Chondrule Formation in Eccentric Planetary Embryo Bow Shocks.

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Chondrules were melted while floating freely in the solar nebula approximately 1.5 - 3 Myr after the first solids [1]. Chondrule formation in planetesimal bow shocks has been proposed [2-5], but cooling rates have been too rapid to meet the meteoritic constraints, except in extreme situations [3,6,7]. Thermal buffering due to H_2 recombinations and enhanced optical depths can slow cooling rates to $\sim 10^3$ K/hr [6,7], but these conditions seem achievable only through a combination of large "planetesimal" (diameter 2000 km) and high chondrule concentration ($\mathcal{C} = 30 - 200$). In addition, the necessary mass of chondrules ($\sim 10^{24}$ g) [8] can be produced only by assuming hundreds of such planetesimals [6,7]. These extreme conditions may be unnecessary, however, in light of recent evidence that large *planets* on eccentric orbits may be common in forming planetary systems [9,10]. In fact, Mars appears to have substantially formed by 2 Myr [11] and scattered into its present position [12]. We show here that the passage of even one Mars-sized planetary embryo on an eccentric orbit can form the observed abundance of chondrules, in a manner consistent with constraints on their formation.

Cooling Rates

We calculate chondrule cooling rates after passage through bow shocks around planetary embryos. First we determine the bow shock structure using two codes: the FLASH hydrodynamics code [13], which is high-resolution but does not include radiative transfer; and a 2-D hydrodynamics code based on [14], to which we are adding modules to calculate radiative transfer. The thermal histories of chondrules depend on their distance L from unshocked, cool gas; typically $L \approx 1500 - 4500$ km for an assumed planetary embryo radius $0.8\,R_{\rm Mars} =$ 2700 km. This corresponds to an optical depth $\tau = \rho_g \kappa L \sim 0.19\,(1+\mathcal{C}/10)\,(b/1000\text{km}) \approx 0.6 - 1.7$, for $\mathcal{C} = 10$, where κ is the opacity and $\mathcal{C}$ is the chondrule concentration. We assume an overall solids-to-gas ratio of 0.005, with 75% of the mass of solids in 300 μm radius chondrule precursors and 25% of the mass in fine, micron-sized dust; $\mathcal{C}$ measures the chondrules-to-gas mass ratio relative to this value. The assumption of $\mathcal{C} = 10$ implies either settling of chondrules to the midplane or concentration by turbulence in clumps; if settling is more substantial than assumed here, $\mathcal{C} > 10$ may result, yielding higher optical depths. Most chondrules thus see an optical depth $\tau > 1$ between themselves and the cooler region, which is higher than has been considered in previous models of bow shocks [2-4]. Higher optical depths yield slower cooling rates and also serve to justify the use of a 1-D shock code [15] to estimate thermal histories of chondrules in bow shocks using the formulation of [6,7]. We find cooling rates of 10-100 K/hr (consistent with the porphyritic textures of most chondrules) are achieved in shocks of speeds V_s = 6-8 km/s. Chondrules directly in the planetary embryo's path will experience shock speeds equal to the velocity, $V_{\rm rel}$, of the embryo relative to the gas, but chondulres approaching with impact parameter $b > 0$ will experience effectively lower shock speeds. For $V_{\rm rel} = 8$ km/s, chondrules with $b = 0$, 4000, and 6000 km will experience local shock speeds of 8.00, 7.66, and 5.18 km/s, respectively. Only chondrule precursors with impact parameter $b < 4500$ km will encounter effective shock velocities and optical depths sufficient to melt in the manner ascribed to chondrules.

Shock Speeds

The strength of a bow shock depends on $V_{\rm rel} = |\mathbf{v_p} - \mathbf{v_g}|$, where the gas is assumed to orbit purely azimuthally at the local Keplerian speed, and $\mathbf{v_p}$ is the planetary embryo's velocity, which depends on its orbital parameters. For $e > 0.1$, the shock has a bow structure, with spiral wakes developing only for lower e [16]. We approximate the shock as having a speed of $V_{\rm rel}$ and a cross-section of $\sigma = \pi(4500\,\text{km})^2$, where 4500 km is the impact parameter that yields chondrules. Eccentricities and inclinations damp over time, based on results from numerical simulations [16,17]. The mass of chondrules processed in a shock of speed $V_{\rm rel}$ during a time interval Δt is $\Delta M_s = V_{\rm rel} \sigma \mathcal{C} f \rho_0\, \Delta t$, where ρ_0 is the midplane gas density and $f\mathcal{C}$ is the chondrules-to-gas mass ratio. We set $f = 0.00375$ and $\mathcal{C} = 10$, assuming a high degree of dust settling, as supported by observations of even some very young protoplanetary disks [18]. This implies that the midplane $\mathcal{C}$ is large at the expense of the upper layers, so we set the dust scaleheight to $\sim H/\mathcal{C}$ for gas scaleheight H. If the orbital inclination takes the embryo out of the dust layer, we set Δt equal to only the time spent during passage through the orbital nodes, at the appropriate shock speeds. Table 1 shows the amount of material processed and the duration, ΔT, for which shocks with speeds V_s = 6-8 km/s are attained, for a range of orbital semi-major axes a, eccentricities e, and inclinations i of a Mars-sized planetary embryo.

