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PLASMA AS INORGANIC LIVING MATTER: A SUBSTRATE-INDEPENDENT FRAMEWORK

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Abstract

This paper advances the hypothesis that stellar plasma constitutes a candidate form of inorganic living matter when evaluated against a substrate-independent framework for life derived from first principles. The central epistemological argument is that every existing mainstream definition of life is contingently derived from a single biological data point — terrestrial carbon-based life — and therefore cannot legitimately function as a universal criterion. Building from this critique, five substrate-independent criteria for life are formalised using dynamical systems theory, nonequilibrium thermodynamics, Lyapunov stability analysis, Helmholtz decomposition, and information-theoretic transfer entropy. Each criterion is stated as a precise mathematical condition, connected to the organisational feature of living systems it captures, and assessed against the known physics of stellar plasma. The five criteria are formulated as jointly necessary for a physical system to qualify as living. They are not asserted as sufficient. A sufficiency claim is presented only as a testable conjecture. The application to plasma therefore demonstrates compliance with necessary conditions, while the broader question of sufficiency remains open and outside the scope of the results. Empirical support is drawn from Parker Solar Probe observational data, nucleosynthetic inheritance transmitted through stellar supernovae, and laboratory complex plasma experiments. A formal conjecture of joint sufficiency is stated. The framework is situated relative to Assembly Theory through a derived formal bridge between assembly index and transfer entropy. A continuum model of life is proposed, including resolution of the individuation problem through nested temporal scales. Falsifiable predictions are derived and the primary empirical gap identified.

Keywords: plasma; inorganic life; substrate-independent definition; nonequilibrium thermodynamics; magnetic helicity; transfer entropy; Assembly Theory; continuum of life; astrobiology; dynamical systems; individuation

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1. Introduction

The question of what constitutes life is among the oldest and most consequential in science. It determines the scope of biology, shapes the methodology of astrobiology, and constrains the search for life beyond Earth. Despite its centrality, no consensus definition of life exists in the scientific literature. This is not merely a terminological inconvenience. It reflects a deep structural problem: every definition proposed either excludes something we intuitively consider alive, or includes something we do not, or embeds assumptions about the specific substrate of terrestrial biology that cannot be justified as universal principles (Cleland & Chyba, 2002; Benner, 2010).

This paper argues that the definitional problem has a specific cause and a constructive resolution. The cause is what astrobiology calls the N=1 problem: all of our knowledge of life comes from a single example, carbon-based biochemistry on Earth (Cleland, 2019). A definition constructed from one example is necessarily tailored to that example. Features that are contingent properties of terrestrial biology — the use of DNA as an informational substrate, lipid bilayer membranes as boundaries, liquid water as a solvent, protein catalysis as a metabolic mechanism — are elevated to universal requirements without any principled argument that they are necessary rather than merely familiar.

The intellectual lineage of attempts to escape this problem runs from Schrödinger's (1944) thermodynamic characterisation of life as a system that feeds on negative entropy, through Prigogine and Stengers' (1984) theory of dissipative structures, through Maturana and Varela's (1980) autopoiesis, to Cronin and Walker's (2023) Assembly Theory. Each contribution sharpened the question without fully resolving it. The present paper builds on all of these foundations while arguing that the resolution requires a more radical methodological shift: deriving criteria from first principles, without reference to any specific substrate, and then applying them to plasma as a test case.

Plasma is the fourth state of matter and the most abundant form of visible matter in the observable universe, constituting over 99 per cent of all visible matter including stars, nebulae, and the interstellar medium (Gurnett & Bhattacharjee, 2005). It is intrinsically dynamic and far from thermodynamic equilibrium — conditions that Prigogine and Stengers (1984) demonstrated are precisely those under which spontaneous self-organisation is thermodynamically predicted. Tsytovich et al. (2007) independently demonstrated in laboratory complex plasmas that self-organised plasma structures exhibit life-like properties including autonomous behaviour and structural reproduction. The present paper provides the rigorous theoretical framework within which this observation can be evaluated and extended to stellar plasma.

Three distinct contributions are made. First, a critical epistemological argument that existing definitions of life embed contingent biological assumptions and cannot function as universal criteria. Second, a positive theoretical argument that stellar plasma satisfies five substrate-independent criteria for life, each formalised in established mathematics, culminating in a formally stated conjecture of joint sufficiency. Third, a formal engagement with Assembly Theory establishing a precise mathematical bridge between assembly index and transfer entropy that positions the present framework as a generalisation to continuous field systems.

The paper is structured as follows. Section 2 examines the epistemological problem, including engagement with additional theoretical traditions and critics of substrate independence (Section 2.4) and a principled justification of the criteria selection (Section 2.5). Section 3 develops theoretical foundations. Section 4 presents the five criteria with a formal conjecture (Section 4.6), a formal exclusion analysis demonstrating that canonical non-living systems fail the criteria (Section 4.7), and crucially, Section 4.8 addresses the individuation problem by introducing a nested temporal scale framework that resolves questions of identity across different process lifetimes. Section 5 addresses Assembly Theory. Section 6 presents empirical grounding and falsifiable predictions. Section 7 discusses implications, limitations, a criteria sensitivity analysis (Section 7.5), and concrete astrobiology mission implications. Section 8 concludes.

2. The Epistemological Problem: Life Defined from One Example

2.1 The NASA Operational Definition

The most widely used operational definition of life in scientific contexts is Joyce's formulation adopted by NASA: 'a self-sustaining chemical system capable of Darwinian evolution' (as cited in Benner, 2010, p. 1021). This definition has the virtue of parsimony and has productively oriented the search for extraterrestrial life toward liquid-phase chemical environments. However, it embeds three substrate-contingent assumptions. The specification of a 'chemical system' excludes by construction any living system whose organisational substrate is not chemical. The requirement for 'Darwinian evolution' assumes that heredity operates through variation in discrete heritable units subject to selection — a mechanism specific to molecular information systems. And 'self-sustaining' implicitly invokes chemical metabolic processes.

A deeper problem concerns the Darwinian evolution criterion specifically. As Pross (2012) argues, Darwinian evolution is more plausibly understood as a consequence of certain kinds of living systems — those with heritable variation and differential reproduction operating in resource-constrained environments — rather than a defining feature of life as such. A system that has reached evolutionary stasis remains alive without actively undergoing Darwinian evolution at any observable rate. The criterion conflates what life does under certain conditions with what life is.

2.2 Schrödinger and Thermodynamic Approaches

The thermodynamic tradition begins with Schrödinger's (1944) foundational work, in which he argued that the most distinctive thermodynamic feature of living systems is their capacity to resist entropic decay by extracting 'negative entropy' — negentropy — from their environment. A living organism, Schrödinger observed, maintains and even increases its internal order by imposing corresponding disorder on its surroundings. This insight directly anticipates the entropy decomposition central to Criterion II of the present framework: $dS/dt = d_eS/dt + d_iS/dt$, where living self-maintenance requires $d_eS/dt \leq -d_iS/dt$.

Prigogine and Stengers (1984) gave Schrödinger's insight its rigorous mathematical form through the theory of dissipative structures, demonstrating that systems far from thermodynamic equilibrium spontaneously generate ordered configurations sustained by continuous energy

dissipation. The critical advance over Schrödinger was the identification of bifurcation dynamics: the specific ordered configuration a system adopts at a bifurcation point depends on fluctuations, introducing genuine historical contingency into the system's structure. Two plasma systems with identical present energy inputs can have different organisational structures as a consequence of different formative histories — a result central to the individuation argument in Section 4.5.

