CHONDRULES, CHONDRITES, AND CHONDRITIC ASTEROIDS: PLANETARY BUILDING BLOCKS OR DEBRIS FROM PLANETARY ACCRETION? Ian S. Sanders[1] and Edward R. D. Scott[2]. [1]Trinity College Dublin 2, Ireland; isanders@tcd.ie. [2]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu HI 96822, USA; escott@hawaii.edu.

Introduction: Chondrules are commonly thought to have formed by rapid melting of preexisting dust clumps in the solar nebula and have therefore been considered as an essential first step in forming planetesimals from primordial nebula dust [1]. However, many chondrules have properties that are difficult to reconcile with an origin from preexisting dust clumps. In addition, their ages of 1.5 to 2.5 Myr after CAIs, based on Al-Mg [2], Pb-Pb [3] and Hf-W [4] dating suggest that chondrites accreted >2 Myr after CAIs in the waning stages of nebula evolution. If most chondrules formed instead from melt droplets created by collisions between partly molten plantesimals [5-7], chondritic asteroids are not primary planetesimals that accreted from the primordial disk but secondary planetesimals formed from a disk of debris that replaced the primordial disk.

The parent bodies of magmatic iron meteorites appear to be primary planetesimals and are plausibly related to the partly molten bodies that are the source for chondrules. Their deficit in ^{182}W shows that they had already accreted and melted <1 Myr after CAIs, some 1-2 Myr prior to the accretion of the chondrite parent bodies [8]. Here we review the arguments for chondrule formation by impacts of partly melted planetesimals and compare the formation of chondritic and differentiated asteroids.

Chondrule formation: Many features of chondrules are difficult to reconcile with an origin by melting of nebula dust clumps. Olivine-rich and pyroxene-rich chondrules are very unlikely to have formed from mm-sized clumps of micrometer-sized dust grains as nebular processes would not generate mm-sized monomineralic dust-clumps. Such chondrules could, however, reflect different degrees of olivine crystal settling in primitive magma prior to impact. Some chondrules contain polycrystalline olivine aggregates that are more likely to be products from planetesimal differentiation than grain aggregates that were annealed in the nebula [9]. Mm-sized olivine crystals that occupy >90% of the chondrule volume could not have crystallized from chondrule-sized melt droplets and must have originated in much larger volumes of melt. FeO-rich silicates, which constitute type II chondrules, cannot readily be generated under plausible nebula conditions [10]. Instead they could have been generated from partly molten planetesimals that had accreted water ice that oxidized metal to form FeO-bearing magma [11].

The concentration of Na in olivine crystals inside chondrules and the absence of isotopically mass fractionated isotopes of alkalis require high concentrations of alkalis in the gas when chondrules were molten [12]. These properties point to high gas pressures and chondrule densities that should have been high enough to cause gravitational collapse. How could dust clumps have been concentrated to this extent, then fortuitously melted and finally been mixed with primitive matrix dust prior to rapid accretion? By contrast, impact disruption of largely molten planesimals could provide transient dense clouds of droplets capable of retaining high Na concentrations. Such clouds are also consistent with the widespread occurrence of compound chondrules, and with chondrule cooling times of several hours inferred from the experimental replication of their textures. Dispersal of droplets after solidification near the periphery of the cloud would allow mixing of chondrules from different impacts and addition of primordial dust containing presolar grains from the nebula or unmelted planetesimal crusts.

The inferred accretion times for iron meteorite and chondrite parent bodies are entirely consistent with thermal models for ^{26}Al heating given the inferred initial concentration of ^{26}Al in CAIs. The insulated interiors of bodies that accreted <1.5 Myr after CAI formation and were >20 km in diameter potentially would have been melted completely by heat from ^{26}Al whereas bodies that accreted >1.5 Myr (~2 half-lives of ^{26}Al) after CAIs were heated but not completely melted, and those accreting after 2.2 Myr (~3 half-lives) could never have melted [13]. Importantly, during the period of chondrule formation between 1.5 and 2.5 Myr after CAIs, many early-accreted bodies would have been at their peak level of melting and ripe for generating cascades of chondrule spray on impact, with convectively mixed primitive magma oceans beneath thin (< 1 km) rigid crusts.

In this vein, FeO-poor, refractory (Type I) chondrules may be derived from partially molten bodies that accreted at high temperatures in the young, hot inner nebula, as proposed by [18], and their cores in some cases had evidently formed in the first 0.5 Myr [8].

Chondrites: Chemically most chondrites are similar to the Sun in terms of condensable elements, but not identical to it. L and LL chondrites have large deficits in siderophile elements, which plausibly is because the cores of merging molten planetesimals ended up mostly in the target body, with a complementary predominance of silicate in the chondrule-rich plume of ejecta that later accreted to the L and LL parent bodies. The molded chondrule shapes in some chondrites, described as hot accretion textures [14] may represent droplets that remained gravitationally bound to the target body [6] and fell back to it before having time to solidify fully. Many successive collisions may explain the wide variety of constituent grains in any chondrite, the approximation to primitve solar chemistry, and perhaps also the chemical complementarity between chondrules and matrix in some chondrites [15]. s

Chondrites and iron meteorites: A plausible explanation for the large number of iron meteorite parent bodies, and the lack of asteroid families from differentiated targets and associated mantle meteorites is that iron meteorites and other differentiated meteorites come from bodies that accreted early at 1-2 AU from the Sun [16]. The majority of these differentiated asteroids presumably ended up inside planets, but fragments of them, plus Vesta, plus an enormous volume of chondrule spray were scattered into the asteroid belt where chondritic asteroids accreted.

Asteroids: If ordinary chondrites represent S-type asteroids and carbonaceous chondrites are derived from C-type asteroids, then most asteroids accreted >2 Myr after CAIs. Since Jupiter was fully accreted in 5 Myr, we should expect to find that most meteorite parent bodies and asteroids accreted more quickly from the primordial disk. One possibile explanation is that the asteroid belt was emptied by Jupiter when it first migrated inwards to 1.5 AU and then returned to 5 AU after Saturn became trapped in the 2:3 resonance [17]. In this case, the chondritic asteroids may be products of a second epoch of planetesimal accretion. If chondrules are largely formed from impacts involving partly molten planetesimals, as argued above, then chondrites may have accreted when there was still enough nebula gas to concentrate impact debris from partly molten planetesimals.

In summary, chondrules, like magmatic iron meteorites, may be derived from a wide variety of differentiated planetesimals that accreted at 1-2 AU <1 Myr after CAIs formed. They may have been scattered into the asteroid belt and accreted 1-2 Myr before the metallic cores from which the irons were derived were fragmented and dispersed into the asteroid belt.

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