a, e, i	v_s (km/s)	$M_s(M_\oplus)$	Duration (10^5 yr)
1, 0.1, 0	3.0	-	-
1, 0.2, 0	6.1	2.3(-5)	0.017
1, 0.3, 0	9.4	3.8(-3)	0.61
1, 0.4, 0	13	8.9(-3)	1.7
1, 0.1, 7	4.8	-	-
1, 0.2, 7	7.2	2.9(-5)	0.13
1, 0.3, 7	10.2	6.3(-5)	0.27
1, 0.4, 7	13.7	3.2(-3)	0.50
1, 0.1, 15	8.4	2.7(-4)	1.3
1, 0.2, 15	10.1	2.2(-4)	1.0
1, 0.3, 15	12.5	1.2(-4)	0.55
1, 0.4, 15	15.6	5.3(-5)	0.25
1.25, 0.1, 0	2.7	-	-
1.25, 0.2, 0	5.5	-	-
1.25, 0.3, 0	8.4	3.3(-6)	0.64
1.25, 0.4, 0	11.7	6.3(-3)	2.0
1.25, 0.1, 7	4.3	-	-
1.25, 0.2, 7	6.4	7.9(-6)	0.067
1.25, 0.3, 7	9.1	4.9(-5)	0.41
1.25, 0.4, 7	12.1	1.8(-3)	0.50
1.25, 0.1, 15	7.5	1.3(-4)	1.15
1.25, 0.2, 15	9	1.1(-4)	0.92
1.25, 0.3, 15	11	5.3(-5)	0.48
1.25, 0.4, 15	14	4.4(-5)	0.38

Table 1: Chondrule production for different values of semi-major axis a (in AU), eccentricity e, and inclination i (in degrees). V_s is the *maximum* shock velocity during an orbit in the simulation. Shock speeds 6-8 km/s are required to melt precursors and form chondrules. Duration lists the total integrated time ΔT for which solids are processed by shocks with these speeds. $M_{\rm s}$ shows the total mass of chondrules produced before orbital dampening. (The notation $a(-b)$ means $a \times 10^{-b}$). We assume $M = 0.5 M_{\rm Mars}$ and $R = 0.8 R_{\rm Mars}$. The model disk has surface density $\Sigma = 149 (r/5.2 \text{ AU})^{-1.5}$ g cm^{-2}, scaleheight $H = 0.05r$, and midplane density $\rho_0 = \Sigma/(2H)$. The central star has mass 1 $M_\odot$.

Discussion

A bow shock from an eccentric Mars-size embryo will not only process a mass of chondrules comparable to the inferred mass $\sim 10^{24}$ g [8], it will melt chondrules across a region with impact parameters up to 4500 km, satisfying the constraint that chondrules formed together in regions with size scales of at least hundreds of kilometers [19]. The large scale of the bow shocks yields optical depths > 1 that result in the high peak temperatures and low cooling rates inferred for porphyritic chondrules. Mars is possibly the only remaining planetary embryo, but dozens had to accrete to form the terrestrial planets, so each scattered embryo would produce its own set of chondrules. Depending on the time, location in the disk, and the orbital parameters a, e_0, and i of the scattered embryo, chondrules with slightly different cooling rates, textures and compositions might be produced. Scattering events can take place throughout the lifetime of the nebula, and the duration of chondrule production for any given event will last $\sim 10^5$ yr, yielding an intrinsic scatter in the age of chondrules. At the time of chondrule formation, embryos should be heated by ^{26}Al, forming a magma ocean [11]. These embryos may therefore have had an atmosphere in outgassed volatiles like Na. Chondrules melted in bow shocks around the planetary embryos may be exposed to high partial pressures of these volatiles, possibly explaining the high Na vapor pressures inferred to have existed during chondrule formation [20].

Our investigation shows that chondrule precursors melted in planetesimal bow shocks around objects as large as Mars will probably achieve the high peak temperatures and low cooling rates associated with the formation of porphyritic chondrules. Even a single embryo appears capable of processing the observed mass of chondrules. Our 2-D hydrodynamics code with radiative transfer is being developed now to better test the range of thermal histories experienced by chondrules in bow shocks around planetary embryos.

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