AN ASTROPHYSICAL SITE FOR CHONDRULE FORMATION.

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Introduction: The existence of chondrules within primitive meteorites remains famously unexplained despite a major scientific effort spanning decades [1]. Unless and until we achieve a better understanding of how chondrules and chondrites formed, it will be hard to be confident about the initial stages of planet formation in the Solar System or of how to decode the wealth of information about it available from the study of meteorites.

Proposal: We propose that chondrules formed during the accretion of small (km-sized), primitive planetesimals (SPPs) to large (100 km-sized) differentiated planetesimals (LDPs) in the chondrule-formation epoch, t = 1.5 to 4 Myr [2]. An accreting SPP will generally be disrupted during this process, either tidally or by collision, and $10^{1\pm1}$ m-sized fragments on ballistic orbits may commonly suffer exposure to magma from the interior of the LDP, briefly raising their temperatures high enough for chondrules to form [3]. Fragments may be irradiated during the initial encounter or later if an accretion disk forms, or both. Radiant energy from the magma within the LDP may be released to space by the collision and/or later by ongoing volcanism (see Fig. 1). This proposal is rooted in many observational constraints on chondrules and chondrites, as well as laboratory simulations [3]. Novel aspects include: 1) chondrule precursors are grains within porous solids, not independent objects embedded in a nebular gas, or drops from a liquid reservoir, 2) the heating mechanism is radiative, and does not require nebular gas or collisional energy, and 3) chondrite formation may accompany chondrule formation – they are not necessarily separate processes.

Chondrule Formation Within a Porous Solid: Chondrules are known to have formed at such high densities that their precursors may not have been independent grains embedded in a nebular gas, as is commonly assumed, but porous solids. Abundance ratios of oxygen-bearing minerals in chondrite components [4,5], as well as Na abundance and zonation measurements [6] indicate that chondrules formed in regions of space where the density of solids was much higher than current nebular models can explain. A similar result follows from the high frequency of compound chondrules [7] and the existence of cluster chondrites [8]. If chondrule formation involves the gradual heating, partial melting, vaporization and trapping of gas atoms within a solid having a closed pore structure, the severe constraints on ambient conditions derived from these studies, including the high partial pressures of O and Na at the time of chondrule formation, can be satisfied [3]. In addition, gas atoms released by the forming chondrules may be trapped within the pores and condense to a fine-grained matrix as the object cools, potentially accounting for complementarity [9,10]. Chondrite formation by hot isostatic pressing (HIPping) may accompany the chondrule formation, satisfying the full set of constraints known as “hot accretion” [11].

Chondrule Formation by Radiative Heating: Heating m-scale solids in the early solar system to interior temperatures of 1600 K or more requires a radiative process, which in turn requires exposure to a heat source of at least that temperature. Fortunately, there is likely to be an abundant source of such hot material in the asteroid belt at the chondrule-forming epoch, namely magma within LDPs [12]. All that is required is to release some of that energy to space at the right time by fracturing the LDP crust. As noted previously, this could occur by direct impact of the SPP onto the LDP or by volcanism on the surface of the LDP. Other sources of hot material, such as a proto-Jupiter, or the Sun itself, seem too misplaced in space and/or time to be plausible alternatives.

Radiation has long been recognized as an attractive heating mechanism for chondrule formation [13,14,15] but has received relatively little attention over the years because no plausible source of the radiation could be identified. Our proposal addresses that and prompts us to remind the reader why some earlier investigators found the case for radiative heating so attractive. The main reason is that it leaves a distinctive imprint on igneous material, an imprint that may already have been observed in chondrules. When heated radiatively, the temperature reached by any particle immersed in the energy field depends on its efficiency at absorbing photons with energies near the peak of the Planck distribution; this, in turn depends on the size and composition of the particle. For example, small ($\leq 50\mu$) silicate grains embedded in a radiation field with $T \leq 3000$ K can remain solid even as larger particles around them melt, because of their relative transparency to near-IR radiation. That can explain otherwise puzzling observed phenomena including relict grains, dusty rims, the narrow size distribution of chondrules, size-sorting, and the survival of pre-solar grains [14,15].

Chondrules are a Minor Component of Primitive Matter: If chondrules were as abundant in the early asteroid belt as they are in chondrites, where they make up ~50% of the mass, then ~10^{24} kg of material would have to be melted to form them, requiring a global heating mechanism. However, their ^{26}Al ages [2] and planetesimal growth simulations [16] suggest that most of the mass in the asteroid belt was already packaged into large asteroids before the earliest chondrules even formed. And, if we judge the frequency of chondrules within the remaining primitive material by what impacts the Earth at the top of the atmosphere, rather than at the surface, chondrules appear much rarer. Based on the known meteorite flux of 2900-7300 kg yr^{-1} [17], and the fractional abundance of chondrites among meteorites, 85-90% [18], the flux of chondrules at the Earth's surface is 1.3-3.3 x 10^3 kg yr^{-1}. This may be compared to the total mass flux at the top of the atmosphere, 1-6 x 10^7 kg yr^{-1}, derived from meteor rates, impacts on space hardware and other studies [19]. Chondrules, therefore, are only a minor component of the material impacting the Earth at the top of the atmosphere, ~0.01% of the mass. Most of the impacting mass arrives in particles much smaller than chondrules and does not resemble ground-down chondrules, in general being much more porous [20]. Adopting the results of the Weidenschilling [16] simulations, only ~10^{15} kg, or roughly one-billionth of the original mass in the asteroid belt, needs to be melted to account for today's observed abundance of chondrules, not ~10^{24} kg. This is well within the reach of the chondrule formation mechanism proposed here.

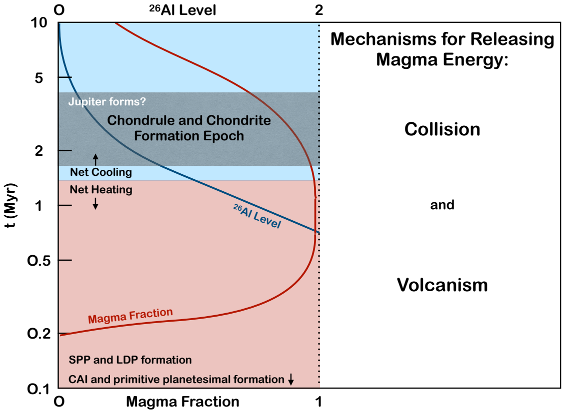

Fig. 1. A schematic chronology of the early asteroid belt. CAI formation defines t = 0 and primary planetesimals are assumed to form quickly, followed by SPPs and LDPs [16]. Within a few hundred thousand years most of the mass is in the form of LDPs, which have large magma cores (red line labeled magma fraction). The energy source is ^{26}Al, whose observed initial level is approximately 4 times the amount needed to fully melt a large asteroid that forms near t = 0 [12]; it declines with a half-life of 0.7 Myr. At around a level of 1, cooling dominates heating, and the magma fraction begins to fall, opening the door for some accreting primitive material to survive. A small fraction of the matter accreting thereafter is irradiated by exposure to hot magma released either by collision or volcanism. Chondrites (with chondrules) are born in these events and eventually accrete to the cooling surfaces of the LDPs where they can survive. Chondrite formation ends when the LDPs have cooled sufficiently that accreting SPPs never encounter near-IR radiation from magma. Jupiter may form at around 3-4 Myr and begin clearing the asteroid belt of most of its large LDPs [16].

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