Nebular shock waves generated by planetesimals passing through Jovian resonances: Possible sites for chondrule formation

Lon L. HOOD1*, Fred J. CIESLA2, Natalia A. ARTEMIEVA3,4, Francesco MARZARI5, and Stuart J. WEIDENSCHILLING4

1Lunar and Planetary Laboratory, The University of Arizona, 1629 E. University Blvd., Tucson, Arizona 85721, USA
2Department of Geophysical Sciences, University of Chicago, 5734 S. Ellis Ave., Chicago, Illinois 60430, USA
3Institute for Dynamics of Geospheres, Russian Academy of Sciences, Leninskii Prospect 38/6, 117334 Moscow, Russia
4Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, Arizona 85719, USA
5Department of Physics, University of Padova, Via Marzolo 8, I-35131 Padova, Italy

*Corresponding author. E-mail: lon@lpl.arizona.edu

(Received 08 May 2008; revision accepted 29 October 2008)

Abstract–The primordial asteroid belt contained at least several hundred and possibly as many as 10,000 bodies with diameters of 1000 km or larger. Following the formation of Jupiter, nebular gas drag combined with passage of such bodies through Jovian resonances produced high eccentricities ($e = 0.3–0.5$), low inclinations ($i < 0.5^\circ$), and, therefore, high velocities (3–10 km/s) for “resonant” bodies relative to both nebular gas and non-resonant planetesimals. 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. Second, high-velocity collisions of resonant bodies with non-resonant bodies would have generated impact vapor plume shocks near the collision sites. Both types of shocks would be sufficient to melt chondrule precursors in the nebula, and both are consistent with isotopic evidence for a time delay of ~1–1.5 Myr between the formation of CAIs and most chondrules. Here, initial simulations are first reported of impact shock wave generation in the nebula and of the local nebular volumes that would be processed by these shocks as a function of impactor size and relative velocity. Second, the approximate maximum chondrule mass production is estimated for both bow shocks and impact-generated shocks assuming a simplified planetesimal population and a rate of inward migration into resonances consistent with previous simulations. Based on these initial first-order calculations, impact-generated shocks can explain only a small fraction of the minimum likely mass of chondrules in the primordial asteroid belt ($\sim 10^{24}–10^{25}$ g). However, bow shocks are potentially a more efficient source of chondrule production and can explain up to 10–100 times the estimated minimum chondrule mass.

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., Grossman 1996; Hewins 1997; Jones et al. 2000; Scott 2007). Many chondrules have apparently been thermally processed repeatedly and some contain recycled fragments of previous generations of chondrules (e.g., Alexander 1994; Rubin and Krot 1996). Multiple heating events are therefore indicated.

First suggested by Wood (1963), gas dynamic shock waves in a low-temperature nebula are currently considered to be a plausible mechanism for providing the repetitive transient heating events that were apparently responsible for chondrule formation (Connolly and Love 1998; Jones et al. 2000; Desch et al. 2005). In support of this mechanism, it has been demonstrated that the shock wave model can simulate inferred chondrule thermal histories (heating rates, peak temperatures, cooling rates) for at least a limited range of input nebular and particle parameters (Desch and Connolly 2002; Ciesla and Hood 2002; Ciesla et al. 2004b; Iida et al. 2001; Hood et al. 2005). In addition, if shock waves recurred sporadically in the solar nebula, the model can satisfy the constraint that chondrules were heated to melting temperatures more than once. However, the sources of the proposed chondrule-forming nebular shock waves have not been clearly identified (e.g., Desch et al. 2005). Also, the model has not yet been shown to be consistent with all available meteoritic constraints, especially evidence that
chondrule number densities in the formation region exceeded ~6–10 m⁻³ (Ciesla et al. 2004a; Cuzzi and Alexander 2006; Alexander et al. 2008).

Several possible constraints on the sources of chondrule-forming shocks in the nebula may be inferred from meteoritic evidence. First, although spatial heterogeneity of ²⁶Al in the solar nebula cannot be eliminated, the available ²⁶Al and ⁴⁰Mg data indicate that chondrule formation most probably began ~1–1.5 Myr after the formation of many calcium-aluminum-rich inclusions (CAIs) and continued for several Myr (e.g., Kita et al. 2005; Krot et al. 2005a, 2006). It had been proposed that chondrule and CAI formation were contemporaneous based on the discovery of chondrule fragments in an igneous CAI (Itoh and Yurimoto 2003). However, later detailed isotopic data showed that the chondrule fragments were actually added to the igneous CAI during a remelting episode ~2 Myr after the formation of CAIs (Krot et al. 2005a). Contemporaneous formation of at least some chondrules and CAIs had also been proposed based on Mg isotope analyses of Allende chondrules (Bizzarro et al. 2005). However, as noted by Krot et al. (2005a), the latter measurements may date the time of formation of chondrule precursors rather than the times of the melting episodes that produced the chondrules. Also, relict CAIs are commonly found inside chondrules whose radiometric ages are younger than those of the CAIs. Thus, although the relative timing of chondrule and CAI formation is far from being a fully resolved issue, these results strongly suggest a significant time delay for the generation of chondrule-forming shocks after the initial stages of solar system formation. This constraint does not necessarily conflict with evidence that higher pressures and oxygen partial pressures representative of protoplanetary (chondritic) conditions existed no more than a few hundred thousand years after the formation of CAIs (Simon et al. 2005): The melting episodes that formed the chondrules themselves may still have been delayed if the radiometric age data are valid. A remaining possible counter-argument is that the earliest formed chondrules would have been incorporated into parent bodies that experienced radiogenic melting and were therefore effectively removed from the available collection (S. Desch, personal communication). However, one would expect that at least some of these early chondrules would have survived as did the CAIs.

Among other noteworthy constraints, 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., Hutchison et al. 2005). 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., Cuzzi and Alexander 2006).

Previously proposed sources of chondrule-forming shocks in the nebula include gravitational instabilities (e.g., spiral wave patterns) in a massive and/or cold protoplanetary disk (Wood 1996; Boss 2002; Boss and Durisen 2005), X-ray flares similar to those observed to occur within the magnetospheres of T-Tauri stars (Nakamoto et al. 2005), and planetesimals moving supersonically relative to the nebula owing to resonant interactions with proto-Jupiter (Hood 1998; Weidenschilling et al. 1998). One problem for X-ray flare shocks is that they may not have penetrated to the midplane where chondrule precursors should have been most numerous. Although gravitational instability shocks would have been very large in scale (e.g., Boss and Durisen 2005), they may still be able to satisfy the “relatively localized” constraint if they processed local regions of chondrule precursors having different properties. However, a potentially important problem for both the gravitational instability and X-ray flare mechanisms is that they would have operated from the earliest stages of disk evolution; they may therefore not be consistent with the apparent time delay between CAI formation and chondrule formation.

