Prolonged duration and multiple mechanisms of chondrule formation

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Chondrule formation is one of the most important but still poorly understood processes in the early Solar System. Among the currently discussed mechanisms are shock waves of different nature [1] [2], collisions between differentiated planetesimals with or without chondritic crust [3] [4], and current sheets [5]. The Pb-Pb absolute ages of porphyritic chondrules from type 3 ordinary, CV3, and CR2 chondrites indicate that chondrule formation started contemporaneously with CAIs and lasted for ~4 Myr [6] [7]. The mineralogy, petrography, and O-isotope compositions of porphyritic chondrules (major type in most chondrites) suggest formation by incomplete melting of isotopically diverse solid precursors during highly localized transient heating events in various regions of the protoplanetary disk [8]. The chondrule precursors included refractory inclusions (e.g., [8] [9]), fragments of chondrules of earlier generations (e.g., [10]), matrix-like material (e.g., [11] [12]), and possibly fragments of pre-existing planetesimals [14]. These observations preclude formation of porphyritic chondrules by collision between differentiated planetesimals [3]; instead, they are consistent with nebular melting of dust balls by bow shocks [2] and current sheets [3]. Some porphyritic chondrules in type 4–6 ordinary chondrites (OCs) are enriched in coarse chromite [14], a metamorphic mineral that is absent in type 3 OCs. It is suggested that chromite-rich chondrules formed by impact melting of thermally metamorphosed OC material [14]. Magnesian non-porphyritic chondrules in CB and CH chondrites formed in an impact generated gas-melt plume ~5 Myr after CAIs, possibly in the debris disk [15–17]. Some porphyritic chondrules in CH chondrites appear to contain relict ^{16}O-depleted igneous CAIs that may have resulted from the impact plume event [18], and, therefore, might have postdated the impact. Formation of these chondrules by impact jetting [4] seems plausible. We conclude that there are multiple mechanisms of chondrule formation that operated during the accretionary and debris stages of the protoplanetary disk evolution.

[1] Desch *et al*. (2010) *ApJ* 725:692. [2] Morris *et al*. (2012) *ApJ* 752:27. [3] Asphaug *et al*. (2011) *EPSL* 308:369. [4] Johnson *et al*. (2015) *Nature* 517:339. [5] McNally *et al*. (2013) *ApJ* 767:L2. [6] Connelly *et al*. (2012) *Science* 338:651. [7] Bollard *et al*. (2014) *MAPS* 49:5234. [8] Krot *et al*. (2015) *LPSC* 46:1596. [9] Nagashima *et al*. (2015) *LPSC* 46:2477. [10] Kita *et al*. (2010) *GCA* 74:6610. [11] Nagashima *et al*. (2013) *LPSC* 44:1780. [12] Nagashima *et al*. (2015) *GCA* 151:49. [13] Libourel & Krot (2006) *EPSL* 251:232. [14] Krot & Rubin (1993) *LPSC* 24:827. [15] Krot *et al*. (2005) *Nature* 436:589. [16] Krot *et al*. (2014) *LPSC* 45:2142. [17] Bollard *et al*. (2013) *Min. Mag*. 77:732. [18] Krot *et al*. (2012) *GCA* 74:2190.