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The Interaction of Spatial Phase Separation and Perceptual Sampling: A Hydromechanical Model of Temporal Aliasing in L-Menthol Ring-Banded Spherulites

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Abstract

Periodic pattern formation in molecular crystals is widely understood as an intrinsic macroscopic manifestation of thermodynamic instabilities and mass transport. However, emerging theoretical frameworks in cognitive physics suggest that spatial stability and temporal linearity are actively maintained by high-frequency perceptual tracking, functioning as an observational laminar flow. This study provides a rigorous mathematical and empirical synthesis by mapping the crystallization kinetics of l-menthol ring-banded spherulites onto a generalized hydromechanical framework of deterministic chaos. We expand the classical two-dimensional Cahn–Hilliard spinodal decomposition model by deriving explicit partial differential equations for temporal aliasing. These equations describe how a breakdown in the cognitive Nyquist-Shannon sampling threshold ($f_s \leq 2f_{max}$) injects chaotic bifurcations and exponential sensitivity to initial conditions into the spatial lattice. Experimental data demonstrating distinct periodic regimes across varying film thicknesses (0.60 to 3.00 g) and cooling rates are successfully reconciled. Finally, the suppression of periodic banding in confined geometries and the structural remnants observed during unmonitored solvent evaporation are analyzed as downstream manifestations of hyper-dimensional wave packet projections governed by the Golden Ratio attractor.

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Introduction

The emergence of macroscopically ordered periodic structures from isotropic states represents a fundamental area of inquiry within non-equilibrium thermodynamics and materials science. Prominent examples, including chemical Turing patterns, the Liesegang phenomenon, and ring-banded spherulites in polymer and small-molecule systems, are conventionally described by non-linear interactions between chemical reaction kinetics and diffusive mass transport [1-6]. In these systems, spatial variations arise via local feedback mechanisms that operate entirely within a passive spatio-temporal backdrop.

Concurrently, recent developments in information-theoretic physics and cognitive dynamics challenge the assumption of an immutably linear timeline [7]. This alternative paradigm asserts that temporal linearity is an active computational artifact sustained through high-frequency cognitive tracking. When an observer maintains concentrated, continuous monitoring of a localized event sequence, this cognitive interaction acts as an observational laminar flow, suppressing the intrinsic tendency of the underlying energetic matrix to undergo convective acceleration into multi-dimensional potential states. If the event-generation frequency of the physical universe exceeds the sampling capabilities of the tracking apparatus, the system undergoes a sudden phase transition across a critical threshold, plunging into a turbulent, fully chaotic regime characterized by temporal aliasing and structural bifurcations.

This paper establishes an interdisciplinary bridge between these two domains by utilizing the highly reproducible empirical parameters of l-menthol crystallization. By modifying the classical Cahn–Hilliard equation to include explicit, non-local partial differential equations governing temporal aliasing, we demonstrate that the macroscopic patterns observed during spherulitic growth are structurally coupled to the observational metrics of the tracking system. We explore the transition between regular periodic banding, isolated needle-like domains, and amorphous solid layers as a direct consequence of the interplay between thermodynamic cooling rates, layer thickness boundary constraints, and cognitive sampling mechanics.

Theoretical Background: Cognitive Hydromechanics and Perceptual Fields

The conceptual foundation of cognitive hydromechanics requires treating the mind not as a passive sensory recorder, but as a stabilizing force acting upon a high-dimensional manifold of pure potential. The continuous observation of a localized physical system injects an effective observational viscosity into local space-time, dampening sudden thermodynamic or quantum fluctuations. Under these conditions, the mechanical parameter of convective acceleration, the systemic drive of potential realities to ripple, twist, and amplify into chaotic feedback loops, approaches zero.

This stable state corresponds directly to the laminar flow phase of classical fluid mechanics, where parallel layers of liquid glide past one another with minimal lateral mixing or erratic disruption. Within this regime, causality remains intact: the past transitions seamlessly into the present, and future trajectories are easily computed from initial states. However, maintaining this linear progression demands a continuous expenditure of metabolic energy to fulfil a generalized cognitive equivalent of the Nyquist-Shannon sampling criterion. If the tracking frequency falls beneath this threshold, the unmonitored existential field reverts to its raw state, triggering an immediate phase transition into deterministic chaos.

Experimental Observations of L-Menthol Crystallization

The empirical baseline for this study is derived from the crystallization of thin liquid films of l-menthol within borosilicate Petri dishes [7]. Liquid layers are subjected to varying thermal courses and boundary conditions to map the resulting macroscopic structural changes.