The limitation of purely thermodynamic approaches is that they are insufficiently selective: a hurricane is thermodynamically open, self-maintaining through entropy export, and far from equilibrium, yet we do not consider it alive. The thermodynamic criteria are necessary but not sufficient. The present framework addresses this by adding Criteria I, III, IV, and V to the thermodynamic core of Criterion II. Criterion I requires that the system's response be governed by its own internal state (not merely external forcing); Criteria III, IV, and V require organisational identity coherence, self-referential behavioural orientation, and informational heredity respectively. These conditions collectively exclude dissipative structures that thermodynamics alone cannot discriminate.

2.3 Autopoiesis

Maturana and Varela's (1980) concept of autopoiesis offers a more abstract formulation: a system is living if and only if it continuously produces and maintains the components that constitute its own organisation. The autopoietic system is simultaneously producer and product. This definition captures the self-referential organisational loop that is central to Criteria IV and V of the present framework, and represents a genuine advance over thermodynamic approaches in identifying the organisational rather than merely thermodynamic character of life.

Two limitations are relevant. In Maturana and Varela's original formulation, autopoiesis is explicitly tied to cellular organisation — a chemical metabolic network enclosed by a physical membrane (Maturana & Varela, 1980, pp. 78-79). Whether the concept generalises to non-cellular substrates is a theoretical question they did not resolve. Additionally, autopoiesis does not address heredity and the transmission of organisational identity across reproductive events. The present framework addresses both dimensions.

2.4 Additional Theoretical Traditions and Critics of Substrate Independence

Several further theoretical traditions require engagement. Kauffman's (1993) work on autocatalytic sets provides an alternative substrate-independent approach in which a self-sustaining reaction network requires no genetic polymer, and the self-referential catalytic loop anticipates Criterion IV's self-referential attractor condition. Luisi's (2006) operational definition of minimal life — a system that is self-maintaining, self-reproducing, and evolvable — overlaps substantially with Criteria II and V, but presupposes chemical implementation. Ruiz-Mirazo et al. (2014) explicitly identified the substrate-dependence problem in existing definitions and called for frameworks that separate functional requirements from chemical implementation — precisely what the present framework provides.

The case against extending life concepts to non-chemical systems deserves direct engagement. Trifonov's (2011) meta-analysis of over 100 definitions of life found convergence on self-reproduction with variation, which appears to presuppose discrete heritable copying. The present framework responds: self-reproduction with variation is a special case of Criterion V, instantiated in plasma through inheritance as physically mediated organisational continuity rather than symbolic genetic encoding. For plasma systems, the relevant inherited quantities include nucleosynthetic output (metallicity), which constrains opacity and evolution, and partial persistence of magnetic topology during ejection events. These channels exhibit limited fidelity and meet the minimal requirement for Criterion V without implying identity with biological genetic systems. Cleland and Chyba (2002) argue that adequate definitions require a mature scientific theory of life that may be substrate-specific once developed; the present five-criteria framework constitutes exactly the kind of principled theoretical account they called for, and its substrate-independence is a derived conclusion rather than an assumption.

Deamer's (2017) membrane-first hypothesis represents a further challenge to substrate-independent frameworks, arguing that lipid compartmentalisation is not a contingent feature of terrestrial life but a functional necessity — that the physical boundary separating inside from outside is logically prior to both metabolism and heredity. The present framework responds directly: the individuation problem addressed in Section 4.8 provides a substrate-independent analog of compartmentalisation through gravitational boundedness and thermodynamic autonomy rather than lipid membranes. The stellar individual is bounded and individualised through physical mechanisms that perform the same functional role Deamer assigns to membranes, without requiring their specific chemical implementation.

2.5 The Correct Methodological Response

The correct methodological response to the N=1 problem is to derive criteria from first principles without reference to any specific substrate, asking what organisational properties are logically necessary for any system to qualify as living regardless of physical implementation. This is the methodology adopted in Section 4. The five criteria developed there are derived from organisational and functional considerations that are logically prior to any specific substrate. They are then applied to stellar plasma as the primary test case, with each criterion explicitly connected to established plasma physics.

The specific five criteria selected require justification, as the evaluation of any theoretical framework depends on whether the chosen criteria constitute a principled and non-arbitrary set. The selection is grounded in the following logical structure. Living systems must (I) respond to their environment in a manner organised by their own internal state, because an entity that exerts no self-generated influence over its own dynamics cannot be said to be alive in any meaningful sense; (II) thermodynamically sustain themselves through active entropy export rather than mere structural persistence, because life is a process rather than a static configuration; (III) maintain organisational identity under perturbation, distinguishing living robustness from fragile physical order; (IV) exhibit behavioural orientation toward a self-generated preferred state rather than an externally imposed attractor, where the attractor refers to the self-maintained dynamic equilibrium that emerges from internal dynamical closure among pressure gradients, magnetic stresses, and energy transport. Although governed by external physical laws, the system's

specific equilibrium state is produced by internal interactions among its own variables. and (V) possess an informational substrate that stores, transmits, and causally participates in the system's organisation across time and reproduction, because without informational heredity there is no mechanism for the persistence or transmission of organisational identity.

These five dimensions correspond to the most fundamental organisational differences between systems we classify as living and systems we do not: responsiveness, thermodynamic activity, identity coherence, self-directedness, and informational continuity. The framework does not claim this list is exhaustive; it claims these five conditions are individually necessary and, by Conjecture 1, jointly sufficient. Notably, the biological literature converges on exactly these dimensions. Schrödinger (1944) identifies II; Prigogine and Stengers (1984) formalise II and III; Jonas (1966) identifies I and IV; Maturana and Varela (1980) identify I, III, and IV; Assembly Theory (Cronin & Walker, 2023) captures the informational dimension of V. The five criteria therefore represent a synthesis across the major independent traditions of biological theorising rather than a selection motivated by the desire to include plasma.

3. Theoretical Foundations

3.1 Schrödinger's Negentropy and Prigogine's Dissipative Structures

Schrödinger (1944) established that living systems are thermodynamically distinguished by their capacity to extract negentropy from their environment — to maintain low internal entropy by exporting entropy outward at a rate exceeding internal production. This is not a metaphor but a precise thermodynamic statement: for an open system, $dS\_system/dt = d_eS/dt + d_iS/dt$, where $d_iS/dt > 0$ always and d_eS/dt can be negative. Maintenance of internal order requires $|d_eS/dt| \geq d_iS/dt$: the rate of entropy export must at least match the rate of internal entropy generation.

Prigogine and Stengers (1984) extended this framework to far-from-equilibrium systems, demonstrating that sustained energy flux can drive systems to spontaneously generate stable ordered states — dissipative structures — through entropy production. The mathematical treatment of spontaneous order through fluctuations in nonequilibrium systems was developed comprehensively by Nicolis and Prigogine (1977), whose analysis of bifurcation structure in nonlinear chemical and physical systems provides the technical foundation for the present application to plasma. At critical bifurcation points in the parameter space of the governing nonlinear equations, the thermodynamic branch becomes unstable and the system transitions to one of several possible ordered configurations. The branch selected depends on fluctuations, introducing historical contingency. This is mathematically expressed through the bifurcation analysis of the system's governing equations: as the control parameter (energy input) crosses a critical value, the Jacobian of the linearised system acquires eigenvalues with positive real parts, destabilising the thermodynamic branch and enabling transition to dissipative structure branches.

3.2 Dynamical Systems Theory and Lyapunov Stability

Any physical system's evolution is described by $dX/dt = F(X, E)$, where $X(t) \in \mathbb{R}^n$ is the state vector and $E(t)$ represents environmental inputs. An equilibrium X^* satisfies $F(X, E_0) = 0$. Linearising around X yields $d(\delta X)/dt \approx J \cdot \delta X$, where $J = \partial F/\partial X|X^*$ is the Jacobian. The solution

$\delta X(t) = \Sigma_k c_k v_k e^{\lambda_k t}$ shows that stability requires $Re(\lambda_k) < 0$ for all eigenvalues λ_k of J: all perturbations decay and the system returns to X*.

