetesimals. Previously published estimates for the efficiency of potential chondrule production by this mechanism (10) have relied on orbital simulations for resonantly excited planetesimals that considered only individual test bodies evolving sunward in the presence of gas drag and Jupiter's perturbations (11). Results showed that relatively high eccentricities (e > 0.3) are typically achieved. In the present work, we employ an improved planetesimal accretion and orbital evolution code that includes the damping effects of collisions and mutual gravitational scattering between embryos. The goal is to provide more accurate estimates of potential chondrule formation efficiency by the bow shock mechanism. In addition, initial estimates for the collision frequency of resonant bodies with non-resonant bodies are given based on the code output. Finally, we consider expanded bow shocks due to impact-generated clouds of dust and debris around large resonant planetesimals.

Planetesimal Evolution Code and Results: A population of 240 bodies with diameters between ~750 and 5000 km and with a total mass of ~ 1 Earth mass is distributed between 2 and 4 AU, interacting with a background of ~ 1 Earth mass of small bodies having sizes in the range of 1 to 400 km. Such a population is plausible for the primordial asteroid belt region prior to removal of most large bodies through mutual gravitational perturbations into outer planet resonances (12, 13). A symplectic N-body integrator is applied to calculate the orbital evolution of the large bodies. In recent simulations, Jupiter is assumed to be at 5.2 AU and Saturn is at 8 AU, with initial eccentricities of 0.02 and 0.01, respectively. After 250 kyr, Jupiter's eccentricity has decreased to 0.005 while Saturn's is about 0.05.

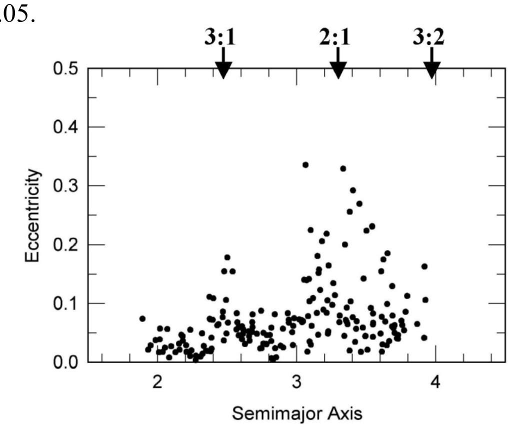

Figure 1

Figure 1 shows the resulting orbital eccentricities for the remaining discrete bodies at a single time of 250 kyr after initiation of the simulation. Several percent of the bodies have eccentricities e > 0.25 and would have midplane shock velocities > 5 km/s. At other times, a few bodies occasionally reach e > 0.4. For comparison, the earlier simulations of ref. 11 yielded 20 to 30 % of planetesimals with e > 0.25. The damping effect of the smaller bodies therefore decreases the efficiency of the mechanism by about an order of magnitude. If the minimum shock velocity for chondrule formation is ~ 8 km/s (14), then e must exceed ~ 0.4, which would further decrease the efficiency. Results also indicate that the orbital inclinations are ~ several degrees and there is no significant dependence of e on the mass of the planetesimal.

Extended Shock Fronts: An impact of a small body on a large planetesimal or asteroid produces a transient cloud of dust, debris, and vaporized rock. A present-day example of this may be the ~ 100 km diameter main belt extinct-comet asteroid 596 Scheila that recently produced a transient ``coma'' (15; Figure 2). Although cometary outgassing is a possible explanation, it is more likely that a recent impact produced a small (~ 100 m) crater, expelling a cloud of dust and debris (16). Such collisions would have been more common in the primordial belt; resonant bodies in eccentric orbits would have experienced the highest impact rate due to collisions with non-resonant smaller bodies. As shown in ref. 10, outward expansion of the impact vapor-melt cloud into the nebula would produce strong shocks capable of processing more precursor particles. In addition, the residual debris cloud would have increased the effective obstacle size, producing broader bow shocks in the nebular gas. This process could increase the efficiency of the bow shock chondrule formation mechanism.

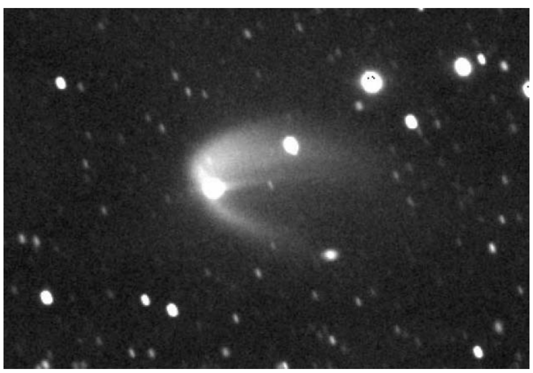

Figure 2. Composite image of (596) Scheila taken a few days after discovery on Dec. 11, 2010 by Steve Larson of a coma-like outburst using Catalina Sky Survey imagery (ref. 15; image by Alex Gibbs and Steve Larson, Univ. of Arizona).

An examination of the planetesimal evolution code output for the simulation of Figure 1 shows that bodies with e > 0.2 and diameters of 1000 – 3000 km typically gained mass at rates of $10^{16} – 10^{17}$ g/yr during the interval from 200 to 250 kyr. The corresponding impact interval for 1 km sized bodies (mass ~ 10^{15} g) is days to weeks. A 1 km diameter body impacting at ~ 5 km/s would produce a substantial dust and debris cloud capable of temporarily standing off the incident nebular gas. The vast majority of thermally processed mm-sized particles passing through these bow shocks would be swept around the sides where they would be free to accrete to non-resonant planetesimals (17).

Conclusions: Simulations conducted to date using an improved planetesimal accretion and orbital evolution code show that the damping effect of collisions with smaller bodies reduces the number of bodies whose eccentricities are excited above 0.25 by about an order of magnitude relative to previous simulations that did not consider this effect. Consequently, our previous estimate (10) for the maximum potential chondrule production in planetesimal bow shocks of ~ 10^{28} g should be revised downward by a factor of roughly 10. If minimum eccentricities of 0.4 are actually required to form chondrules, then a further reduction in the estimated efficiency would be necessary. On the other hand, the most recent simulations also indicate that the likely collision interval for 1000-km sized resonant bodies with km-sized non-resonant bodies bodies is of order days to weeks. In addition to producing vapor-melt cloud shocks in the nebula, the residual dust and debris cloud resulting from such collisions would expand the effective shock front cross section, increasing the potential efficiency of chondrule production by this mechanism.

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