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Capillary-Mediated Interface Perturbations

Deterministic Pattern Formation

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Abstract Experiments in microgravity showed that the axial ratios of ellipsoidal 'needle' crystals fell by an order-of-magnitude (becoming spheroidal) when melting reduced their long axes below ca. 5 millimeters, and their diameters below ca. 500 micrometers. These dramatic shape changes and the tdeparture from self-similar melting were reported and ascribed to effects of capillarity. The origin of these unexpected shape changes at mesoscopic size scales is investigated in depth for both melting and crystal growth by applying the Reynolds transport theorem and using standard field-theory. Leibniz-Reynolds analysis identifies a 4^{th}-order capillary-mediated energy field that is responsible for shape changes observed during melting, and for interface speed perturbations during crystal growth. Field-theoretic principles also show that capillary-mediated energy distributions cancel over large length scales, but modulate the interface shape on smaller mesoscopic scales. Speed perturbations reverse direction at specific locations where they initiate inflection and branching on unstable interfaces, thereby enhancing pattern complexity. Simulations of pattern formation by several independent groups of investigators using a variety of numerical techniques confirm that shape changes during both melting and growth initiate at locations predicted from interface field theory. Finally, limit cycles occur as an interface and its capillary energy field co-evolve, leading to synchronized branching. Synchronous perturbations produce classical dendritic structures, whereas asynchronous perturbations observed in isotropic and weakly anisotropic systems lead to chaotic-looking patterns that remain nevertheless deterministic.

Keywords capillarity · thermodynamic fields · solid-liquid interfaces · diffusion-limited patterns · perturbations · dendritic branching

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