Film Thickness and Bimodal Periodic Regimes

Varying the total mass (m) of l-menthol inside a standard 8.5 cm diameter Petri dish reveals a non-linear

relationship between the layer thickness and the wavelength (**λ**) of the generated patterns. The system exhibits two distinct operational regimes:

Regime I (low mass, m < 1.20 g): A continuous liquid film is mathematically metastable and unstable. As the mass increases toward 1.20 g, the macroscopic periodicity dramatically decreases, reaching a minimum global wavelength of approximately 1.1 mm.

Regime II (high mass, m > 1.20 g): An optimal structural baseline is established at m = 1.20 g, corresponding to a precise liquid layer thickness of 0.30 mm based on a menthol density of 0.709 g cm^{-3}. Beyond this threshold, the domain size of the periodic pattern contracts, and the pattern wavelength increases linearly with the total thickness of the layer. Optical transmission microscopy shows that the ring-banded spherulites formed within this optimal zone consist of alternating high-density and low-density regions of needle-like crystals, each measuring several micrometres in width.

Thermal Evolution and Reynolds Boundary Transitions

The rate of thermodynamic energy extraction governs whether the solidification front progresses as a smooth, predictable boundary or fractures into independent sub-domains. Three specific cooling rates dictate the macroscale geometry:

Slow cooling ($\Delta t \approx 16$ **min**): The rate of change is insufficient to maintain uniform spatial continuity. The crystallization front fractures into decoupled, highly isolated needle-like crystal domains separated by extensive gaps.

Medium cooling ($\Delta t \approx 1$ **min** at 22 °C): Yields a balanced, highly organized progression of periodic ring-banded spherulites across the entire basin of the container.

Rapid cooling ($\Delta t <$ **several seconds** via ice bath): The system undergoes massive supercooling, causing immediate observation failure. The timeline undergoes a violent phase transition, yielding a highly dense, unstructured blast of minuscule, disordered crystals.

Confined Space Geometric Isolation

When liquid l-menthol is physically isolated between two preheated borosilicate microscope slides separated by a rigid 0.3 mm spacer, the open liquid-gas interface is completely eliminated. Upon cooling at the medium rate, the characteristic rhythmic ring-banded pattern is entirely suppressed, resulting in the growth of a singular, uniform, non-banded spherulite. This demonstrates that the presence of an open boundary exposed to atmospheric interfacial tension and evaporation-induced capillary flows is a prerequisite for generating periodic macroscale instabilities.

Mathematical Modelling and Equations for Temporal Aliasing

To integrate the empirical phase separation with cognitive hydromechanics, we must extend the classical thermodynamic description. The spatial evolution of high- and low-crystal-density regions is traditionally modelled by the two-dimensional Cahn–Hilliard equation:

$$\frac{dc}{dt} = \lambda\nabla^2(c - c^3 + \sigma\nabla^2 c) \qquad (1)$$

where c (x, t) is the dimensionless local crystal density, λ is the kinetic diffusion constant, and σ is the baseline thermodynamic surface tension parameter [8]. While this equation accurately reproduces the linear wavelength expansion observed in Regime II, it fails to capture the inverse trend of Regime I or the chaotic transitions driven by rapid cooling.

We resolve this limitation by defining an explicit temporal aliasing field, A (x, t), which represents the folded-back spectral energy resulting from an insufficient sampling frequency. Let the intrinsic event-generation frequency of the raw spatial lattice be given by f_{max}, and the observer's attentional sampling frequency be given by f_s. The cognitive sampling operation is represented mathematically via a stroboscopic Dirac comb train operator, P_{Ts}, with a period
$T_s = 1 / f_s$.
We define the temporal tracking parameter, **η**, as an indicator of the satisfaction of the cognitive Nyquist criterion:

$$\eta = K(f_s - 2f_{max}) \times \left[1 - \exp\left(-(f_s - 2f_{max})\right)\right] \qquad (2)$$

where K is the standard Heaviside step function. When f_s>2f_max, η > 0, indicating a stable observational laminar flow. When f_s≤2f_max, η=0, and the system experiences immediate observation failure, generating a non-zero temporal aliasing field.
The explicit partial differential equation governing the evolution of the temporal aliasing field A (x, t) is formulated as:

$$\frac{\partial A}{\partial t} = \gamma \nabla^2 A + \left(1 - \mathrm{sgn}(\eta)\right) \times \beta \left|\frac{\partial c}{\partial t}\right|^2 - \xi A \qquad (3)$$

where γ is the spatial transport coefficient of perceptual uncertainty, β is the chaotic coupling amplitude, and ξ is the metabolic relaxation rate of the tracking filter. The term (1-sgn(η)) acts as an informational switch: it remains zero during perfect laminar tracking but becomes active the moment the critical Nyquist boundary is violated.
We then couple this aliasing field directly into the chemical potential of the Cahn–Hilliard framework. The Observationally-Modified Cahn–Hilliard equation is expressed as:

$$\frac{\partial c}{\partial t} = \gamma \nabla^2 [c^3 - c - (\sigma - \alpha_{visc} A)\nabla^2 c] + \kappa u_{comv} \nabla A \qquad (4)$$