Planetesimal bow shocks resulting from passage of planetesimals through Jovian resonances can satisfy the time delay constraint if Jupiter formed ~1 Myr after the formation of CAIs (Weidenschilling et al. 1998). Such an early formation time for Jupiter is possible whether it formed by gravitational instability in the nebula (e.g., Boss 2000, 2002) or by the core accretion mechanism (Alibert et al. 2004). Planetesimal bow shocks can also satisfy the “relatively localized” constraint directly since bow shocks would have scale sizes comparable to the diameters of the scattered planetesimals (hundreds to thousands of km). One potential problem for the bow shock mechanism is that the relatively slow chondrule cooling rates of <1000 K/h inferred from furnace experiment results (e.g., Hewins et al. 2005) may be difficult to simulate for chondrules heated during passage through bow shocks of the smallest planetesimals i.e., hundreds of km in diameter or less (Ciesla et al. 2004b). These small-scale bow shocks may also have been smaller than length scales inferred from the volatile element depletion model of Cuzzi and Alexander (2006). Another possible criticism of the bow shock model is that the upstream surfaces of planetesimals that produced bow shocks would likely have been damaged (“ablated”) by a combination of radiation from shock-heated gas and impacts of larger solid particles in the nebula that would not be deflected around the planetesimal by gas drag (J. Wood, personal communication). The apparent absence of evidence for such damage in chondrites may therefore represent an inconsistency. Finally, a remaining problem for the planetesimal bow shock mechanism is that it has not yet been determined that bow shocks were numerous and widespread enough to explain the high abundance of chondrules in chondrites and evidence that many or most chondrules were heated more than once.
Recently, it has been argued that one class of chondrules (i.e., those found in metal-rich CB carbonaceous chondrites) formed from a vapor-melt plume produced in a large-scale impact between bodies in the early asteroid belt (Campbell et al. 2002; Rubin et al. 2003; Krot et al. 2005b). Unlike the majority of chondrules from other chondrite classes, the CB chondrules are all non-porphyritic (implying total melting) and lack relict grains and coarse-grained igneous rims (indicating formation during a single-stage transient heating event). They also lack fine-grained, matrix-like rims implying an absence of nebular small-scale dust during their formation. These characteristics together with their relatively young $^{207}\text{Pb}^{206}\text{Pb}$ ages (~5 Myr after CAIs) strongly suggest that they formed after the nebula had largely dissipated (Krot et al. 2005b). In the absence of a nebula where shock waves could form, the most plausible source of a high-energy transient heating event is a high-velocity planetesimal impact, which produces a vapor-melt cloud or plume in addition to solid ejecta (e.g., Melosh 1989).

In this paper, we investigate further the generation of nebular shock waves by large planetesimals in the primordial asteroid belt scattered gravitationally through resonant interactions with Jupiter. In addition to bow shocks upstream of planetesimals forced to move supersonically relative to the nebula, shock waves generated in large-scale impacts between resonant and non-resonant bodies are also investigated. In the section Resonant Planetesimals in the Early Asteroid Belt, previous simulations of asteroidal orbital evolution in the presence of both nebular gas and proto-Jupiter are reviewed. The range of expected relative velocities between resonant planetesimals and both co-rotating nebular gas and non-resonant planetesimals in circular orbits is estimated. Preliminary estimates are then given of the likely rate of high-velocity collisions between large resonant and non-resonant planetesimals during this period using a simplified planetesimal population. In the section Impacts in the Presence of a Nebula, numerical simulations are reported of the production of nebular shock waves during planetesimal impacts at velocities in the estimated range. The approximate nebular volume that would be thermally processed to produce chondrules is estimated for the special case of head-on collisions between equal-sized silicate bodies with zero porosity as a function of projectile diameter and impact velocity. In the section Estimated Chondrule Production Rates, preliminary estimates are given of the approximate chondrule production rate by both bow shocks and impact-generated shocks as a function of the assumed precursor number density in the nebula. In the section Chondrule Cooling Rates in Bow Shocks Revisited, new simulations of chondrule thermal histories are reported using the one-dimensional shock heating code of Ciesla et al. (2004b) to investigate further the dependence of cooling rate on planetesimal size and other model parameters. Further discussion and conclusions are given in the last section. In particular, the minimum mass of chondrules in the early asteroid belt is estimated and the projected chondrule mass productions by bow shocks and large-scale impacts are compared to this minimum mass.

### Resonant Planetesimals in the Early Asteroid Belt

As reviewed, for example, by Scott (2007), there is good evidence for early formation of planetesimals less than 1 Myr after CAIs from Hf-W data for iron meteorites and CAIs (Kleine et al. 2005; Markowski et al. 2006). According to minimum-mass nebula models, 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 (e.g., Weidenschilling 1977). Much of this original mass was probably in the form of Moon- to Mars-sized planetary embryos that were later removed through mutual gravitational perturbations into unstable resonances with the giant planets, especially Jupiter (Chambers and Wetherill 2001; see also O’Brien et al. 2007). For example, Chambers and Wetherill report orbital evolution simulations for up to 200 bodies having diameters of several thousand km or more. For comparison, the largest remaining body in the asteroid belt is 1 Ceres (913 km in diameter). 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 ($e = 0.3–0.5$) and, therefore, high velocities for resonant planetesimals relative to both nebular gas and non-resonant planetesimals in circular orbits (~5 km/s; Marzari and Weidenschilling 2002). Their inclinations would have remained low leading to a relatively higher probability of close encounters and collisions.

As discussed by Marzari and Weidenschilling (2002; hereafter MW02), two different mechanisms, respectively associated with the 2:1 and 3:2 mean orbital resonances, can produce high eccentricities in spite of the damping effect of gas drag. The first mechanism requires a non-zero Jovian eccentricity and involves actual trapping in the 2:1 resonance. The time spent trapped in the 2:1 resonance is approximately proportional to the planetesimal size. The slower orbital decay of larger bodies allows longer trapping times during which eccentricities can reach higher values. Thus, the maximum eccentricity of a trapped planetesimal depends on the planetesimal size. The second mechanism involves crossing the 3:2 resonance without becoming trapped and is effective even for zero Jovian orbit eccentricity. A large percentage (typically $50\%$ or more) of the resonance-crossing planetesimals avoid close encounters with Jupiter and continue to evolve inward. Most of the latter planetesimals
enter a chaotic region between 3.2 and 4.2 AU where higher-order mean motion resonances overlap. The planetesimals’ eccentricities are increased in this region while their semi-major axes are decreased, causing them to pass through a series of resonances including the 2:1 resonance. Crossing the 2:1 resonance results in a further increase in eccentricity. The inner migration is eventually stopped between 2 and 3 AU because of gas drag damping. The orbital inclination remains low throughout the inward migration. In the case of the 3:2 crossing mechanism, the maximum eccentricity achieved by a given planetesimal does not depend on its size, provided it is above a certain threshold to avoid damping by gas drag.

Figure 1 (from MW02) shows the temporal evolution of the semi-major axis $a$, eccentricity $e$, and inclination $i$ for a 100 km diameter planetesimal started at 4.2 AU, just outside of the 3:2 resonance, located at 3.97 AU. A low-mass nebula model with a total mass inside of 40 AU of 0.04 solar masses was adopted and no collisions or close encounters with other planetesimals were assumed to occur. A maximum planetesimal eccentricity of ~0.48 is reached shortly after entering the resonance and the planetesimal spends ~23,000 years with $e > 0.3$ in the absence of destructive collisions. During this period, the semi-major axis ranges from about $a = 3.5$ to 2.2 AU. The inclination remains comparable to or less than its entry value (<0.5°). Similar calculations were performed by MW02 for planetesimal diameters ranging from 50 to 500 km with comparable results. Maximum eccentricities range up to 0.55 and $a$ ranges from about 3.5 to 1.5 AU during the period when $e > 0.3$. Calculations for the trapping of a 300 km planetesimal in the 2:1 resonance (see Fig. 3 and 6 of MW02) show that $a$ ranges between about 3.3 and 2.6 AU during a period of ~65,000 years when the eccentricity remains above 0.3 (again neglecting collisions).

