

TIDAL DISRUPTION AND ACCRETION DURING THE CHONDRULE FORMATION EPOCH. W.

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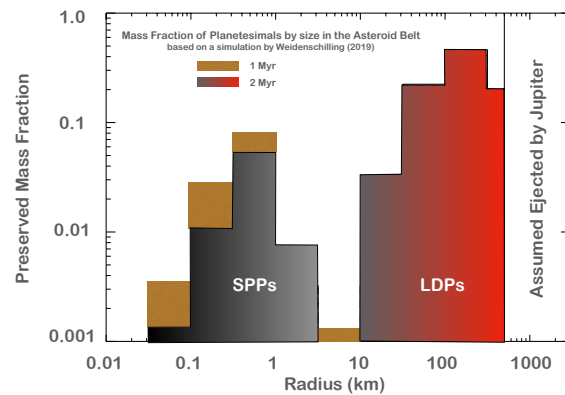
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Introduction: The origin of chondrules remains a famously unsolved problem, leaving their role in planet formation uncertain. Here we build on the chondrule formation theory proposed in [1], examining its efficiency at producing chondrules given the conditions expected in the early asteroid belt, according to simulations by Weidenschilling [2]. We propose that tidal capture and disruption may be important features of the accretion of primitive material to large planetesimals at early times and discuss the potential relevance of this to chondrule formation.

The chondrule formation epoch: Radioactive dating studies of chondrules by Pb-Pb, Al-Mg and other techniques agree that the main epoch of chondrule formation was between 1.5 and ~4 Myr, where $t = 0$ is defined by CAI formation [3,4]. Whether *any* chondrules formed prior to ~1.8 Myr remains controversial. Simulations of planetesimal growth in the asteroid belt (1.5-4 AU) during the first 2 Myr have been constructed by Weidenschilling [2]. Fig. 1 shows a representative result at two epochs, $t = 1$ (burnt orange) and 2 (red/grey) Myr. Already by 1 Myr most of the mass is in the form of large (100-km scale) planetesimals. These are labeled LDPs (large differentiated planetesimals) and colored red on the figure because thermal models show they will be fully melted by ²⁶Al decay [5,6]. They are presumably the parent bodies of the iron meteorites and an attractive heat source for chondrule formation. Their mass distribution does not change perceptibly on the figure between 1 and 2 Myr.

According to these simulations, ~90% or more of the mass in the asteroid belt has already accreted to an LDP well before the time of chondrule formation. Preserving sufficient mass in undifferentiated form until $t = 1.5$ -2 Myr is a challenge for theorists [2]. Note that what is plotted in Fig. 1 is the “preserved mass fraction”, defined as the mass fraction remaining after all objects larger than Ceres have been removed from the counts. This action is intended to simulate Jupiter’s formation (at $t > 2$ Myr) and subsequent ejection of a considerable amount of mass from the belt, mostly in the form of LDPs, thereby enhancing the mass fraction of remaining undifferentiated material. Without this step in the calculation the mass fraction of material available for chondrule formation is extremely small.

In the simulation depicted, the remaining primitive matter is mostly packaged in ~1 km scale planetesimals, labeled SPPs (small primitive



planetesimals) and colored grey on Fig. 1 to indicate that they are too small to have retained much heat from ²⁶Al decay. The SPPs harbor the raw material for chondrule formation as well as the CAIs and pre-solar grains found in many chondrites. In the simulation shown, a few percent of this (preserved) primitive mass accretes to LDPs during the 1-2 Myr interval.

Theory Overview: How can one form chondrules out of km-scale SPPs accreting to LDPs? One idea is that the SPP impacts the LDP releasing hot subsurface material in a “splash” and this mixes with primitive material and coalesces into a chondrule [6]. It remains to be seen whether a theory of this sort can produce objects with the observed characteristics of a chondrule. We favor the idea that accreting SPPs will often be subject to brief blasts of high intensity infrared radiation from volcanic hot spots on the surfaces of the largely molten LDPs. As shown by both theory and experiment, flyby heating of primitive granular material exposed to incandescent lava can produce objects with chondrule-like textures [1,7,8]. An added advantage is that this same heating event can lithify material through hot isostatic pressing (HIP) leading to the formation of chondrites [1].

