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Microgravity Controls Crystallization in Chondrule- and CAI-like Melts

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CAIs and chondrules record high-temperature processing in the early Solar System, but laboratory crystallization experiments under terrestrial gravity may not capture melt-transport conditions in weak-gravity environments [1,2]. We report paired levitation experiments on chondrule- and CAI-like compositions performed under sustained microgravity aboard the China Space Station [3] and in parallel ground-based runs under matched thermal and chemical conditions.

Despite comparable peak temperatures and cooling histories, products diverge systematically. In chondrule-like melts, microgravity favors forsterite while suppressing enstatite relative to 1g runs. In CAI-like melts, microgravity suppresses interior silicate crystallization, with spinel dominating while melilite and other major silicates are reduced or absent. These outcomes indicate that gravity primarily modifies crystallization kinetics rather than bulk phase stability.

To explain this contrast, we combine petrography with numerical modeling of partially molten droplets. Under 1g, residual surface crystals migrate and aggregate through gravity-driven capillary interactions (Cheerios-type), generating particle-enabled internal circulation. Under microgravity, this capillary coupling collapses and melt transport shifts to a weaker, Marangoni-dominated regime. Sensitivity tests show that crystal size and surface loading strongly modulate particle-driven advection, while crowding/collision effects at high surface coverage mainly cap the upper transport velocity rather than remove the Earth–microgravity contrast.

We then translate this transport-regime switch into a transport-controlled interfacial silica depletion factor and test it using a reaction-quotient framework at peak-temperature conditions. The inferred depletion windows reproduce the observed phase selectivity (e.g., olivine growth with suppressed pyroxene in chondrule-like melts, and inhibited silicate growth in CAI-like melts) without requiring any change in thermodynamic stability.

These results identify gravity-controlled melt transport as a first-order regulator of phase-selective crystallization in silicate droplets and provide a new framework for interpreting meteoritic mineralogies beyond thermal history alone.

Reference:

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[2] McClure, M. K. *et al.*(2025) Refractory solid condensation detected in an embedded protoplanetary disk. *Nature* **643,** 649–653.

[3] Zhang, P. *et al.*(2022) 1D and 3D co-simulation and self-adaptive position control of electrostatic levitation in China's Space Station. *npj Microgravity* **8,** 2