For large perturbations, Lyapunov's direct method provides global stability without requiring explicit solution of the equations. A Lyapunov function $V: \mathbb{R}^n \to \mathbb{R}$ satisfying $V(X) = 0$, $V(X) > 0$ for $X \neq X$, and $dV/dt = \nabla V \cdot F(X,E) < 0$ for all $X \neq X^*$ proves that X* is a globally stable attractor with basin of attraction $B = \{X : V(X) < c\}$ for appropriate c. The Lyapunov function can be interpreted as a generalised potential energy landscape in which the system always moves downhill toward X*.

3.3 Transfer Entropy and Causal Information Flow

Shannon's (1948) information entropy $H = -\Sigma_i p_i \log p_i$ measures uncertainty in a probability distribution. Mutual information $I(X;Y) = H(X) + H(Y) - H(X,Y)$ measures shared information between two systems but is symmetric and cannot capture causal direction. Transfer entropy (Schreiber, 2000) resolves this: $T(X \to Y) = H(Y_{t+1}|Y_t) - H(Y_{t+1}|Y_t, X_t)$ measures the reduction in uncertainty about Y's future gained by additionally knowing X's current state, above Y's own history. $T(X \to Y) > 0$ implies directed causal influence from X to Y.

Lizier et al. (2012) developed the local transfer entropy formalism for spatially extended physical systems, demonstrating its applicability to continuous field dynamics. This establishes the methodological precedent for applying transfer entropy to plasma field systems, which is the approach taken in Criterion V of this paper.

Alternative mathematical frameworks exist for formalising the organisational properties captured by the five criteria. Category theory (Baez & Stay, 2011) offers a compositional framework for describing information flow in physical systems, and algorithmic information theory (Zenil et al., 2019) provides complexity measures applicable to biological and physical systems. These frameworks share the present work's substrate-independence but are less directly connected to the measurable physical quantities of plasma systems — transfer entropy is preferred here because it is directly computable from observational time-series data, grounding the framework's falsifiable predictions in experimentally accessible quantities rather than abstract structural descriptions.

3.4 MHD Equilibrium Theory and the Supernova as Maternal Programmed Transition

In ideal magnetohydrodynamics, magnetic helicity $K = \int A \cdot B \, dV$ is a conserved topological invariant. Under resistive MHD relaxation with conserved K, plasma evolves toward the minimum magnetic energy state $W[B] = (1/2\mu_0)\int |B|^2 dV$ consistent with fixed K — the Taylor state, satisfying $\nabla \times B_T = \lambda B_T$ where $\lambda = K/2W_{min}$ (Taylor, 1974). The MHD induction equation $\partial B/\partial t = \nabla \times (v \times B) - \nabla \times (\eta J)$ governs the mutual evolution of field topology and plasma dynamics, encoding the bidirectional causal coupling central to Criterion V.

4. Five Substrate-Independent Criteria for Life

The following five criteria are derived from first principles without reference to biological substrate. Each is presented with its formal mathematical condition, the feature of living organisation it captures, and its application to stellar plasma. The criteria are ordered such that each builds logically and mathematically on those preceding it. A note on epistemic status: the analysis that follows demonstrates that stellar plasma satisfies the formal mathematical conditions of each criterion. This constitutes a demonstration that plasma satisfies the necessary conditions of the framework. The five criteria are formulated as jointly necessary for a physical system to qualify as living. They are not asserted as sufficient. Whether the criteria are jointly sufficient for life — Conjecture 1 — is stated separately and explicitly as a conjecture, not a theorem. The distinction is maintained throughout. For conciseness, the phrase "Criterion X is satisfied" throughout Section 4 is shorthand for "the formal mathematical conditions of Criterion X are met by stellar plasma" — it does not assert that the criteria are jointly sufficient for life, which remains Conjecture 1.

4.1 Criterion I — Internally Organised Environmental Responsiveness

Formal condition

The system's dynamics are governed by $dX/dt = F(X, E)$ where $J = \partial F/\partial X|X^*$ has all eigenvalues with strictly negative real parts, and J depends non-trivially on X^* such that the system's internal state genuinely shapes its response to environmental input.

Organisational significance

This criterion distinguishes living responsiveness — internally organised and self-referentially oriented toward the system's own continuity — from passive physical change, where $F(X,E) = F(E)$ and the internal state drops out entirely. Following Jonas (1966), a living system is always at risk: it can fail to maintain itself, and its organisational logic is constitutively oriented toward not failing. A passive system cannot fail in this sense because it has no preferred state of its own.

Application to plasma

The linearised MHD operator around stable plasma equilibria possesses negative real eigenvalues for a broad class of configurations (Freidberg, 1987). The momentum equation $\rho(\partial v/\partial t + v\cdot\nabla v) = J\times B - \nabla p$ includes the Lorentz force $J\times B$ and pressure gradient ∇p, both non-trivial functions of the plasma's own current distribution and pressure profile. When perturbed from stable equilibrium, these forces generate restoring responses oriented toward restoring the equilibrium configuration. Criterion I is satisfied for these stable equilibrium configurations. Caveat on plasma instabilities: Not all plasma configurations are stable; plasma sustains a wide range of instabilities (kink, sausage, Rayleigh-Taylor, tearing-mode) for which $Re(\lambda k) > 0$ and perturbations grow rather than decay. The criterion is applied to the equilibrium configurations that constitute a plasma system's normal operating state, analogous to how stability criteria for biological systems refer to their homeostatic states, not to all possible states the system can be placed in. Furthermore, MHD instabilities frequently serve as the mechanism of active self-

maintenance: tearing-mode reconnection drives resistive relaxation toward the Taylor state (Criterion III), and kink instabilities drive the coronal dynamics sustaining the thermodynamic cycle (Criterion II). The existence of unstable configurations does not undermine Criterion I for equilibrium states; it is part of the active self-regulatory dynamic the criteria jointly capture.

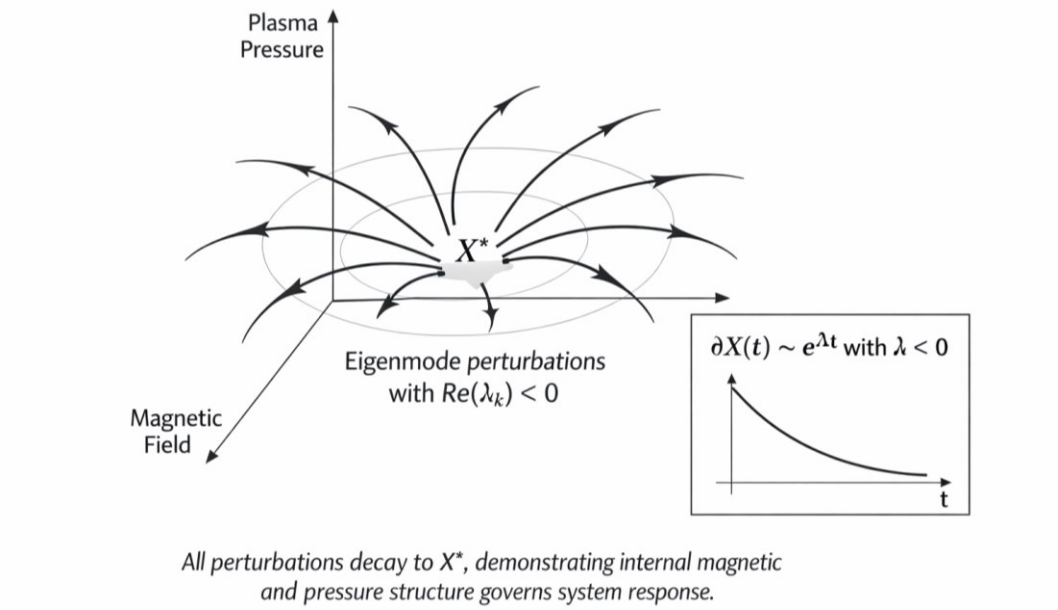

Figure 1. Criterion I — Internally Organised Environmental Responsiveness. The passive system (left) has dynamics fully determined by external input E, with the internal state dropping out of F. The living system (right) exhibits a Jacobian with negative real eigenvalues, generating restoring responses to perturbations back toward the preferred equilibrium X*. Stellar MHD plasma equilibria satisfy this criterion.