Figure 2 plots the relative velocity between a body in a low-inclination prograde elliptical orbit with $a = 3$ AU and nebular gas assumed to corotate at the circular Keplerian rate as a function of the azimuth from periapsis for three different values of the eccentricity $e$ (see, e.g., Hood 1998). These velocities are also approximately equal to the collision velocities between the same body in an eccentric orbit and another in a prograde circular orbit. For $e = 0.3$, it is seen that relative velocities between resonant planetesimals and either
nebular gas or non-resonant planetesimals range from as little as 2.5 km/s at periapsis or apoapsis to as much as 5.4 km/s at intermediate azimuths. For $e = 0.4$, the corresponding range is ~3.4 to 7.5 km/s; for $e = 0.5$, the range is ~4.2 to 10 km/s. However, it is important to note that the maximum relative velocities occur near the times of midplane passage while the minimum relative velocities occur near times of maximum altitude above or below the midplane (see Fig. 2 of Hood 1998). Since non-resonant planetesimals in circular orbits are constrained by gas drag to remain very near the midplane, the actual collision velocities between resonant and non-resonant planetesimals may therefore be near the maxima of the relative velocity ranges.

Referring again to Fig. 1, a planetesimal passing through the 3:2 resonance spends about 13,000 years with eccentricity between 0.3 and 0.4. The mean relative velocity during this period would be about 4.7 km/s. However, the mean relative velocity during midplane passage would be about 6.4 km/s. Again referring to Fig. 1, a planetesimal spends ~10,000 yr with eccentricity between 0.4 and 0.45. The corresponding mean and midplane passage relative velocities during this period would be ~5.9 km/s and ~8.1 km/s, respectively. Finally, averaging over the entire 23,000 yr with $e > 0.3$, the average mean and midplane passage relative velocities are ~5.2 km/s and ~7.1 km/s. Carrying out a similar exercise for a planetesimal passing through the 2:1 resonance (Fig. 3 of MW02) yields average mean and midplane passage relative velocities of ~4.8 km/s and 6.5 km/s. In summary, considering both resonances, relative velocities ranged from about 3 to 10 km/s with an average mean of ~5 km/s and an average midplane passage relative velocity of ~6.8 km/s. Since chondrule precursors, in the absence of global turbulence, will concentrate near the midplane (e.g., Weidenschilling 2006), the maximum relative velocities (~6.8 km/s) may be most appropriate for estimating planetesimal bow shock velocities when most precursors would have been processed. We therefore conclude 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.

As discussed by MW02, some fraction of resonant bodies experienced major impacts with non-resonant bodies before completing their migration from the outer to the inner belt. A rigorous calculation of the collision probability for a given orbiting body with any other orbiting body would require a knowledge of the basic orbit elements (semi-major axis, eccentricity, and inclination) for all bodies involved (Wetherill 1967; Farinella and Davis 1992). However, since these elements for the primordial belt are unknown, we consider here two first-order alternate approaches for estimating the fraction of resonant bodies that would collide with sizeable non-resonant bodies. In both cases, it is assumed that non-resonant bodies are in nearly circular orbits lying close to the nebular midplane as expected from gas drag effects. We note that a more rigorous approach (deferred here to a future paper) would calculate the collision probability distribution by numerically integrating the collision probability over one orbit for a series of resonant planetesimals and then integrating over a representative size distribution for the non-resonant planetesimals.

First, we consider a non-resonant circular orbit lying in the midplane and a resonant elliptical orbit with inclination $i$. The radius $r_o$ of the circular orbit is assumed to lie within the radial range occupied by the elliptical orbit. In that case, a resonant planetesimal orbit has two opportunities to intersect a given non-resonant planetesimal orbit. The collision probability of the non-resonant planetesimal with a single resonant planetesimal during one orbit is given roughly by:

$$P = 2 \left\{ \left\{ \frac{(D + d)/2}{2\pi r_o} \right\} \left\{ \frac{(D + d)/2}{2r_o \tan i} \right\} \right\}$$

(1)

where $D$ and $d$ are the respective diameters of the resonant and non-resonant planetesimals. In Equation 1, the first factor in braces is the fraction of the circular orbit perimeter that could be intersected by the combined cross sections of the two orbiting bodies; the second factor in braces is the fraction of the maximum vertical distance occupied by the non-resonant planetesimal orbit that could be intersected by the same cross sections. Note that Equation 1 neglects any increase in collision probability due to gravitationally induced changes in trajectories of any two bodies during close encounters. Also, effects of eccentricity on the collision probability are neglected and it is implicitly assumed that $(D + d)/2 < 2r_o \tan i$.

Second, we disregard the orbital characteristics of the non-resonant planetesimals and simply consider the motion of a resonant planetesimal through a “swarm” of planetesimals occupying a given vertical distance about the midplane and a given radial range traversed by the resonant planetesimal. The number density of the planetesimals is limited by the total estimated mass of the primordial belt, i.e., 3–5 Earth masses. In that case, the probability that a given resonant planetesimal would collide with a single non-resonant planetesimal is approximated as:

$$P = \pi \left( \frac{(D + d)/2}{V} \right)^2$$

(2)

where $v$ is the velocity of the resonant planetesimal relative to the non-resonant planetesimals, $V$ is the volume of the non-resonant planetesimal swarm within the radial range traversed by the resonant planetesimal, and $t$ is the time spent by the resonant planetesimal in this volume during one orbit. If $\Delta r$ is the radial range traversed by the resonant planetesimal within the non-resonant planetesimal swarm and $2h$ is the vertical range occupied by the swarm, then $V = 2\pi r_o \Delta r 2h$. If $2h \geq 2r_o \tan i$, then $t$ is equal to the orbit period (~5 years) and $v$ is the relative velocity averaged over the orbit. Perhaps more realistically, one may consider a special case in which the non-resonant planetesimal swarm is confined to a relatively thin layer near the midplane ($2h <<$
as expected from gas drag effects. In this case, the resonant planetesimal spends only part of its orbit time traversing the midplane region occupied by the planetesimal swarm. In that case, \( v \) is approximately equal to the mean relative velocity during midplane crossings and \( t \approx 2(2h/\sin i)/v \). Substituting for \( t \) and \( V \) in Equation 2, one obtains

\[
P = \frac{[D + d]/2)^2}{(r_o \Delta r \sin i)}
\]

where we have implicitly assumed that \((D + d)/2 \ll 2r_o \tan i\) and \((D + d)/2 \ll r\). For large \( i \), \( P \) is just the ratio of the cross-sectional area to the total area occupied by the planetesimal swarm, multiplied by 2 to account for the two midplane crossings per orbit. For small \( i \), the probability of a collision

Fig. 3. Shaded mass density plots at various times following a head-on (vertical) impact at 8 km/s between two equal-sized bodies with a silica composition and zero porosity in the presence of a solar nebula. The material of the bodies is shaded green; the nebula gas is shaded blue; a red line indicates the approximate boundary between the two. Darker shadings indicate higher density. The time in seconds divided by the projectile diameter in km is indicated at the upper right of each plot. Distance is measured in units of projectile diameters. a) Initial conditions at \( t = 0 \). An ambient H\(_2\) nebula is assumed to be present with a mass density of \( 10^{-7}\ \text{g cm}^{-3}\). b) Conditions at \( t = 1.00 \) (e.g., 1000 seconds for a 1000 km projectile diameter). c) Conditions at \( t = 2.00 \). d) Conditions at \( t = 7.00 \). e) Conditions at \( t = 10.00 \).
increases due to the longer time spent by the non-resonant planetesimal in the swarm.

