CHONDRULE AND CAI FORMATION IN THE CONTEXT OF THE PLANETESIMAL NEBULAR SHOCK MODEL.

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Introduction: 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 melting of chondrule precursors (e.g., [1]). It is also possible that shock waves in a higher-temperature nebula environment at an earlier time and/or nearer to the Sun were responsible for the melting of coarse-grained refractory inclusions, e.g., Type B CAIs [2].

For both chondrules and Type B CAIs, multiple transient heating events were apparently common, implying that the shock generation process was repetitive [3,4]. In the case of chondrules, heating was rapid enough (minutes or less) to prevent loss of volatiles such as S (e.g., [5]) while cooling occurred in two stages: An initial rapid rate above the liquidus of ~ 5000 K/hr followed by a slower rate of 10-1000 K/hr (according to furnace experiments) [6]. Type B CAIs were only partially melted and cooled at rates of 2-50 K/hr, significantly slower than for chondrules [7]. Both chondrules and CAIs apparently spent time in dusty environments following their formation, as evidenced for example by the common occurrence of fine-grained rims (dust mantles) [8]. There is isotopic evidence that the formation of most chondrules was delayed by 1-1.5 Myr after the formation of most CAIs and continued for several Myr [9,10]. Finally, compositional and physical evidence suggests that chondrules in different chondrite groups formed at different heliocentric distances and locally near their parent bodies while CAIs formed in a separate reservoir near the Sun and were later transported into the chondrule formation region [2].

In this paper, we examine whether one proposed mechanism for providing chondrule-forming nebular shocks, i.e. shocks generated as a consequence of planetesimal and planet orbital evolution and impacts on and between planetesimals, could be consistent with the above experimental constraints.

The Planetesimal Nebular Shock Model: As described in [11], the planetesimal nebular shock model postulates that chondrules were melted in shock waves generated by planetesimals in the nebula. Included are both planetesimal bow shocks produced by bodies ejected into eccentric orbits (e.g., by passage through Jovian resonances) and impact vapor plume shocks produced by high-velocity collisions between planetesimals and other bodies. One positive attribute of this model is that it can potentially explain the apparent time delay between the formation of CAIs and most chondrules. This is because the model requires the prior existence of Jupiter, which may have formed 1-2 Myr after CAIs, in order to produce shocks capable of melting chondrule precursors in a cool (< 600 K) nebula at 2 to 4 AU. However, recent numerical simulations using an improved planetesimal accretion and orbital evolution code indicates that the canonical version of the model (with Jupiter at its present location near 5 AU and a planetesimal population evolving in the asteroid belt region) is not efficient enough, i.e., it does not produce enough strong shocks to account for the large abundance of chondrules in chondrites [12]. Also, there are questions about whether the resulting shocks, which would have scale sizes comparable in size to the planetesimal, would produce chondrule cooling rates that are slow enough to be consistent with furnace experiment results [13].

The inefficiency problem could be reduced or resolved by modifying the canonical version of the model to consider a radially migrating Jupiter. Present theories for the early evolution of the solar system usually require a substantial radial migration of the giant planets immediately following their formation (e.g., [14]). This would increase the scattering of planetesimals into eccentric orbits, leading to stronger bow shocks and more high-velocity impacts on planetesimals. One of us (SJW) is currently modifying the planetesimal evolution code to allow an investigation of this possibility. However, the cooling rate issue remains since rather large planetesimals (> 1000 km in diameter) would be needed to produce cooling rates as low as 1000 K/hr. Also, the model in its current form does not directly explain the constraint that chondrules and CAIs spent time in dust-rich zones following their formation.

Planetesimal Dust and Debris Clouds: A further improvement of the planetesimal nebular shock model may be obtained by considering impact-generated dust and debris clouds. In the primordial asteroid belt, bodies in eccentric orbits would have experienced the highest impact rate due to collisions with smaller bodies in near-circular orbits. The high frequency of such impacts at that time would result in a quasi-static cloud of dust and debris that would be gravitationally bound around most large planetesimals. Subsequent high-velocity impacts would then produce vapor-melt plumes that would expand rapidly from the impact point, producing shock fronts in the solids-gas mixture around the planetesimal. Because of the high concentration of solids, melting of submillimeter-sized silicate particles in these shock fronts could be an efficient source of chondrules. The cooling rates of these melted particles would be reduced relative to those of particles exposed to a bow shock in the nebula because they would be immersed in the heated dust and debris cloud around the planetesimal. Moreover, the formed chondrules would be in a dust-rich environment immediately after formation.

Application to CAIs: CAIs apparently formed in a relatively hot nebular environment, probably near to the Sun, before being transported outward to large radial distances in the course of protoplanetary disk evolution [15,16]. Their formation occurred during the first 0.5 Myr of solar system history when large planetesimals already existed (e.g., [17]). At this early time, the giant planets probably had not formed so planetesimals would not have been resonantly perturbed into highly eccentric orbits, as needed to produce strong shocks. However, at smaller radial distances in a hot nebula, weaker shocks would be required to melt silicate precursors of a given size. Also, larger precursors could be melted for a given shock velocity. Moreover, planetesimal circular orbit speeds and relative velocities near to the Sun (within 1 AU) for a given range of eccentricities would be considerably greater than at 2-4 AU. The net consequence would be that, during this early accretional stage near to the Sun, planetesimal nebular shocks (either bow shocks or impact-generated vapor-melt plume shocks) could have more easily melted large refractory silicate precursors, as needed to explain the formation of Type B CAIs. In order to explain the very slow cooling rates and fine-grained rims of many CAIs, it is more likely that they were melted by impact-generated vapor-melt plume shocks in the near vicinities of large planetesimals rather than in bow shocks. The large planetesimals themselves may have been lost to the Sun by type 1 inward migration due to tidal coupling to the nebula (or may have been accreted into the terrestrial planets) but some of the formed CAIs would have survived and been transported outward to be incorporated later into chondrites.

Summary & Discussion: CAIs may have been transiently melted by a number of mechanisms including, e.g., turbulent transport into and out of the hottest part of the nebula, passage through large-scale shocks in the nebula associated with gravitational instabilities or infalling gas, and/or in smaller-scale nebular shock waves associated with planetesimals.

In the context of the planetesimal nebular shock model, CAIs most probably formed during the early accretional stage near the Sun where planetesimal orbit speeds were higher, the nebular gas was hotter, and weaker shocks were required to melt large refractory silicate precursors. It is more likely that they formed in impact-generated shock fronts in a mixture of nebular gas and solids around large planetesimals than in bow shocks. The planetesimals were either incorporated into the terrestrial planets or were lost to the Sun by tidal coupling to the nebula but some of the partially melted CAIs were transported outward where they could have been eventually accreted on chondrite parent bodies.

Following the formation of Jupiter and during its radial migration, the frequency and strength of planetesimal nebular shocks would have increased, leading to melting of submm-sized ferromagnesian particles in large numbers. This would have been possible even in a relatively cool nebula at 2-4 AU. In order to be consistent with the relatively slow cooling rates of chondrules and their dust rims, it is likely that these particles were mainly melted in impact-generated shocks within a zone surrounding large planetesimals containing large amounts of dust and debris as well as nebular gas.

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