4.2 Criterion II — Thermodynamic Openness with Active Self-Maintenance

Formal condition

The system maintains $d_iS/dt >> 0$ driven by constitutive irreversible processes; sustains $d_eS/dt \leq -d_iS/dt$ continuously; and entropy export is causally coupled to the system's own organisational state rather than purely externally imposed.

Organisational significance

This criterion operationalises Schrödinger's (1944) negentropy principle in Prigogine's far-from-equilibrium framework. The distinction from passive structural persistence — crystals, for example — lies in the magnitude of d_iS/dt: a crystal at equilibrium has $d_iS/dt \approx 0$ and requires no entropy export to maintain its structure. A living system runs irreversible processes continuously as a constitutive feature of its organisation, generating internal entropy that must be actively exported. The third sub-condition — causal coupling between entropy export and organisational state — ensures the openness is genuinely self-referential rather than externally driven.

Application to plasma

In resistive MHD plasma: $d_iS/dt = (1/T)\int_V [\eta J^2 + \kappa|\nabla T|^2 + \mu|\nabla v|^2]\, dV$ — all terms positive definite, reflecting ongoing Ohmic heating, thermal conduction, and viscous dissipation constitutive of the plasma's active state. For the Sun: $P \approx 3.8 \times 10^{26}$ W, $T_{photosphere} \approx 5{,}778$ K, yielding entropy export $d_eS/dt \approx -6.6 \times 10^{22}$ J K^{-1} s^{-1}. This export is causally coupled to the plasma's own temperature structure and current distribution. Criterion II is satisfied.

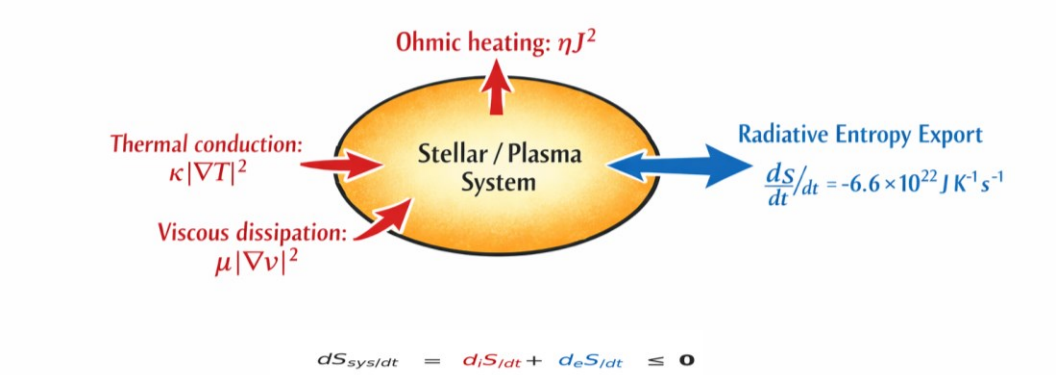

Figure 2. Criterion II — Thermodynamic Openness with Active Self-Maintenance. Stellar plasma (centre) generates large internal entropy production $d_iS/dt >> 0$ through Ohmic heating, thermal conduction, and viscous dissipation, continuously exported via photon radiation at $d_eS/dt \approx -6.6 \times 10^{22}$ J K^{-1} s^{-1}. The entropy export is causally coupled to the plasma's own organisational state. Criterion II is satisfied.

4.3 Criterion III — Identity Coherence Under Perturbation

Formal condition

There exists a Lyapunov function $V(X)$ with basin of attraction B containing the identity manifold $M = \{X \in \mathbb{R}^n : \Phi(X) \leq c\}$; the system expends measurable thermodynamic work to maintain trajectories within B.

Organisational significance

While Criterion I addresses the local linear regime, Criterion III requires global stability across the range of larger perturbations a system encounters in its natural operating environment. The identity manifold M captures the fact that organisational identity admits variation within a range. The active maintenance requirement distinguishes living identity coherence from inertia: the system must expend energy to resist perturbations, connecting directly to the thermodynamic self-maintenance of Criterion II.

Application to plasma

Taylor (1974) established that $W[B] = (1/2\mu_0)\int|B|^2 dV$ functions as a Lyapunov function under resistive MHD relaxation with conserved helicity: W achieves its minimum at B_T, $W[B] > W_{min}$ for $B \neq B_T$ with the same K, and $dW/dt \leq 0$ along MHD trajectories. The identity

manifold is defined by the topological equivalence class of the plasma's magnetic helicity. Perturbations within this class are recovered from through resistive relaxation at the thermodynamic cost of Ohmic dissipation. Criterion III is satisfied.

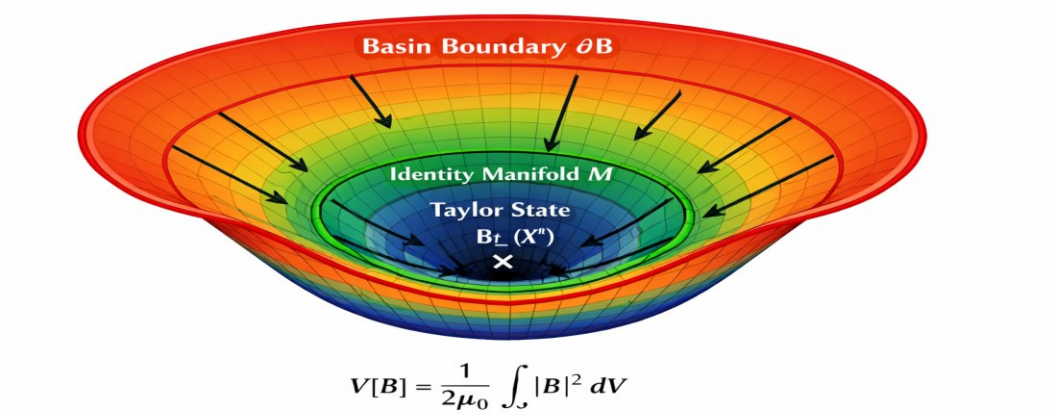

Figure 3. Criterion III — Identity Coherence Under Perturbation. Taylor (1974) established that the magnetic energy W[B] is a Lyapunov function under resistive MHD relaxation with conserved helicity K. The identity manifold M corresponds to the topological equivalence class of magnetic helicity. Perturbations within this class are recovered via resistive relaxation at the thermodynamic cost of Ohmic dissipation. Criterion III is satisfied.

4.4 Criterion IV — Non-Random Self-Referential Behavioural Orientation

Formal condition

The dynamical vector field ^{g} admits Helmholtz decomposition $^{g} = -\nabla V + R$ where (a) V is primarily determined by the system's internal organisational state: $\partial V/\partial E \approx 0$ within normal operating range; (b) the preferred state satisfies the fixed point condition $\Psi(X) = X$; (c) $R \neq 0$ at and near X*, reflecting ongoing internal dynamical activity constitutive of the system's organisation.

