

## DID CHONDRULES FORM IN THE NEBULA?

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**Introduction:** Any model for chondrule formation must explain their abundance, range of textures (reflecting cooling rate and peak temperature), size distributions, elemental and O isotopic compositions, and the evidence for chondrules having undergone multiple heating events (e.g., relict grains and igneous rims). While most features of chondrules are consistent with formation in the nebula (i.e., protoplanetary disk), as opposed to on asteroidal surfaces or by collisions between planetesimals, there is no definitive evidence that this is where they formed. The case for a nebular origin is largely indirect, relying as it does on substantial objections to other proposed mechanisms [e.g., 1].

**Non-nebular models:** Volcanism on asteroids is unlikely to efficiently produce abundant chondrules, and cannot explain the range of O isotopic and elemental compositions or the evidence for multiple formation events. Impacts can produce chondrule-like objects (e.g., lunar spherules), but in cold targets (e.g., a regolith) most of the impact energy goes into fragmentation rather than melting. Hyper-velocity impacts between partially or fully molten planetesimals would probably produce copious amounts of chondrule-like objects. However, such bodies are likely to undergo rapid metal-silicate differentiation, and crystal-liquid fractionation in their mantles; there is no evidence for either process in chondrules. Collisions of such bodies are unable to explain the evidence for multiple heating events preserved in individual chondrules.

**Nebular models:** Nebular formation mechanisms are not without their problems. The differences in the physical, textural and chemical properties of chondrules from different chondrite groups, as well as the range of chondrule cooling rates, point to large but relatively localized formation events [2]. Preservation of these differences in a turbulent nebula requires chondrule formation shortly before accretion of the parent bodies [3]. In this context, and if it is real, the apparent 1-2 Ma range in ages of chondrules from a given meteorite [e.g., 4] are difficult to understand. The volatile element inventories and the lack of isotopic fractionation are also difficult to understand if chondrules formed under canonical nebular conditions because models and experiments predict substantial evaporation should occur at near-liquidus temperatures. In moderately dust-enriched environments ( $10^2$ - $10^3$ ×solar), re-equilibration between gas and chondrules should erase isotopic fractionations on reasonable timescales. The presence of moderately and highly volatile elements in chondrules would require that gas-chondrule exchange continue to low temperatures. However, our recent finding that Na was present in chondrules at current abundances even at near-liquidus temperatures [5] seems to require dust enrichments (order  $10^6$ - $10^7$ ×solar) that are hard to achieve with current nebular models.

**References:** [1] Taylor et al. 1983. In *Chondrules and their Origins* 262–278. [2] Cuzzi and Alexander 2006. *Nature* 441: 483–485. [3] Alexander 2005. In *Chondrites and the Protoplanetary Disk* 972–1002. [4] Kita et al. 2005. In *Chondrites and the Protoplanetary Disk* 558–587. [5] Alexander et al. 2007. Abstract #2012. 38th Lunar & Planetary Science Conference.