A RE-EVALUATION OF CHONDRULE FORMATION IN LARGE-SCALE SHOCKS.

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Introduction:

Chondrules are significant indicators of processes occuring in the early solar nebula. However, the method of their formation is a continuing source of debate. There are a number of constraints on chondrule formation provided by careful chemical and isotopic analysis, as well as experiments undertaken in order to reproduce chondrules in the lab. Any proposed formation method must meet this wide range of constraints. Shocks in the solar nebula remain the most promising chondrule-forming mechanism, due to their ability to meet the majority of constraints, especially those on the thermal histories experienced by chondrules [1]. The type of nebular shock has also been hotly debated, but has largely been narrowed down to two: large-scale shocks, such as those due to disk instabilities and bow shocks around large protoplanets [2,3]. Recent work [4] has shown that bow shocks around large protoplanets, while still a likely candidate for some types of chondrules, are not ideal for producing the majority (those with porphyritic textures). Hence, we feel it necessary to re-evaluate chondrule formation in large-scale shocks.

The large-scale shock model of [2] met most of the constraints on chondrule formation, especially their thermal histories, with the exception of excess "pre-heating". Solids will be pre-heated ahead of the shock (in the pre-shock region; Figure 1), due to the propagation of a radiation front (known as a Marshak wave) originating in the hot, post-shock region [2]. Pre-heating of chondrules ≥ 1300 K is constrained to under 30 minutes, in order to prevent isotopic fractionation of sulfur [5]. In the model of [2], the solids were pre-heated to temperatures exceeding 1300 K for over 4 hours. It has been demonstrated that the inclusion of a population of smaller particles will eliminate this problem [6], due to an increase in opacity in the pre-shock region that does not affect the cooling rates of chondrules in the post-shock region. Here we examine this problem in more detail and discuss the ramifications.

Methods:

We use the shock code of [2], modified to include a population of intermediate-sized particles. The mass fraction of solids in the nebula is assumed to be 0.05, a concentration ten times that proposed by [7]. Submicron-sized dust makes up $\sim 25\%$ of the solids. Of the remaining 75% of solids, 2/3 are large (300 μm) chondrule precursors, and 1/3 are particles of intermediate-size. The dust, considered coupled to the gas, evaporates completely and nearly instantaneously at 1500 K [2]. Chondrules and intermediate-sized particles evaporate at identical, energy-limited rates when their temperatures exceed their liquidus temperature of ~ 1820 K. Vapor evaporated from the chondrule precursors and intermediate-sized particles is added back to the gas. We have performed parameter studies with intermediate particle sizes of radius $a = 10, 15, 20$, and 30μm to determine the effects on the thermal histories of chondrules.

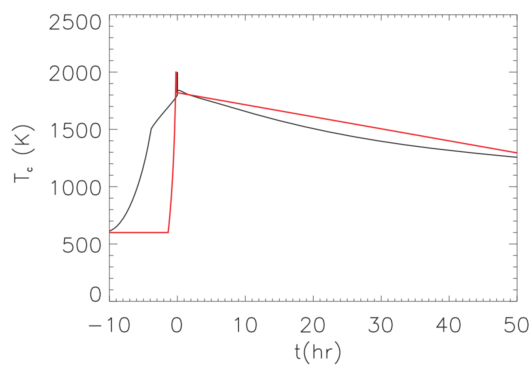

Figure 1: Thermal histories of chondrules. The dashed curve indicates those predicted by the shock model of Morris & Desch (2010), as compared to those inferred from experimental constraints (solid curve).

Results and Discussion:

We find that peak temperatures and cooling rates of chondrules are largely unaffected by the inclusion of intermediate-sized particles of all radii considered (Table 1). Cooling rates through the crystallization temperature range are raised only slightly over the canonical case of [2]. However, with the inclusion of particles of radius $a = 10\mu$m, the time spent at $T > 1300$ K before the shock is reduced to < 30 minutes, meeting the constraint on isotopic fractionation of sulfur [5]. The inclusion of a population of particles with radii $a = 15, 20$, and 30μm, shorten the time at high temperature, but do not eliminate excess pre-heating. Our calculations show that 10μm-sized particles will largely evaporate in the shock, with only large particles remaining for incorporation into chondrite parent bodies, along with nearby nebular dust.

Table 1.

Radius (μm)	$T_{\rm peak}$ (K)	Cooling rates (K/hr)[a]	$t_{\rm pre-heat}$ (min)
10	1963	20-40	16.1
15	2000	10-30	50.6
20	2000	10-30	55.6
30	2000	10-30	74.0

[a]Cooling rates through crystalization temperature range

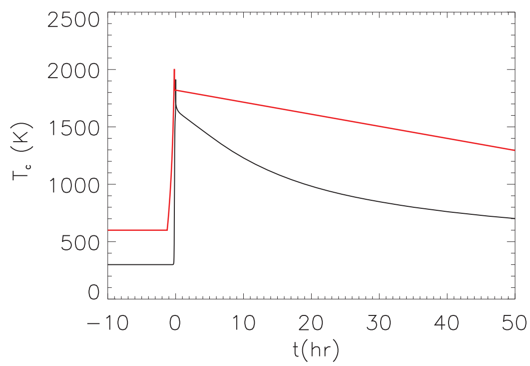

Figure 2: The black curve indicates chondrule thermal histories as predicted by the shock model of Morris & Desch (2010), with the inlusion of particles with radius 10μm, as compared to those inferred from experimental constraints (red curve).

Conclusion:

The introduction of a population of intermediate-sized particles of radius $a = 10\mu$m into the shock model of chondrule formation of [2] results in thermal histories that meet all thermal constraints (Figure 2). Such a population of particles, at 25% of the total solids mass, is not seen in meteorites. This implies that if they existed in the solar nebula, they were mostly lost, either by destruction in chondrule-forming shocks, or by coagulation into larger particles. Their existence, if established by the need to match constraints on chondrule formation, could inform models of particle growth.

The sole constraint not met by the large-scale shock model is the high partial pressure of Fe metal, Na, and S in chondrule-forming environments inferred by [8-11]. Passage of a shock through a very dense clump of chondrule precursors, with concentrations higher than thought possible, may produce the required vapor, but this has not yet been modeled. Alternative models, including models of chondrule formation in impacts [12,13] or impact/shock combinations [14], have been proposed to account for isotopic constraints, deformed and compound chondrules, and chondrule clasts [10,15]. However, these models have not been quantitatively tested, and as such, have not demonstrated that they can explain high partial pressures of Na (and Fe metal and S) either. The large-scale shock model remains the most promising mechanism for the formation of most chondrules.

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