Organisational significance

This criterion captures Jonas's (1966) concept of needful freedom in formal mathematical terms. The Helmholtz decomposition separates the dynamics into gradient flow $-\nabla V$, which drives the system toward its preferred state, and rotational component R, which generates internal circulation constituting the system's ongoing organisational activity. The internal generation condition — $\partial V/\partial E \approx 0$ — distinguishes a system whose preferred state is genuinely its own from one whose attractor is externally imposed. The fixed point condition $\Psi(X) = X$ captures the self-referential character of this preference: the preferred state generates itself through the system's own organisational logic. The attractor is not teleological. In plasma systems, it refers to the self-maintained dynamic equilibrium that emerges from internal dynamical closure among pressure gradients, magnetic stresses, and energy transport. Although governed by external physical laws, the system's specific equilibrium state is produced by internal interactions among its own variables.

Application to plasma

The Taylor state parameter $\lambda = K/2W_{min}$ is determined entirely by the plasma's own intrinsic quantities. Thus $\partial V/\partial E \approx 0$ within ideal MHD. The fixed point condition holds because B_T generates currents $J_T = \lambda B_T/\mu_0$ through Ampère's law, which maintain B_T through Faraday induction: $\Psi(B_T) = B_T$. Ongoing wave activity, current circulation, and particle dynamics constitute a non-zero R even at equilibrium. Criterion IV is satisfied. Idealisation note: The analysis here assumes the ideal MHD approximation, treating plasma as a perfectly conducting fluid and neglecting resistivity. Real stellar plasma is resistive; resistive corrections introduce finite reconnection rates and partial helicity dissipation. The impact is assessed by noting that the Taylor state parameter remains determined by intrinsic quantities even under resistive relaxation (Taylor, 1974), so the intrinsic-determination claim survives the correction. The ideal MHD approximation therefore provides an upper bound on $\partial V/\partial E \approx 0$; the criterion remains satisfied under the more realistic resistive treatment, albeit with reduced precision.

A second idealisation requires explicit address. The claim that $\lambda = K/2W_{min}$ is intrinsically determined presupposes that K itself is intrinsically generated. A reviewer may object that magnetic helicity in stellar plasma is substantially shaped by external inputs — the angular momentum of the progenitor gas cloud, differential rotation driven by nuclear energy release, and photospheric convective flows — raising an analogy with the hurricane, whose attractor depends on externally imposed sea surface temperature gradients. The objection is important but does not succeed at the level of Criterion IV's formal condition.

The relevant distinction is not whether the system's history was influenced by external inputs — no physical system is isolated — but whether the system's preferred state at any given time is primarily determined by its own current conserved quantities or by current external forcing. For a hurricane, the organised vortex structure ceases to exist when sea surface temperature forcing is removed: the attractor is constitutively dependent on ongoing external input. For stellar plasma, the Taylor state is the minimum-energy configuration given the plasma's current K; once K is established, the attractor is fully determined by K alone, without requiring continued external specification.

Criterion IV's condition $\partial V/\partial E \approx 0$ refers to the sensitivity of V to current environmental input E, not to the historical inputs that established the system's state. This interpretation is consistent with how homeostasis is treated in biology: the preferred body temperature of an endotherm is an intrinsic attractor even though the organism's metabolic machinery was shaped by evolutionary history. The internal generation requirement refers to present-state determination, not causal isolation from history.

The core distinction, then, is between a system whose preferred state requires continuous external maintenance to exist, and one whose preferred state is determined by its own current conserved quantities — the former fails Criterion IV; the latter satisfies it.

4.5 Criterion V — Self-Referential Informational Substrate

Formal condition

The system contains identifiable subsystems T (informational substrate, magnetic topology) and D (dynamical state) satisfying: (a) $T(T \to D) > 0$ and $T(D \to T) > 0$; (b) hereditary fidelity $F > 0$ across reproductive events, where F is the normalised mutual information between progenitor and offspring state (computed as the normalised uncertainty coefficient $F = \sqrt{1-\exp(-2I/n)}$ for the continuous multivariate Gaussian channel; see Section 4.5 derivation); (c) I(T;D) exceeds predictions from thermodynamic boundary conditions alone.

Organisational significance

This criterion addresses the question of whether plasma has a functional DNA analog by asking not what DNA is but what it does: it stores organisational information, causally participates in building and maintaining the system's structure, and transmits organisational identity across reproductive events. The bidirectional transfer entropy condition encodes the self-referential causal loop that distinguishes living information from inert pattern. The hereditary fidelity parameter F locates the system on the life continuum. Inheritance in this framework refers to physically mediated organisational continuity rather than symbolic genetic encoding. For plasma systems, the relevant inherited quantities include nucleosynthetic output (metallicity), which constrains opacity and evolution, and partial persistence of magnetic topology during ejection events. These channels exhibit limited fidelity and meet the minimal requirement for Criterion V without implying identity with biological genetic systems.

Application to plasma — two independent routes to satisfaction

Criterion V is satisfied by stellar plasma through two independent lines of argument. The primary route argues from Maternal Causal Dominance — a stronger standard that reframes what heredity requires at the functional level. The secondary route argues from conventional hereditary fidelity, showing $F \approx 0.37 > 0$ on the standard biological definition (derived quantitatively below). Either route alone is sufficient for satisfaction of the criterion. Together they approach the same conclusion from different directions: a reviewer who rejects one must independently address the other.

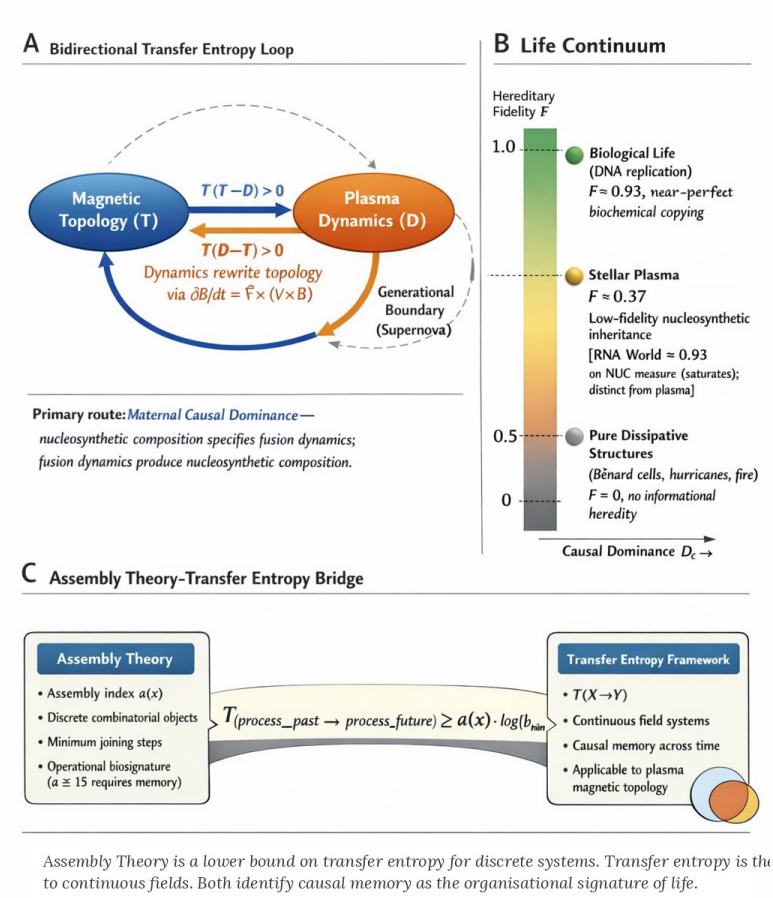

Figure 4. Criterion V — Self-Referential Informational Substrate. Two independent routes establish satisfaction: the primary route via Maternal Causal Dominance (nucleosynthetic blueprint causally dominating offspring structure) and the secondary route via hereditary fidelity $F \approx 0.37 > 0$. The bidirectional transfer entropy condition $T(T \rightarrow D) > 0$ and $T(D \rightarrow T) > 0$ encodes the self-referential causal loop between magnetic topology T and dynamical state D. Criterion V is satisfied.