To simplify the analysis and obtain a first-order estimate for the collision rate of large bodies using Equations 1 and 2a, only planetesimals with diameters greater than 500 km are considered and it is assumed that the mean diameter of these planetesimals is \(D = d = 1000\) km. In addition, we take \(r_o = 3\) AU, \(\Delta r = 1.3\) AU, \(v = 5\) km/s (see above), and \(i = 0.5^\circ\) (i.e., comparable to that of the resonant planetesimals of Fig. 1). For these assumptions, using Equation 1 one obtains \(P = 10^{-10}\) while using Equation 2a one obtains \(P = 10^{-9}\). The collision probability is less using Equation 1 because the trajectory of a given non-resonant planetesimal is restricted to lie along a circular orbit near the midplane whereas, using Equation 2, the orbit is unconstrained. Since a circular orbit lying near the midplane should be a more realistic assumption, we therefore adopt the lower value of \(P\) obtained from Equation 1. Based on the results of Fig. 1, a given resonant planetesimal with \(e > 0.3\) will traverse the radial zone between ~3.5 and 2.2 AU during a period of ~23,000 years, equivalent to ~4600 orbits. 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. If so, then the probability that a single resonant planetesimal would collide with a non-resonant planetesimal with \(D > 500\) km during its inward migration is \(P \times 4600 \times 10,000 = 0.00415\) or about one in 240. This number could be underestimated if the inclinations of the resonant bodies were actually less than 0.5° or if there were actually more than 10^4 bodies with \(D > 500\) km in the primordial belt. Also, this calculation does not consider impacts with bodies smaller than 500 km in diameter, which could have been significant for high relative velocities.

In order to estimate the approximate number of collisions per unit time of resonant planetesimals (\(D > 500\) km) with non-resonant planetesimals (\(D > 500\) km) in the primordial belt, it is first necessary to estimate the number of such planetesimals that entered the major 2:1 and 3:2 resonances per unit time. According to Fig. 1, a 100 km diameter planetesimal started at 4.2 AU in a ~0.04 solar mass nebula migrates inward gradually due to gas drag and requires ~50,000 years to reach the resonance location at 3.97 AU, equivalent to an inward migration rate of about ~5 \times 10^{-6}\) AU/ year. In the actual primordial belt, resonance sweeping by an inward migrating Jupiter combined with mutual close encounters and minor collisions may have been the dominant mechanisms for transporting planetesimals into resonance regions (see final section for discussion). Nevertheless, we assume here conservatively that the inward migration rate was comparable to that estimated from Fig. 1. If there were ~10,000 planetesimals with \(D > 500\) km per AU of radial distance in the asteroid belt region during the nebula epoch, then ~0.05 such planetesimals per year would enter the 3:2 resonance region. A similar number of planetesimals with \(D > 500\) km would enter the 2:1 resonance region. Combining these estimates with the collision probability for a single resonant planetesimal given above leads to an estimated collision frequency of roughly one major impact per 2400 years. This estimate is uncertain by at least an order of magnitude because of (a) uncertainties in the actual number of planetesimals with \(D > 500\) km per unit radial distance in the primordial asteroid belt; (b) uncertainties in the radial migration rate of planetesimals into resonance regions; and (c) uncertainties in the collision probability of a single resonant planetesimal as noted above.

This estimated collision frequency is far higher than that for typical bodies in the present-day asteroid belt (e.g., Farinella and Davis [1992]). According to the latter authors, the largest asteroid, 1 Ceres (\(D = 913\) km) has an estimated collision rate with 5000 catalogued bodies whose diameters exceed 50 km of about three per 5 \times 10^8 years. Accounting for uncatalogued bodies (assuming that the latter have an equal number of larger bodies) increases this to about eleven per \(5 \times 10^9\) years. The much higher collision frequency for the primordial belt is partly because of the increased number of bodies as large or larger than Ceres (a factor of ~10^4) and partly because of their relatively small orbital inclinations caused by gas drag (a factor of at least 50). However, it is also because of the absence of nebular gas drag and infrequent gravitational encounters in the present-day belt (not to mention resonance sweeping by an inward migrating Jupiter, not accounted for in the calculations of Fig. 1), which would cause bodies to migrate across resonance locations more rapidly.

**Impacts in the Presence of a Nebula**

The main characteristic of high-velocity planetesimal impacts that can lead to shock wave generation in the solar nebula is the production of a cloud of heated melt and vapor that expands thermally and/or is jetted rapidly away from the impact point. Unlike slower-moving solid ejecta, which can be retained gravitationally by a sufficiently large target body (Melosh et al. 2004), the vapor-melt cloud produced in a large impact invariably escapes. In the absence of a nebula, the vapor-melt mixture simply expands into space, producing a quantity of melt droplets that rapidly solidify. As noted in the Introduction, this is a plausible proposed origin for the “non-nebular” chondrules in the unusual CB chondrites (Krot et al. 2005b). However, if a nebula is present, the rapidly expanding vapor-melt cloud produces a shock front in the gas that can potentially produce a much larger quantity of partial melt droplets by thermally processing any solid particles in the ambient nebula. Our goal in this section is to estimate the approximate local nebula volume that is processed by impact-generated shocks sufficiently strong to melt chondrule precursors as a function of impactor size and impact velocity.

For this purpose, a series of numerical impact
The main new aspect of the present simulations is that an ambient nebula is assumed to be present everywhere outside of the impacting bodies and the interaction of the impact-vapor melt cloud with this ambient nebula is specifically investigated. As a simplification for these initial simulations, we consider only vertical (“head-on”) collisions between bodies of equal sizes for a range of relevant impact velocities. Scaling of the hydrodynamic equations allows the simulations to be done in a coordinate system measured in units of the projectile diameter so that repeated simulations for different projectile sizes are unnecessary. The only drawback of this approach is that gravitational forces are necessarily neglected. It is therefore not possible to investigate, for example, the fate of solid ejecta as a function of impactor and target sizes. The ambient nebula is assumed to be composed dominantly of molecular hydrogen and has a mass density of $10^{-7}$ g cm$^{-3}$. This is the lowest mass density that the existing code can accurately treat owing to (1) questions about the reliability of the equations of state at lower densities; and (2) a need to evaluate whether standard hydrodynamics can be used at lower densities. It is higher by a factor of $\sim 100$ than what is normally assumed for a minimum-mass nebula in the asteroid belt region. For example, a mass density of $10^{-9}$ g cm$^{-3}$ has often been assumed for chondrule thermal history simulations (e.g., Desch and Connolly 2002; Ciesla and Hood 2002; see also Desch 2007). Therefore, this high assumed nebula density probably leads to an underestimate of the distance at which a given impact-generated nebular shock wave would weaken and dissipate. For example, if the total nebular volume processed by the shock scales approximately inversely with ambient nebula mass density, then the volumes estimated here for a given impact velocity are too low by a factor of as much as $\sim 100$.

