

MULTIPLE MECHANISMS OF TRANSIENT HEATING EVENTS IN THE PROTOPLANETARY DISK: EVIDENCE FROM PRECURSORS OF CHONDRULES AND IGNEOUS CA,AL-RICH INCLUSIONS.

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Porphyritic chondrules are the dominant textural type of chondrules in most chondrite groups. The mineralogy, petrography, and oxygen-isotope compositions of porphyritic chondrules suggest their formation by melting (often incomplete) of isotopically diverse solid precursors during localized transient heating events in different dust-rich regions of the accretionary disk characterized by ¹⁶O-poor average compositions of dust ($\Delta^{17}\text{O} \sim -5\text{‰}$ to $+3\text{‰}$). The chondrule precursors included Ca,Al-rich inclusions (CAIs), amoeboid olivine aggregates (AOAs), chondrules of earlier generations, fine-grained matrix-like material, and, may be, fragments of pre-existing thermally processed planetesimals. Reprocessing of refractory inclusions during formation of porphyritic chondrules resulted in their melting to various degrees, destruction of Wark-Lovering rims, gas-melt interaction, replacement of melilite by Na-bearing plagioclase, oxygen-isotope exchange, and transformation into Type C-like igneous CAIs and anorthite-rich chondrules [1]. Whether chondrule precursors were completely anhydrous or partially hydrated is not known [2]. These observations preclude formation of porphyritic chondrules by splashing of differentiated asteroids. Instead, they are consistent with melting of dust-balls during localized nebular transient heating events in the protoplanetary disk (PPD), such as bow-shocks [3] short circuits [4], and collisions between chondritic planetesimals [5].

Like porphyritic chondrules, coarse-grained igneous CAIs formed by melting, often incomplete, of isotopically diverse solid precursors during localized transient heating events [6, 7]. In contrast to porphyritic chondrules, the precursors of igneous CAIs consisted exclusively of refractory inclusions of earlier generations \pm ¹⁶O-rich forsterite-rich dust, and the melting occurred predominantly in an ¹⁶O-rich gas ($\Delta^{17}\text{O} \sim -24\text{‰}$) of approximately solar composition, most likely near the protoSun [8]. The U-corrected Pb-Pb absolute and ²⁶Al-²⁶Mg relative chronologies of igneous CAIs [9–11] indicate that the CAI melting events started at the very beginning of the PPD evolution and appear to have lasted up to 0.3 Ma after condensation of CAI precursors, providing clear evidence for very early transient heating events capable of melting refractory dust-balls in the innermost part of the PPD. Melting of CAIs may have resulted from their ejection from the inner solar accretion disk via the centrifugal interaction between the solar magnetosphere and the inner disk rim [12]. There is no evidence that chondrules were among the precursors of igneous CAIs, consistent with an age gap between CAIs and chondrules [11].

In contrast to typical chondrites, the CB chondrites contain exclusively magnesian non-porphyritic chondrules with skeletal olivine (SO) and cryptocrystalline

(CC) textures. These chondrules formed in an impact generated gas-melt plume about 5 Myr after CV CAIs, either in the late-stage accretionary disk or the debris disk [13, 14]. Bulk chemical compositions of CB chondrules and equilibrium thermodynamic calculations suggest that the collision involved differentiated bodies [15, 16]. However, the ¹⁵N-rich bulk compositions of CB chondrites and the presence of CAIs in CB chondrites suggest that some amount of chondritic material must have been reprocessed in the plume as well. The uniformly ¹⁶O-depleted igneous CB CAIs most likely formed by complete melting of pre-existing CAIs accompanied by gas-melt interaction in the plume [17]. Therefore, the uniformly ¹⁶O-depleted igneous CB CAIs are chondrules formed by melting of precursors composed entirely of the CAI-like material.

CH chondrites represent a mixture of the CB-like material (magnesian SO and CC chondrules and uniformly ¹⁶O-depleted igneous CAIs) and the typical chondritic material (magnesian, ferroan, and Al-rich porphyritic chondrules, uniformly ¹⁶O-rich CAIs, and chondritic lithic clasts). We infer that CH chondrites contain multiple generations of chondrules formed by different mechanisms [1, 17].

Some relict CAIs inside CH porphyritic chondrules are texturally (igneous, spinel-rich) and isotopically (uniformly ¹⁶O-depleted) similar to the CB-like CAIs, which are interpreted as a result of complete melting and oxygen-isotope exchange in the CB impact plume [1]. If this is the case, the CH porphyritic chondrules with the CB-like relict CAIs must have postdated the impact plume event. Formation of these chondrules by asteroidal impacts seems most likely. This mechanism may also be responsible for the formation of at least some chromite-rich chondrules in equilibrated ordinary chondrites [18], and sulfur-rich chondrules in unequilibrated Rumuruti chondrites [19].

We conclude that there are multiple mechanisms of transient heating events that operated during the accretionary and debris stages of the PPD evolution and resulted in formation of chondrules and igneous CAIs.

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