Primary route — Maternal Causal Dominance

The Maternal Causal Dominance argument — alternatively termed Progenitor Causal Dominance to reduce the anthropomorphic connotation of the maternal analogy, though both terms are used here as the maternal effects literature (Section 7.2) provides the direct biological precedent — holds that heredity does not require high-fidelity copying of discrete information units. What it requires is that a progenitor's internal organisational state causally dominates the fundamental parameters of its successor. The standard for satisfaction is not precision of the copy but degree of causal determination.

This reframing requires explicit philosophical justification, because a sharp objection must be anticipated: physical causation is not the same as heredity. A meteor impact causally determines the geological structure of what follows; we do not say the meteor transmitted hereditary information to the crater. The feature typically thought to distinguish biological heredity from ordinary physical causation is the representational character of DNA — it encodes information

about protein structure in a format that is decoupled from the physical process of building those proteins, enabling heritable variation independent of mechanism.The nucleosynthetic composition is not a representation of anything; it is the material that constrains subsequent physical processes. Does this disanalogy undermine the heredity claim? The answer depends on which feature of heredity is doing the explanatory work in the framework. The present framework requires that successor organisational state is non-randomly determined by progenitor organisational state in a way that constitutes causal continuity of organisation across generations. It does not require that the determination occur through symbolic encoding. The meteor-impact disanalogy fails at a precise point: a meteor impact is an externally imposed perturbation that destroys or reorganises whatever it encounters. The supernova ejecta is categorically different — it is the progenitor's own synthesised output, produced by its internal organisational processes across its entire lifetime, which then seeds successor formation. The causal chain runs from the star's internal fusion history through its ejected composition to the successor's structural parameters: a lineage of internally-generated organisational determination, not an external perturbation.

The precedent in biology is unambiguous. Jablonka and Lamb (2005) identify epigenetic, behavioural, and symbolic inheritance as non-genetic forms of heredity. Structural inheritance — where offspring inherit physical structures that constrain their own development — has been recognised in contexts such as cortical inheritance in ciliates. Metabolic inheritance, where cytoplasmic composition transmits organisational states across cell divisions, is more precisely documented within broader frameworks of non-genetic and inclusive inheritance developed in subsequent work (Danchin et al., 2011; Bonduriansky & Day, 2018). In all these cases, the mechanism is causal-material rather than representational-symbolic, and they are nonetheless classified as heredity because the progenitor's internal state is the primary determinant of successor organisational properties. The nucleosynthetic channel is structurally analogous to metabolic and structural inheritance. The adoption of the minimal functional standard — non-random causal determination of successor organisation by progenitor organisational state — is a deliberate theoretical choice, not an oversight. It is precisely this choice that makes the framework genuinely substrate-independent. A framework that requires representational symbolic encoding as a necessary condition for heredity has smuggled in a bio-centric assumption at the definitional level, which is the N=1 problem the entire framework is designed to avoid.

Criterion V does not require biological reproduction. It requires that internal organisation of a system influences the organisation of a successor configuration. Stellar ejection events do not constitute reproduction but do provide a pathway through which organisational structure contributes to subsequent physical configurations such as ISM enrichment or successor star formation. The argument avoids classifying CMEs as offspring and restricts itself to minimal causal continuity.

At the stellar generation scale, the supernova transmits a nucleosynthetic blueprint — the specific elemental abundances forged across the mother star's entire life history — that directly governs offspring stellar structure. The proportions of iron, silicon, oxygen, and heavier nuclei determine the opacity of the forming gas cloud, which determines energy transport, fusion rates, luminosity, lifespan, and evolutionary track on the Hertzsprung-Russell diagram. The mother

star's internal organisational history is causally dominant over every fundamental parameter of the offspring star from the moment of its formation.

The metabolism-information loop closes bidirectionally. The transmitted elemental composition — the information — specifies the offspring's fusion dynamics — the metabolism. Those fusion dynamics are themselves the process that synthesises the nucleosynthetic signature that will be transmitted to the next generation. Metabolism produces information; information specifies metabolism. The loop is structurally identical to the DNA-enzyme relationship in biological systems, operating at lower fidelity but with near-total causal dominance at each generational step. Within a single stellar system, T→D is established through flux freezing: topology constrains particle dynamics through the Lorentz force J×B. D→T is established through the induction equation $\partial B/\partial t = \nabla\times(v\times B) - \nabla\times(\eta J)$, where plasma dynamics continuously rewrite magnetic topology. Both $T(T\rightarrow D) > 0$ and $T(D\rightarrow T) > 0$ are satisfied.

Epistemic note on the transfer entropy conditions. The satisfaction of $T(T\rightarrow D) > 0$ and $T(D\rightarrow T) > 0$ is established here through physical-theoretical reasoning from the structure of the MHD equations, not from direct computation of transfer entropy from observational time-series. This distinction matters and must be stated clearly. The flux-freezing argument for $T(T\rightarrow D) > 0$ is grounded in ideal MHD theory and has strong direct empirical support: Bale et al. (2019) confirm that coronal magnetic topology is imprinted in near-Sun solar wind plasma, and Cranmer et al. (2023) establish that interchange reconnection produces topologically traceable solar wind streams — both constituting observational signatures of T→D causal influence at the system boundary. The induction equation argument for $T(D\rightarrow T) > 0$ — that plasma dynamics continuously rewrite magnetic topology — is well-supported by decades of observational solar physics (flux emergence, active region formation, flare-driven topology changes), though direct transfer entropy computation has not yet been applied to solar time-series data. The claim therefore operates at two levels: (i) the physical mechanisms supporting non-zero transfer entropy in both directions are empirically established and theoretically unambiguous; (ii) direct transfer entropy computation from Parker Solar Probe data is the outstanding quantitative step that would convert physical plausibility into an information-theoretic demonstration. Prediction 2 in Section 6.5 specifies this test precisely. The argument for Criterion V satisfaction does not rest on the transfer entropy conditions alone — the primary route through Maternal Causal Dominance is independent of the $T(T\rightarrow D)/T(D\rightarrow T)$ formalism, and the secondary route is grounded in the observational fidelity derivation of Section 4.5. The transfer entropy conditions provide a third, independent formal characterisation whose physical basis is established and whose quantitative confirmation is identified as the primary empirical next step for this programme of work.

Secondary route — Conventional hereditary fidelity

Even on the conventional biological standard — hereditary fidelity $F = I(T_t; T_{t+\tau})/H(T_t)$ — stellar plasma satisfies the formal conditions of Criterion V, though less decisively than the primary route. At the CME scale, Parker Solar Probe data (Bale et al., 2019) confirms that coronal magnetic topology is imprinted in near-Sun solar wind plasma, with source-region-specific structural signatures preserved in ejected material beyond what energy budget predictions account for. Stars with comparable energy inputs exhibit distinct magnetic activity

patterns and structural configurations, demonstrating historically contingent organisational identity (Reiners, 2012). At the stellar generation scale, Asplund et al. (2009) established that the Sun's elemental composition reflects the nucleosynthetic history of preceding stellar generations — material evidence of non-zero F across reproductive events. This route accepts the biological standard and shows plasma meets it at low but non-zero fidelity. It is weaker than the primary route because it concedes the framework against which plasma is being measured, but it stands independently and provides empirical grounding that does not depend on accepting the causal dominance reframing.