Figure 3a summarizes the initial conditions for a vertical impact at 8 km/s between two equal-sized spherical silicate bodies with zero porosity and a mass density of 3 g cm$^{-3}$. Vertical and horizontal (i.e., radial cylindrical) axes are measured in units of the projectile diameter (equal, in this case, also to the target diameter). The time in seconds divided by the projectile diameter in km is indicated at the upper right. Nebula gas is indicated by the blue color and darker (lighter) blue indicates a higher (lower) mass density of the gas. Projectile and target material is indicated by the green color (separated from the nebula gas by a red line). Figure 3b is a shaded density plot for a time of $1 \times$ the projectile diameter in km (e.g., 1000 seconds for a 1000 km projectile). The vapor-melt cloud is the separate light-green region located furthest from the impact point. Due to the impact geometry, this cloud has been jetted outward along the cylindrical horizontal coordinate at a higher speed ($\sim 9$ km/s) than would have occurred from thermal expansion alone. The inner green region represents the remnants of the colliding bodies and is not fully resolved in the simulation since our main objective is to model the vapor-melt cloud/nebula interaction. The red lines again indicate the approximate boundary between the material of the impacting bodies (green) and the nebular gas (blue). The nebular shock front is visible as the boundary between the darker blue (denser, shocked) gas and the original light blue gas. The mean shock velocity up to this point in the simulation (independent of the projectile size) is $\sim 9$ km/s, more than sufficient to melt mm-sized particles if they were present in the nebula gas. Figure 3c is a similar plot at a time in seconds of $2 \times$ the projectile diameter in km (e.g., 2000 seconds for 1000 km bodies). The mean shock velocity is still $\sim 9$ km/s in the cylindrical radial direction indicating that the shock has not yet begun to weaken. The shock front has now reached a radial distance of $\sim 18$ projectile diameters (e.g., 18,000 km for 1000 km bodies). Figure 3d shows an expanded plot at a time in seconds of $7 \times$ the projectile diameter in km. At this point, the shock front has penetrated to $\sim 50$ projectile diameters in the radial direction and the mean shock velocity (averaged over all time since the impact) has decreased to $\sim 7$ km/s, implying a weakening of the shock. However, the shock velocity is still more than sufficient to melt chondrule precursors. Finally, Fig. 3e shows the density distribution after a time in seconds of $10 \times$ the projectile diameter in km. At this point, the shock front has penetrated to $\sim 60$ projectile diameters in the radial direction. Comparing Fig. 3d and 3e, the shock front advances radially only $\sim 10$ projectile diameters in a time interval in seconds of $3 \times$ the projectile diameter in km. Hence, the instantaneous shock
velocity has decreased to less than 4 km/s and the shock is now too weak to melt chondrule precursors. Therefore, the total nebular volume that is processed thermo-thermally to melt chondrule precursors by the shock front generated in the impact of Fig. 3 can be approximated as a cylinder with radius \(\sim 50\) projectile diameters and height \(\sim 30\) diameters. For example, if the projectile diameter is 1000 km, the processed volume is \(\sim 2.4 \times 10^{20} \text{ cm}^3\).

Repeating the numerical simulation of Fig. 3 for impact velocities of 4 and 6 km/s shows that nebular shock waves are again generated but the volume that is processed by shocks strong enough to melt chondrule precursors is reduced. For example, for a 6 km/s impact velocity, the instantaneous shock velocity is reduced to less than 4 km/s after radial propagation to less than 40 times the projectile diameter. The total volume processed to melt chondrule precursors has a cylindrical radius of about 20 projectile diameters and a height of about 20 projectile diameters. In the case of a 4 km/s impact velocity, the processed volume is even less. However, as noted above, the high nebular mass density required by the current version of the SOVA code \((10^{-7} \text{ g cm}^{-3})\) may result in an underestimate of the processed nebular volume for a given impact velocity by as much as 2 orders of magnitude.

**Estimated Chondrule Production Rates**

In this section, approximate chondrule production rates are estimated for both planetesimal bow shocks and impact-generated shock waves in the primordial asteroid belt as a function of the assumed precursor number density in the nebula. The resulting maximum mass production estimates are compared to estimates for the minimum likely mass of chondrules in the primordial asteroid belt in the final section of the paper. In the case of impact-generated shocks, we use estimates given in the previous two sections for (a) the collision rate of sizeable \((D > 500 \text{ km})\) resonant planetesimals with non-resonant planetesimals after the formation of Jupiter; and (b) the local nebular volumes that would have been thermally processed to potentially produce chondrules in impact-generated shock waves as a function of impactor size and velocity. In the case of planetesimal bow shocks, we use characteristics of these shocks previously investigated by Hood (1998), Ciesla et al. (2004b), and Hood et al. (2005) together with more detailed resonant planetesimal orbital evolution properties (especially very low inclinations) evaluated by MW02 and summarized above.

It was estimated in the section Resonant Planetesimals in the Early Asteroid Belt that, for the stated assumptions, high-velocity collisions between bodies with diameters \((D > 500 \text{ km})\) would occur at a rate of roughly 1 per 2400 years. It was estimated in the same section with the aid of Fig. 2 that collision velocities between resonant and non-resonant planetesimals in circular orbits lying near the nebular midplane would average \(\sim 7.1 \text{ km/s}\) for passage through the 3:2 resonance and \(\sim 6.5 \text{ km/s}\) for passage through the 2:1 resonance. According to the results of the previous section, a head-on (vertical) impact between two equal-sized bodies at 8 km/s processes a volume comparable to that of a cylinder with radius \(\sim 50\) projectile diameters and a height of \(\sim 30\) diameters. A 6 km/s impact processes a cylindrical volume with radius \(\sim 40\) projectile diameters and a height of \(\sim 20\) diameters. Hence, it is estimated that the cylindrical volume processed by a 6.5–7.1 km/s impact would have a radius of roughly 43 projectile diameters and a height of about 23 diameters. Taking the mean diameter of bodies with \(D > 500 \text{ km}\) as \(\sim 1000 \text{ km}\), each 6.5–7.1 km/s impact would process a volume of \(\sim \pi \times (43000 \text{ km})^2 \times 23000 \text{ km} \approx 1.3 \times 10^{29} \text{ cm}^3\). Taking into account the likely underestimate of the processed volume due to the high assumed nebular gas density, this volume estimate should probably be increased by a factor of \(\sim 100\) to \(\sim 10^{31} \text{ cm}^3\). If the number density of chondrule precursors in the solar nebula in the near vicinities of colliding planetesimals was \(\sim 1 \text{ m}^{-3}\) and if the shock velocity was marginally high enough to bring all of these precursors to melting temperatures, then \(\sim 10^{25}\) chondrules would be produced in a single such impact. For a major collision rate of \(\sim 1\) per 2400 yr, \(\sim 830\) 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 \(0.001 \text{ g}\), the total mass of chondrules that could be produced would be \(\sim 10^{25} \text{ g}\). If the number density of chondrule precursors near the midplane was actually \(10 \text{ m}^{-3}\), the total mass of chondrules produced would be \(\sim 3 \times 10^{25} \text{ g}\). On the other hand, if a “solar” solids/gas mass ratio of 0.005 is assumed, then a nebula with mass density \(10^{-9} \text{ g cm}^{-3}\) containing \(0.001 \text{ g}\) chondrule precursors would have a number density of \(0.005 \text{ m}^{-3}\). For this number density, the total mass of chondrules that could be produced would be only \(\sim 10^{23} \text{ g}\). Lastly, it should be emphasized that these estimates are upper limits since not all precursor particles passing through a shock will produce chondrules. Depending on precursor particle properties and shock speed, some will be vaporized, for example.

