TIDAL DISRUPTION AND ACCRETION DURING THE CHONDRULE-FORMATION EPOCH.

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Introduction: As Pape et al. [1] have emphasized, a successful model of chondrule formation requires a chronology that places it in the broader context of planet formation while accounting for the observed properties and abundance of chondrules and chondrites in the Solar System today. Here we employ the well-established Al-Mg chronology [1] along with a numerical simulation of planetesimal evolution in the asteroid belt by Weidenschilling [2] to address the issue. We also rely on early results from the Hayabusa2 mission [3] to constrain chondrule abundance in the Solar System beyond the Earth's surface and tensile strength in primitive material. We show that accretion by tidal disruption and capture is likely during the chondrule formation epoch due to the low internal strength expected for the km-scale planetesimals that are the primary accretors. There are arguably only two chondrule formation models that remain viable within this framework, the splash and flyby models.

The Splash and Flyby Models: Sanders & Scott [4] were the first to recognize that the narrow window of time in which chondrules formed, based on their Al-Mg ages, is arguably coincident with the time at which molten material was likely present near the surfaces of large planetesimals. They [4,5] have proposed that chondrules could form from the splash of such material mixing with primitive ejecta during accretional impacts, a scenario they refer to as the splash or dirty impact plume model. Inspired by this insight, Herbst & Greenwood [6,7] have proposed that radiation from incandescent lava that breaches the surface during such an impact or by volcanic activity could heat primitive accreting material during a close flyby, also resulting in chondrules and even whole chondrites.

Accretion During the First 1-2 Myr: Weidenschilling [2] has simulated the growth of planetesimals in the asteroid belt by accretion from a variety of starting points. He finds that at the time when chondrule formation begins in the Al-Mg chronology, $t \sim 1.5$-1.8 Myr, the size distribution of planetesimals in the asteroid belt can be described as bimodal. Most of the mass is in 100 km-scale objects that formed early and would be largely molten given canonical ^{26}Al abundances and heating models such as discussed in [4,5]. These are presumably the parent bodies of the iron meteorites. The remaining primitive matter, from which chondrules and chondrites could form, is encased in km-scale asteroids too small to have melted. Essentially no mass is left in small dust grains that could be transformed into chondrules by nebular heating mechanisms. Also, as long as Jupiter has not yet formed to gravitationally stir the ensemble, the accretion involves low-velocity impacts, sufficient for the splash model but likely below the threshold for chondrule formation by high-velocity jetting [8]. This is also conducive to tidal capture and disruption.

Tidal Disruption and Accretion: For low-velocity (nearly parabolic) orbits the cross-sections for tidal capture, either as a whole object [9] or as a tidally disrupted fragment stream [10], are generally larger by a factor of a few than the cross-section for accretion by direct hit. We show, based on the analysis of [10], that if km-scale primitive planetesimals are granular aggregates, like small asteroids of today, or if they are monolithic with the tensile strength of Ryugu-like material or less, they will be susceptible to accretion by tidal disruption. We also discuss the possibility of hit and run type accretion events, as discussed by Asphaug et al. [11], which are particularly relevant to the splash model.

Chondrule Abundance: Chondrule formation models need to be sufficiently efficient to account for the inferred number of chondrules in the Solar System today, but that number is highly uncertain. If chondrites like those in our museums formed at $t = 0$, and were the building blocks of planetesimals, then about half the original mass of the asteroid belt, or $\sim 10^{24}$ kg, would need to be processed into chondrules. On the other hand, if chondrules did not even begin to form until $t \sim 1.5$ Myr, and if their abundance in primitive material that reaches the Earth's surface (chondrites) is much higher than in primitive material in space (e.g. Ryugu and Bennu) then a successful chondrule formation theory may only need to account for one-billionth of that, or $\sim 10^{15}$ kg. The fact that no chondrules have been found in the Ryugu sample [3] was not a surprise to all [12], and we expect that the Bennu sample will also contain few, if any, chondrules. Models that involve processing only a miniscule percentage of the mass of the asteroid belt into chondrules and chondrites are not ruled out by current observations, they are arguably required by them.

References: [1] Pape et al. 2019, *Geochimica et Cosmochimica Acta* 244: 416–436. [2] Weidenschilling 2019, *Meteoritics and Planetary Science* 54: 1115-1132. [3] Yada et al. 2021, *Nature Astronomy* 6: 214-220. [4] Sanders & Scott 2012, *Meteoritics and Planetary Science* 47: 2170-2192. [5] Sanders & Scott 2018, in *Chondrules: Records of Protoplanetary Disk Processes* [Russell, Connolly, Krot, Eds.] Cambridge U. Press: 361-374. [6] Herbst & Greenwood 2016, *Icarus* 267: 343-359. [7] Herbst & Greenwood 2019, *Icarus* 329: 166-181. [8] Johnson et al. in *Chondrules: Records of Protoplanetary Disk Processes* [Russell, Connolly, Krot, Eds.] Cambridge U. Press: 361-374 [9] Press & Teukolsky 1977, *The Astrophysical Journal* 213, 183-192. [10] Sridhar & Tremaine 1992, I*carus* 95, 86-99. [11] Asphaug et al. 2006, *Nature* 439, 155-160. [12] Herbst, Greenwood & Yap 2021, *The Planetary Science Journal* 2, 110.