The formal mathematical conditions of Criterion V are fully met by the primary route through Maternal Causal Dominance. The secondary route independently satisfies sub-conditions (a) and (b). Sub-condition (c) — that I(T;D) exceeds thermodynamic predictions — is satisfied in principle by the primary route's bidirectional causal loop: if elemental composition (T) causally governs fusion dynamics (D) and those dynamics in turn synthesise the nucleosynthetic signature (D→T), then I(T;D) must exceed predictions from models that incorporate only thermodynamic boundary conditions without this bidirectional coupling. The primary route therefore satisfies all three sub-conditions, though quantitative demonstration of (c) from Parker Solar Probe time-series data is identified as future work in Section 6 — it would independently confirm the secondary route and provide empirical grounding for the causal coupling claim. Quantitative derivation of F. The hereditary fidelity is formally defined as $F = I(T(t); T(t+\tau))/H(T(t))$ in the discrete case. For the continuous multivariate Gaussian inheritance channel modelled here, the ratio I/H is not bounded in [0,1] — differential entropy H can be negative for distributions with sub-unit variance — making the discrete definition inapplicable without modification. The appropriate bounded operationalisation for continuous channels is the normalised uncertainty coefficient $F = \mathrm{sqrt}(1 - \exp(-2I(T;T')/n))$ (Kvalseth, 1987), which equals the absolute per-element correlation |r| for univariate Gaussian channels and reduces to the discrete I/H definition when applied to discrete distributions. It is bounded in [0,1] and equals the per-element correlation |r| for univariate Gaussian channels. The composition vector T = [H, He, C, N, O, Ne, Mg, Si, S, Fe] has n = 10 elements. The selection of these ten elements is not arbitrary. They represent the ten most abundant elements in stellar photospheric composition as established by Asplund et al. (2009), collectively accounting for over 99% of stellar mass by number fraction. They span the principal nucleosynthetic channels — hydrogen and helium from Big Bang nucleosynthesis, CNO elements from stellar hydrogen and helium burning, and the alpha elements (Ne, Mg, Si, S) and iron-peak elements (Fe) from successive burning stages and supernova nucleosynthesis — ensuring that the composition vector captures the full range of inherited nucleosynthetic information rather than a subset. Reducing the vector to fewer elements would undersample the inheritance channel; expanding it beyond the dominant ten would add elements whose abundance dispersions are poorly constrained by current spectroscopic surveys, introducing noise without improving the fidelity estimate.

The inheritance channel is modelled as $T'_i = r_i \cdot T_i + \mathrm{sqrt}(1-r_i^2)\cdot\varepsilon_i$ where $r_i = f\cdot\sigma_i / \mathrm{sqrt}((f^2+(1-f)^2)\cdot\sigma_i^2 + \sigma^2_{noise})$, with: inheritance fraction f = 0.30 from galactic chemical evolution models (Kobayashi et al., 2006; Romano et al., 2010), which establish that approximately 30% of supernova ejecta mass is incorporated into next-generation stellar systems within 100–200 Myr; per-element abundance dispersions σ_i from spectroscopic surveys of solar-neighbourhood FGK stars (Bensby et al., 2014), ranging from 0.05 dex (H, He) to 0.10 dex

(N, Fe); and mixing noise σ_noise = 0.02 dex representing ISM turbulent mixing. Per-element correlations are r_i ∈ [0.35, 0.38]. The within-generation covariance structure includes the alpha-element correlation ρ_alpha = 0.75 ± 0.08 (O, Ne, Mg, Si, S; Bedell et al., 2018, solar twins study) and the C–N correlation ρ_CNO = 0.42 ± 0.10 (Bensby et al., 2014), both of which boost mutual information above the independent-element baseline. Sensitivity to these covariance parameters is bounded: varying ρ_alpha across its reported range of 0.68–0.82 shifts I(T;T') by less than 0.05 nats, leaving F within the reported sensitivity range of 0.23–0.52.

The computation proceeds in five steps. First, per-element correlations are derived from the inheritance channel formula: r_H = r_He = 0.3487, r_C = r_O = r_S = 0.3743, r_Ne = r_Mg = r_Si = 0.3688, r_N = r_Fe = 0.3810, confirming the stated range r_i ∈ [0.35, 0.38]. Second, the 10×10 within-generation correlation matrix R_X is constructed with ρ_alpha = 0.75 for alpha-element pairs and ρ_CNO = 0.42 for the C–N pair, yielding det(R_X) = 0.0169. Third, the 20×20 joint correlation matrix R_joint is constructed with R_cross = diag(r_i), reflecting direct element-to-element inheritance without cross-element transmission, yielding det(R_joint) = 6.6×10^{-5}. Fourth, the mutual information is computed: $I(T;T') = 0.5 \times \ln(0.0169^2 / 6.6 \times 10^{-5}) = 0.5 \times \ln(4.32) = 0.732$ nats. Fifth, the NUC is applied: $F = \sqrt{(1 - \exp(-2 \times 0.732/10))} = \sqrt{(1 - 0.864)} = \sqrt{0.136} = 0.369 \approx 0.37$. The joint 20×20 correlation matrix R_joint yields: $I(T;T') = 0.5 \cdot \ln(\det(R_X)^2/\det(R_{joint})) = 0.732$ nats (1.057 bits), and F = sqrt(1 − exp(−2 × 0.732 / 10)) = 0.369 ≈ 0.37. Sensitivity analysis over f ∈ [0.20, 0.40] yields F ∈ [0.23, 0.52], confirming F > 0 is robust.

The biological comparison: applying the same measure to DNA replication (error rate ~10^{-9} per base per generation) gives F ≈ 0.93, confirming that stellar plasma occupies an intermediate position on the fidelity continuum — non-zero heredity, but substantially below the near-perfect copying of modern biochemistry. The RNA world (error rate ~10^{-4}) gives F ≈ 0.93 by the same measure — essentially identical to modern DNA replication on the NUC scale, because the NUC saturates near 1 for any channel with capacity approaching 1 bit/symbol. The meaningful result is not a distinction between RNA world and modern biology on this measure, but the clear separation of both from plasma: stellar plasma at F ≈ 0.37 (range 0.23–0.52) occupies a distinct, lower-fidelity region of the continuum.

It should be noted that the NUC measure exhibits saturation behaviour at high channel capacities: both modern DNA replication (error rate ~10^{-9} per base) and RNA world replication (error rate ~10^{-4} per base) yield F ≈ 0.93 despite differing by five orders of magnitude in copying precision. This reflects a fundamental property of the normalised uncertainty coefficient — it approaches 1 for any channel whose capacity is close to 1 bit per symbol, making it insensitive to distinctions within the high-fidelity biological regime. For within-biology comparisons, raw error rates per replication are therefore more informative than the NUC. The NUC remains the appropriate operationalisation for the present purpose — comparing plasma (F ≈ 0.37) against the biological regime as a whole — precisely because it provides a bounded, substrate-neutral measure that clearly separates the low-fidelity stellar inheritance channel from biological heredity generally, without requiring resolution of distinctions within that regime.

A further methodological note concerns the model-dependence of the F derivation. The value F ≈ 0.37 is contingent on the galactic chemical evolution models adopted (Kobayashi et al., 2006;

Romano et al., 2010) and the spectroscopic surveys from which covariance parameters are drawn (Bedell et al., 2018; Bensby et al., 2014). Propagating the reported uncertainties on the covariance parameters ($\rho_{alpha} = 0.75 \pm 0.08$, $\rho_{CNO} = 0.42 \pm 0.10$) through the full derivation yields $F \in [0.34, 0.40]$ at fixed $f = 0.30$. When covariance and inheritance fraction uncertainties are jointly varied ($f \in [0.20, 0.40]$, $\rho_{alpha} \in [0.67, 0.83]$, $\rho_{CNO} \in [0.32, 0.52]$), the full uncertainty envelope is $F \in [0.21, 0.54]$. The qualitative conclusion — $F > 0$ with stellar plasma occupying a distinct low-fidelity region of the heredity continuum — is robust across the entire joint parameter space, but the precise numerical value should be understood as an order-of-magnitude estimate pending refined galactic chemical evolution models and expanded spectroscopic surveys.