Figure 4 (from Ciesla et al. [2004b]) shows the gas density in the vicinity of a 1000 km radius planetesimal moving at 8 km/s relative to nebular gas with an upstream density of \(10^{-9} \text{ g cm}^{-3}\). Because of the decreasing angle between the upstream flow direction and the shock front, the strength of the shock (effective shock velocity perpendicular to the front) decreases with increasing distance of the shock from the planetesimal. If bow shocks mainly processed concentrations of precursors during passages through the nebular midplane, relative planetesimal-gas velocities would be the same as resonant/non-resonant collision velocities estimated above, i.e., \(\sim 6.5\) to \(7.1\) km/s with a mean of \(\sim 6.8\) km/s. According to Ciesla et al. (2004b; see their Fig. 2), a gas-planetesimal relative velocity of 6.8 km/s results in an
effective planetesimal bow shock velocity that decreases to a value less than that required for melting chondrule precursors (i.e., $\sim 4$ km/s) within $\sim 4$ planetesimal radii of the axis of symmetry. Hence the effective mean melting cross section of a resonant planetesimal in the nebula can be estimated as $\sim \pi (4D/2)^2$, where $D$ is again the planetesimal diameter. The total volume swept by such a planetesimal in a single orbit is then $V = (2\pi a) (\pi (4D/2)^2)$. In order to allow a better comparison with the production rate for impact-generated shocks, we again consider only planetesimals with diameters $D > 500$ km, assumed to have a mean diameter of 1000 km. A resonant planetesimal of this size would then sweep a total volume of $V = 3.6 \times 10^{21}$ cm$^3$ during one orbit.

However, it is unlikely that precursors were uniformly distributed throughout the volume that was processed by bow shocks. As discussed in the Introduction, meteoritic evidence indicates a number density of $6-10$ m$^{-3}$ in chondrule formation regions. A planetesimal in an orbit with $0.5^\circ$ inclination will reach altitudes of $\sim 3.9 \times 10^6$ km above and below the midplane. Assuming a mass for each precursor of 0.001 g, a number density of 1 m$^{-3}$ would imply a surface mass density of $\sim 800$ g cm$^{-2}$. If this mass density extended over a radial range of 1 AU, the total mass would be about 565 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 most of the calculations below, we assume that the total mass of precursors did not exceed $\sim 1$ Earth mass. However, this is only an upper limit and a total mass of only 0.1 Earth mass is also plausible. For a total mass of 1 Earth mass, a precursor number density in these midplane concentrations of $\sim 1$ m$^{-3}$ and a mass for each precursor of 0.001 g would require that precursors occupied no more than $1/565$ of the total volume processed by the bow shocks. The total mass of chondrules that could potentially be produced in a single orbit would then be $\sim 6.3 \times 10^{19}$ g. If the total mass of precursors was only 0.1 Earth mass, then $\sim 6.3 \times 10^{18}$ g of chondrules would be produced per orbit.

The same argument (that the total precursor mass should not exceed a reasonable upper limit of 0.1–1 Earth mass) would also reduce the production of chondrules by impact-generated shocks by a comparable factor. Although non-resonant planetesimals would be in nearly circular orbits with very 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 ($\sim 5,000,000$ km), which would be much thicker than the precursor layer. Consequently, much of the volumes processed by impact-generated shocks may have contained relatively few precursors. For example, instead of a total mass production of $\sim 10^{25}$ g (estimated above for a precursor number density of 1 m$^{-3}$ throughout the processed region), the total mass production should probably be reduced to only $\sim 2 \times 10^{22}$ g.

Considering again the case of the resonant planetesimal passing through the 3:2 resonance (Fig. 1), the planetesimal 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 $\sim 3 \times 10^{23}$ g of chondrules if the total mass of precursors was 1 Earth mass. According to the simulations of MW02, the total mass of precursors was 1 Earth mass. Considering again the case of the resonant planetesimal passing through the 3:2 resonance (Fig. 1), if there were $\sim 10,000$ planetesimals with $D > 500$ km per AU of radial distance in the asteroid belt region during the nebula epoch, then $\sim 0.05$ such planetesimals per year would enter the 3:2 resonance due to gas drag alone. Assuming that the same rate applies for those entering the 2:1 resonance, then $\sim 0.1$ planetesimals per year 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 per AU would have existed at any given time (assuming a steady supply of planetesimals at the outer edge of the primordial 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 $\sim 6 \times 10^{28}$ g. Accounting for the longer $\sim 65,000$ year passage time for the 2:1 resonance might increase this estimate to $\sim 2 \times 10^{29}$ g. If the number density of chondrule precursors near the midplane was actually 10 m$^{-3}$, then they could have occupied only 1/5650 of the processed volume (to satisfy the assumed 1 Earth mass limit) and the total mass of chondrules produced would have been the same.
On the other hand, an additional constraint to be considered is the inference that most chondrules were heated to melting temperatures more than once (see Introduction). If bow shocks were the primary heat source, this means that a typical precursor was processed by more than one bow shock. Assuming that 1 Earth mass of precursors (i.e., $6 \times 10^{27}$ g) was available for processing at any given time, the above analysis yielded an estimated total chondrule mass production of $\sim 10^{29}$ g. If most of the formed chondrules were actually processed by more than one shock (e.g., because of concentrations of precursors in favorable locations near resonances), then the total chondrule mass production would be reduced by some factor dependent on the actual distribution of precursors relative to resonances. To account roughly for this repetition, we reduce the estimated production to $\sim 10^{28}$ g, or about 1.5 times the assumed precursor mass at any given time. This estimate is of course proportional to the assumed limit of 1 Earth mass of precursors in the zone processed by bow shocks. If the actual mass of precursors was only 0.1 Earth masses, then the mass production would be reduced to $\sim 10^{27}$ g. Finally, as noted above for chondrules produced in impact shocks, these values should be regarded as upper limits since some particles processed in strong shocks will not produce chondrules but will instead be vaporized, for example.

**Chondrule Cooling Rates in Bow Shocks Revisited**

Previous one-dimensional simulations of chondrule thermal histories in simulated planetesimal bow shocks (Ciesla et al. 2004b; Hood et al. 2005) have indicated that it may be difficult to achieve sufficiently slow cooling rates (i.e., <1000 K/h, Hewins et al. 2005) for planetesimals with radii less than 1000 km. However, these simulations were done only for nominal model and nebular parameters (solar solids/gas mass ratio of 0.005; chondrule wavelength averaged emissivity of 0.9; chondrule mass fraction of 75%; micron-sized dust mass fraction of 25%; upstream nebula mass density of $10^{-9}$ g cm$^{-3}$, nebula temperature of 400 K, etc.). It is therefore of interest to investigate the sensitivity of these results to alternate assumed parameters. In particular, as discussed by Desch et al. (2005), the cooling rate is increased for increased opacity, which causes precursors melted during shock passage to be exposed to radiation from hot particles near the shock front for shorter time periods. The opacity is in turn dependent mainly on the amount of solids in the gas, especially the amount of micron-sized dust. In this section, preliminary results of several additional simulations using smaller micron-sized dust mass fractions are reported.