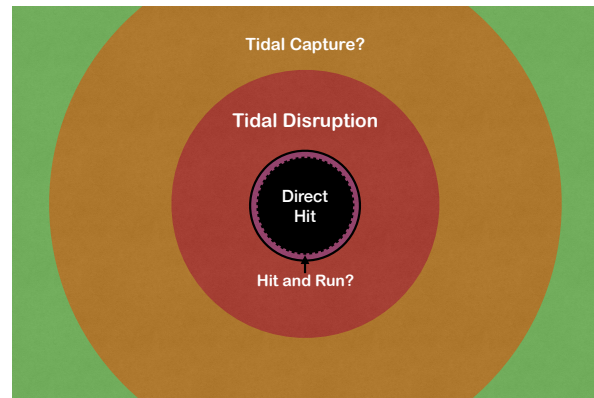
While this mechanism can plausibly account for the observed properties of chondrules and chondrites is it efficient enough to account for all the chondrules we collect? If the primary accretion mode is by direct hit, there would be only one brief opportunity to fly past a hot spot and since the near-IR radiation will penetrate only ~25 m into the object, a ~1 km-sized planetesimal would be largely untouched by it. However, if indirect accretion, which proceeds by tidal capture and disruption, is important there are significant advantages for the flyby model. Larger SPPs would be fragmented into m-scale objects by tidal disruption,

allowing intense near-IR radiation to reach more of the primitive mass. And if the fragments spend considerable time orbiting within an accretion disk, their probability of exposure to a surface volcanic event is greatly enhanced. Are tidal forces important in SPP accretion?

Tidal Capture and Disruption: Km-scale asteroids today are mostly thought to be rubble piles, weakly gravitationally bound granular aggregates with little internal strength [9]. The Ryugu sample reveals extremely fragile material with a tensile strength measure in Pa, rather than MPa, as is common for solid ice or rock [10]. Any gravitationally bound object is responsive to tidal forces and weak materials will not survive disruption if their radii are too large. Press & Teukolsky [11] showed that it is possible to tidally capture an entire incoming object by dissipating orbital energy in tidal oscillations. An estimate of the cross-section for tidal capture based on their analysis and assuming parabolic orbits is shown in Fig. 2, as the burnt orange outer circle. It may not be relevant here, however (hence the question mark on the figure), because the calculation is for an $n = 3$ polytrope representative of stars, not a granular aggregate. The calculation needs to be redone for a uniform density object.

A gravitationally bound SPP, or low tensile strength monolith, that passes within $1.69 R_{LDP}$ of an LDP, on the other hand, is clearly subject to tidal disruption, with half or more of its mass likely captured into bound orbits that will subsequently decay, leading to accretion [12]. This zone is colored red and labeled “Tidal Disruption” on Fig. 2. Accretion can also occur, of course, by a direct hit (black) and “hit and run” glancing collision (purple) [13]. As Fig. 2 illustrates, indirect accretion will dominate if km-scale SPPs are sufficiently susceptible to tidal disruption and if encounters are at relatively low velocity, i.e. nearly parabolic orbits. If Jupiter has not yet formed to stir the planetesimal swarm, the latter condition should be satisfied [2]. Monolithic objects with the tensile strength of ice or chondrites (in the MPa’s) will survive tidal disruption if they are smaller than ~ 100 km [12]. At $t = 1\text{--}2$ Myr, km-scale SPPs are more likely to be either granular aggregates or monoliths of very much lower tensile strength than solid ice or rock (in the Pa’s). The tidal destruction radius scales as the square root of the tensile strength of the material [12] and is plausibly ~ 0.1 km for SPPs at $1\text{--}2$ Myr. For the illustrated simulation this would mean that most of the SPP mass would reach the surface of the LDP through indirect accretion.

Summary: To summarize, we argue that indirect accretion of primitive material to large, hot



planetesimals during the chondrule formation epoch will be at least as important as direct accretion so that the chance of a m-scale fragment of an SPP being irradiated prior to arrival on the surface of an LDP is not negligible. Chondrules make up $\sim 0.1\%$ of the matter incident on the top of the Earth’s atmosphere [14,15], so we would only require that $\sim 0.1\%$ of the SPP matter accreting to an LDP in the $1.5\text{--}4$ Myr time frame suffer such exposure. The phenomenon of complementarity [16] suggests that this same heating event was also responsible for the lithification of chondrites via hot isostatic pressing (HIP) [1]. Further processing of the chondrites over much longer times, resulting in metamorphic changes, can occur once they reach the still-warm surface of the LDP.

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