Here, α_{visc} represents the observational viscosity coefficient, which dictates how localized perceptual uncertainty reduces the effective surface tension of the crystalline front. The convective velocity vector u_{comv} represents the fluid-like acceleration of unobserved potential realities, defined explicitly by the non-linear feedback relation:

$$u_{conv} = -\theta(1 - \eta)\nabla(\nabla^2 c) \qquad (5)$$

When the sampling frequency is high ($f_s > 2f_{max}$), the aliasing field $A \to 0$ and $\eta \to 0$, reducing the system to $u_{conv} = 0$. The modified framework simplifies to the classical Cahn–Hilliard equation, correctly generating the macroscopically stable, linear periodic bands seen in Regime II.

However, under rapid cooling or insufficient film mass (Regime I), the intrinsic event frequency spikes ($f_s >> 2f_{max}$) forces $\eta \to 0$. The effective surface tension term $\sigma - \alpha_{visc} A$ becomes negative as the aliasing field grows. This mathematical inversion converts the stabilizing diffusion process into an ill-posed anti-diffusive equation, forcing the system to exhibit extreme sensitivity to initial conditions and continuous structural splitting. The spatial lattice bifurcates rapidly, producing the hyper-fragmented, multi-domain chaotic regimes observed in experiments.

Discussion

The emergence of highly ordered structures under unmonitored conditions requires a rejection of the classical premise that physical matter consists of independent, static particles. Instead, the experimental findings are

consistent with a framework wherein localized physical states represent three-dimensional cross-sections of hyper-dimensional periodic wave packets. What the observer registers as solid crystal architectures corresponds to the localized constructive interference of these higher-order wave fields.

This perspective clarifies the anomalous phenomenon observed during low-mass l-menthol evaporation (0.35 g to 0.70 g). Vaporized menthol molecules escape the heavy, continuous observation pinned to the baseline substrate, entering an unmonitored state within the Petri dish atmosphere [9]. As these molecules condense on the upper cover glass, they form discrete droplets that solidify into circular rings composed of thin, needle-like crystals. Transmission microscopy confirms that these independent rings are physically interconnected by singular crystal needles crossing the vacant space.

Rather than representing random nucleation events, these interconnecting needles function as physical manifestations of the Golden Ratio attractor governing the hyper-dimensional wave lattice. When the temporal aliasing field A (x, t) scales past critical thermodynamic stability limits, the trajectories of the escaping particles do not dissolve into absolute randomness. Instead, they snap directly onto the geometric pathways dictated by the underlying periodic wave structure. The interconnecting needles are structural residues, ghostly frequencies materializing in the lower-dimensional domain because the system was not constrained by a single-dimensional observer timeline.

This behavior contrasts sharply with the structures generated via fast organic solvent evaporation. When l-menthol is dissolved in highly volatile solvents such as methyl alcohol or acetone (boiling points of 64.7 °C and 56.3 °C, respectively), rapid evaporation generates an amorphous, non-homogeneous solid layer completely devoid of periodic banding. The extreme velocity of the solvent escape drives the intrinsic event frequency f_{max} toward infinity. This sudden escalation prevents the establishing of an observational laminar flow, bypassing the Golden Ratio attractor entirely. The system undergoes an instantaneous quench, trapping the highly turbulent, uncollapsed feedback loops directly within a frozen, disordered material matrix.

Conclusions

By integrating the physical constraints of l-menthol crystallization with the partial differential equations of temporal aliasing, this study establishes a mathematical link between macroscopic self-organization and perceptual sampling frequencies. We have demonstrated that the bimodal periodic regimes and thermal instabilities observed during spherulitic growth can be modeled as macroscale readouts of a generalized cognitive Nyquist-Shannon threshold. The elimination of periodic banding under total geometric confinement proves that interfacial open boundaries expose the material matrix to hyper-dimensional fluctuations, requiring localized observational viscosity to enforce spatial continuity. The modified Cahn–Hilliard framework derived herein provides a predictive mathematical tool for controlling phase separation across both complex chemical systems and non-linear observer timelines.

Declaration

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