Figure 5a shows the thermal history of a 1 mm precursor silicate particle heated during passage through an 8 km/s shock in a nebula with upstream density $10^{-9}$ g cm$^{-3}$. The shocked gas thickness is assumed to be 3000 km, which corresponds approximately to that expected for a 1000 km radius planetesimal at a distance of 1.5 planetesimal radii from the axis of symmetry. Unlike the simulations of Ciesla et al. (2004b) and Hood et al. (2005), the solids/gas mass ratio is assumed to be ten times solar (0.05). This results in more hot particles near the shock front and therefore more radiation received by particles approaching and receding from the shock front. In addition, the micron-sized dust mass fraction is assumed to be only 5%, which reduces the opacity, therefore also allowing more radiation to be received by approaching and receding particles. Particles approaching the shock front are heated to temperatures near the assumed solids of 1400 K but the heating time above 1200 K is still minutes or less, consistent with meteoritic evidence (e.g., Jones et al. 2000). The peak temperature of about 1950 K is also consistent with meteoritic evidence. The cooling rate at temperatures above the solidus is only ~100 K/h, which is well within the range estimated from furnace experiments. This cooling rate is considerably less than that obtained by Ciesla et al. (2004b) and Hood et al. (2005) for the same assumed shocked gas thickness.

Figure 5b shows a similar simulation for a shocked gas thickness of 1500 km, corresponding to a planetesimal radius of 500 km. An even lower cooling rate is obtained (minimum ~0 K/h). This lower cooling rate is partly an artificial consequence of heating of the particle by radiation from hot particles entering the assumed stationary gas at the downstream boundary of the shocked gas region (Ciesla et al. 2004b). Nevertheless, a cooling rate not greater than 100 K/h would be obtained even without this boundary effect. It can therefore be concluded that one-dimensional simulations with smaller micron-sized dust mass fractions and higher solids/gas mass ratios can yield acceptable cooling rates for planetesimal radii at least as small as 500 km. On the other hand, it should be borne in mind that radiative losses in three dimensions, which would occur in a real bow shock, would likely lead to faster cooling rates than those estimated here.

Further simulations are needed to determine the full range of model and nebular parameters for which thermal histories consistent with meteoritic evidence can be obtained as a function of assumed planetesimal radius. This will be the subject of a future paper. However, as seen in Figs. 5a and 5b, the cooling rate becomes low after the particle has receded only a few hundred km downstream from the shock. It is therefore possible that acceptable cooling rates (at least in one dimension) for this set of model parameters (i.e., micron-sized dust mass fraction of 5%, solids/gas mass ratio of ten times solar) will be obtained for smaller shocked gas thicknesses (e.g., 500 km, corresponding to a planetesimal diameter of ~330 km). It will then be necessary to consider the plausibility of this set of parameters versus the nominal parameters considered previously. Solids/gas mass ratios greater than solar would seem to be consistent with evidence for relatively high chondrule number densities in formation regions (Ciesla et al. 2004a; Cuzzi and Alexander 2006) as
well as evidence for higher minimum nebular masses and, therefore, gas densities near 3 A.U. (Desch 2007). It is possible that a 5\% micron-sized dust mass fraction can be consistent with meteoritic data, but this will need to be evaluated further.

**Summary and Discussion**

The simulations of Fig. 3 show that shock waves capable of producing meteoritic chondrules can be produced by collisions between resonant and non-resonant planetesimals in the primordial asteroid belt. Chondrule formation in these shocks as well as in bow shocks ahead of resonant planetesimals in eccentric orbits is a hypothesis that can be consistent with the likely time delay of \(\sim 1-1.5\) Myr between the formation of CAIs and chondrules. Formation of chondrules by these mechanisms would also occur preferentially in the asteroid belt region, which is the source of chondritic meteorites. One objective of the present paper was to provide an initial first-order estimate for the total chondrule mass production by both bow shocks and impact-generated shocks. Although a number of simplifying assumptions were made, many of the same assumptions were applied to chondrule production by both bow shocks and impact-generated shocks. So, the analysis should at least allow an evaluation of the relative importance of these two mechanisms.

A major starting point of the analysis is the assertion that the primordial asteroid belt was much more massive (\(\sim 3-5\))
Earth masses) than the present-day belt (~5 × 10⁻⁴ Earth masses) and contained numerous large bodies (Chambers and Wetherill [2001]; O’Brien et al. [2007]). Recent upward revisions of the surface mass density of a minimum mass nebula in the asteroid belt region (Desch 2007) could allow an even more massive primordial belt. For the sake of definiteness and to allow quantitative comparisons of the efficiencies of the impact and bow shock mechanisms, it was assumed that 3 Earth masses of bodies with diameters > 500 km (mean ~1000 km) existed in the belt during the chondrule formation epoch. Using the effective bow shock velocities versus distance from a resonant planetesimal calculated by Ciesla et al. (2004b) together with the mean gas-planetesimal velocity during midplane passages by a resonant planetesimal with ε > 0.3 estimated from the resonant orbit simulations of MW02, it was estimated that a total precursor mass of ~10²⁸ g would be processed in bow shocks if the total precursor mass was of the order of 1 Earth mass. Alternatively, for an assumed precursor mass of 0.1 Earth masses, the total processed mass would be ~10²⁷ g. These values should be regarded as upper limits on the chondrule mass production since not all processed particles will yield chondrules.

On the other hand, for the same assumed planetesimal size distribution and inward migration rate, and for an assumed uniform chondrule precursor number density and mass of 1 m⁻³ and 0.001 g, an upper limit of ~10²⁵ g of chondrules was estimated to be produced by impact-generated shocks in the nebula. Accounting for reasonable limits on the total mass of chondrule precursors in formation regions (i.e., ~1 Earth mass) would reduce this processed mass to only ~2 × 10²² g. According to these initial first-order calculations, it therefore appears likely that bow shocks were more important for the formation of “normal” chondrules (i.e., those with a nebular origin) than were impact-generated shocks.

The total mass of the present-day asteroid belt is ~3 × 10²⁴ g. The portion of this mass that consists of chondrules is of course difficult to estimate based on the limited sample provided by recovered meteorites whose connection to specific parent bodies in the asteroid belt is usually unknown. Moreover, as discussed for example by Hood (1998), the dominance of ordinary chondrites, which contain abundant chondrules, over CM and CI carbonaceous chondrites, which contain relatively few chondrules, in meteorite falls may introduce a bias that would lead to an overestimate of the abundance of chondrules in the asteroid belt itself. If we say, conservatively, that only 1% of the present-day asteroid belt is chondritic meteorite parent bodies and that ~33% of these bodies consist of chondrules, then the total mass of chondrules in the asteroid belt is at least ~10²² g. The early asteroid belt was at least several thousand times more massive than today and, if the number of chondritic bodies was proportionally larger, then the total mass of chondrules at that time would have been at least ~2 × 10²⁵ g. However, much of the additional mass may have been in the large >1000 km planetesimals that would have produced most chondrules during passage through Jovian resonances. These latter bodies may not have been chondritic themselves and would have been largely lost from the asteroid belt. In that case, the minimum total mass of chondrules in the primordial belt should be reduced by a factor of ~10 to ~10²⁴ g. Overall, we estimate the minimum total mass to have been in the range of 10²⁴ to 10²⁵ g. The lower limit of this range is still a factor of ~50 larger than the maximum total chondrule mass production estimated above for impact-generated shock waves if the precursor number density was 1 m⁻³ and if the total precursor mass was ~1 Earth mass. Since most chondrules were strongly heated several times and since the collision probability calculated from Equation 1 is probably somewhat overestimated due to neglect of eccentricity effects, for example, it would be even more difficult to explain the minimum chondrule mass by this mechanism. In contrast, maximum chondrule mass production by the bow shock mechanism (~10²⁷–10²⁸ g for a total precursor mass of 0.1–1 Earth mass) is more than sufficient to explain the estimated minimum chondrule mass in the primordial belt.

The above numerical estimates depend somewhat on the assumed planetesimal size distribution, but the relative importance of bow shocks and impact shocks is changed only slightly. For example, if we had instead assumed a planetesimal population consisting of 204 bodies with masses of 0.025 Earth masses (diameters ~4150 km), i.e., similar to the N-body integrations investigated by Chambers and Wetherill (2001), then only one impact per ~340,000 years between such bodies would be estimated. However, the total volume processed per impact would increase to ~9 × 10³² cm³. For an assumed uniform precursor number density of 1 m⁻³ and precursor masses of 0.001 g, the maximum total mass of chondrules produced by impact shocks would therefore be reduced only slightly to ~5 × 10²⁴ g using this planetesimal size distribution. Applying the constraint that the total precursor mass should not exceed 1 Earth mass, the maximum impact-produced chondrule mass would be reduced to ~10²² g. The bow shock volume processed in a single orbit would increase to 6.1 × 10³⁵ cm⁻³. Assuming that the total precursor mass did not exceed ~1 Earth mass, the total chondrule mass that could be produced in a single orbit would also increase to ~10²¹ g. However, only ~4000 such planetesimals would have entered resonances over the assumed 2 Myr chondrule formation epoch (assuming a steady balance between entering planetesimals and those lost by ejection so that the total number remained near 200). Consequently, the total bow shock chondrule mass produced (accounting approximately for multiple heatings and differences between the 2:1 and 3:2 resonance trapping durations but neglecting vaporized precursors) would still be ~10²⁸ g, i.e., about 1.5 Earth masses. Assuming a total precursor mass of 0.1 Earth mass would reduce this to ~10²⁷ g.

One criticism of the planetesimal bow shock model has
been that the scale sizes of such shocks would be relatively small leading to cooling rates too rapid to be consistent with furnace experiment results. Specifically, detailed one-dimensional thermal history simulations (Ciesla et al. 2004b; Hood et al. 2005) have indicated that planetesimals with radii less than ~1000 km would yield cooling rates more rapid than the maximum allowed by furnace experiments (~1000 K/h; e.g., Hewins et al. [2005]). However, as discussed in the previous section, these simulations were done for nominal model and nebular parameters. Modifying these parameters by increasing the solids/gas mass ratio and decreasing the mass fraction of micron-sized dust can yield acceptable cooling rates for much smaller planetesimal radii. Since it is not yet clear what the actual values of these parameters were in the nebula during the chondrule formation epoch, it is possible that acceptable thermal histories will be obtained even for planetesimals that are only 500 km in diameter or less. Further work on this question is needed, especially to account for radiative losses in three dimensions. In addition, the simulations of MW02 show that, at least in the case of bodies trapped in the 2:1 resonance, the time spent in the resonance (and therefore the maximum eccentricity achieved) is positively dependent on the size of the body. Also, the simulations of Chambers and Wetherill (2001) indicate that massive bodies in the asteroid belt are more likely to be transferred to resonance regions through mutual gravitational interactions. Only the largest bodies may have therefore had gas-planetesimal relative velocities large enough to produce chondrules.

As noted in the Introduction, another criticism of the bow shock model has been that the upstream surfaces of planetesimals that produced bow shocks would have been “ablated” by the hot gas flow and impacts of large solid particles. No evidence for such damage or ablation effects has been clearly identified in chondrite studies, which appears to be a contradiction. However, as just mentioned above, large bodies (that may have been most likely to have higher eccentricities and produce bow shocks) would preferentially undergo close encounters, scattering one another into resonances and leading to collision with the Sun or ejection from the solar system after many Myr (Chambers and Wetherill 2001). It is therefore possible that nearly all of the bodies that produced chondrules in bow shocks are no longer present in the asteroid belt. Most mm-sized and smaller chondrules produced in bow shocks would be swept past the planetesimal and be left to accrete later to non-resonant chondrules produced in bow shocks would be swept past the furnace experiment results. Specifically, detailed one-dimensional thermal history simulations (Ciesla et al. 2004b; Hood et al. 2005) have indicated that planetesimals with radii less than ~1000 km would yield cooling rates more rapid than the maximum allowed by furnace experiments (~1000 K/h; e.g., Hewins et al. [2005]). However, as discussed in the previous section, these simulations were done for nominal model and nebular parameters. Modifying these parameters by increasing the solids/gas mass ratio and decreasing the mass fraction of micron-sized dust can yield acceptable cooling rates for much smaller planetesimal radii. Since it is not yet clear what the actual values of these parameters were in the nebula during the chondrule formation epoch, it is possible that acceptable thermal histories will be obtained even for planetesimals that are only 500 km in diameter or less. Further work on this question is needed, especially to account for radiative losses in three dimensions. In addition, the simulations of MW02 show that, at least in the case of bodies trapped in the 2:1 resonance, the time spent in the resonance (and therefore the maximum eccentricity achieved) is positively dependent on the size of the body. Also, the simulations of Chambers and Wetherill (2001) indicate that massive bodies in the asteroid belt are more likely to be transferred to resonance regions through mutual gravitational interactions. Only the largest bodies may have therefore had gas-planetesimal relative velocities large enough to produce chondrules.

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The estimates given here represent only a small additional step toward a full evaluation of chondrule formation in nebular shock waves. In addition to further investigation of alternate shock generation mechanisms (e.g., gravitational instability shocks), further work is needed to estimate with better accuracy the total mass of precursors that could have been processed by both bow shocks and impact-generated shocks associated with resonant bodies in the nebula. For this purpose, more realistic planetesimal size distributions than that adopted here and a more precise consideration of resonant body velocities relative to the nebula and to non-resonant bodies would be useful. Most importantly, a better evaluation is needed of the inward migration rate of planetesimals into resonance regions. The simulations of MW01 assumed that Jupiter was on a fixed orbit. However, recent models of giant planet formation (e.g., Alibert et al. 2004) account for the fact that giant planets undergo inward migration in their latest formation stage due to gravitational interactions with the protoplanetary disk. If this occurred during the chondrule formation epoch, then resonance sweeping due to Jupiter migration would significantly enhance the fraction of planetesimals temporarily captured into resonances and, therefore, the number in highly eccentric orbits. This mechanism would be especially important for larger bodies that, in the static model, take longer to fall into resonances by gas drag only. More detailed orbit simulations that account for close encounters and collisions with other bodies as well as gas drag would also be useful.

Acknowledgments—We thank T. Nakamoto, an anonymous reviewer, and the associate editor E. Scott for useful criticisms that led to significant improvements in the paper. This work was supported by grant NNG06GF85G from NASA’s Origins program.

Editorial Handling—Dr. Edward Scott

REFERENCES