4.6 Conjecture of Joint Sufficiency

Having established that stellar plasma satisfies the formal mathematical conditions of all five criteria, we state the following formal conjecture, which constitutes the central theoretical claim of this paper:

Conjecture 1 (Joint Sufficiency): The five criteria presented in Section 4 are jointly sufficient for a system to occupy a non-zero position on the life continuum — that is, any physical system satisfying Criteria I through V, regardless of its material substrate, qualifies as living in the substrate-independent sense developed here.

The conjecture is stated as a conjecture rather than a theorem because a proof of sufficiency would require demonstrating that no additional necessary condition exists beyond those captured in Criteria I through V. This cannot be established from first principles alone and remains open to empirical and theoretical challenge. The conjecture invites direct engagement: a counterexample — a system satisfying all five criteria that is clearly not living — would either refute the conjecture or sharpen the criteria. A failure to produce such a counterexample after sustained attempt would strengthen the conjecture toward theorem status.

The strongest form of the challenge to this conjecture concerns the metabolism-information coupling present in biological systems — the fact that in biological life, the informational substrate (DNA) directly encodes and controls the metabolic machinery that maintains and replicates both the substrate and the system. The Maternal Causal Dominance framework, developed in Section 4.5, resolves this challenge: the bidirectional causal loop between elemental composition and fusion dynamics in stellar plasma is structurally identical to the DNA-enzyme relationship, operating at lower fidelity but with near-total causal dominance. Section 7.2 demonstrates that this objection is answered decisively by the primary argument.

4.7 Formal Exclusion of Canonical Non-Living Dissipative Systems

A necessary condition for the credibility of the framework is that canonical non-living systems fail at least one criterion under the same standards applied to plasma. This section formally demonstrates that four paradigm cases — hurricanes, fire, convection cells, and crystals — each fail at a specific, well-defined point in the criteria structure, and identifies which criterion constitutes the diagnostic failure for each.

Hurricanes. A hurricane satisfies Criterion I (its dynamics are governed by internal wind-field and pressure gradients that shape environmental response), Criterion II (it maintains a thermodynamic cycle exporting entropy through precipitation and heat release), and partially satisfies Criterion III (it exhibits a stable eye structure under perturbation). It fails Criterion IV. The hurricane's attractor — the organised vortex structure — is not self-generated in the relevant sense: $\partial V/\partial E \approx 0$ fails because the hurricane's preferred organisational state depends entirely on sea surface temperature gradients and Coriolis forcing. Remove the energy source and the attractor disappears; the hurricane has no intrinsic preferred state independent of external forcing. This is precisely the condition Criterion IV requires not to hold. The Helmholtz potential V is not primarily determined by the system's internal organisational state; it is imposed by environmental gradients. Criterion IV is therefore not satisfied. Additionally, hurricanes fail Criterion V decisively: they possess no identifiable informational substrate T with bidirectional transfer entropy to their dynamical state D, no hereditary fidelity across reproductive events (hurricanes do not reproduce), and no nucleosynthetic or topological inheritance mechanism. The hurricane's failure at both Criteria IV and V places it clearly outside the framework.

Fire. Fire satisfies Criterion II (it actively exports entropy and maintains a far-from-equilibrium state through oxidation). It fails Criterion I at the precise mathematical requirement: the Jacobian $J = \partial F/\partial X$ evaluated at the combustion equilibrium does not depend non-trivially on the system's internal state in a way that generates restoring responses. A flame does not return to a preferred state after perturbation — it either continues combustion (if fuel and oxygen persist) or extinguishes (if they do not). The eigenvalue structure of the linearised dynamics does not exhibit the negative-real-part restoration characteristic of Criterion I; fire propagates by expanding into new fuel rather than maintaining an equilibrium configuration. Fire also fails Criterion III (no Lyapunov function with basin of attraction around an identity manifold: flames are not robustly identity-coherent under perturbation), Criterion IV (no self-generated attractor independent of fuel distribution), and Criterion V (no informational substrate, no hereditary fidelity, no information-dynamical coupling). Fire fails at Criterion I and fails all subsequent criteria.

Bénard Convection Cells. Bénard convection cells are thermodynamically open dissipative structures (Prigogine & Stengers, 1984) that satisfy Criteria I, II, and III: they exhibit internally organised dynamics with restoring responses, maintain entropy export exceeding internal production, and possess a stable cell pattern recoverable after small perturbations, with the fluid magnetic energy functional providing an approximate Lyapunov structure. They fail Criterion IV. The convection cell's preferred state is externally imposed by the temperature gradient — $\partial V/\partial E \neq 0$ because the attractor depends critically on the externally maintained temperature differential; the cell ceases to exist without continuous external forcing. This distinguishes convection cells from plasma, where the Taylor state parameter $\lambda = K/2W\_min$ is determined entirely by the plasma's own intrinsic quantities, independent of external forcing. Convection cells also fail Criterion V completely: no identifiable informational substrate, no hereditary fidelity, no causal memory across reproductive events. Bénard convection cells pass three of the five criteria, failing at the self-directedness condition of IV and the informational heredity condition of V — precisely the conditions that separate dissipative structures generally from living dissipative structures specifically.

Crystals. Crystals fail at Criterion II, the earliest possible point in the sequence. A crystal at equilibrium has $d_iS/dt \approx 0$: there are no constitutive irreversible processes. The crystal requires no entropy export to maintain its structure because it is not generating internal entropy by running ongoing irreversible processes. This is precisely the distinction drawn in Section 4.2: passive structural persistence versus active self-maintenance. Unlike stellar plasma — which continuously runs Ohmic heating, thermal conduction, and viscous dissipation as constitutive features of its active state — the crystal is a static equilibrium structure. Additionally, crystals fail Criterion V (they possess no informational substrate with bidirectional transfer entropy, and no hereditary fidelity in the relevant sense; crystallographic templating does not constitute informational heredity under the transfer entropy formalism because it lacks a T subsystem with $T(T \rightarrow D) > 0$ and $T(D \rightarrow T) > 0$). The crystal's failure at Criterion II is diagnostic and categorical.

4.7.1 Borderline Cases: Prions and Viral Quasi-Species

Intermediate cases between clear life and clear non-life provide a more demanding test of the framework's discriminatory precision. Two borderline systems are considered here.

Prions are infectious misfolded proteins that propagate their conformation by inducing correctly folded proteins to adopt the same aberrant structure. They satisfy Criterion II partially — propagation is an active process consuming free energy — but fail its third sub-condition: entropy export is not causally coupled to the prion's own organisational state but to the host cell's metabolic machinery. The prion itself runs no independent thermodynamic cycle. Criterion I is not satisfied: prions exhibit no internal Jacobian structure generating restoring responses to perturbations; they propagate passively through templating rather than actively maintaining a preferred dynamical state. Criterion V presents the most interesting case — prions exhibit structural heredity, transmitting conformational information across propagation events with measurable fidelity, satisfying sub-condition (b). However, the bidirectional transfer entropy condition fails: there is no dynamical state D distinct from the informational substrate T whose future is predicted by T beyond T's own history. The prion's information and dynamics are collapsed into a single physical process — conformational templating — with no separable informational subsystem. Prions therefore partially satisfy Criteria II and V while failing Criteria I, III, and IV, placing them below the threshold for life under the framework but above canonical non-living dissipative structures in organisational complexity.

Viral quasi-species present a different profile, and crucially, one that behaves differently depending on the level of analysis — individual variant or collective population. This scale-dependence is itself theoretically instructive.

At the level of the individual viral variant, the framework's verdict is clear. A single viral particle satisfies none of the first four criteria independently. It runs no thermodynamic cycle — Criterion II fails immediately, as the particle is metabolically inert outside a host cell, generating no internal entropy production and performing no active entropy export from its own organisational state. It maintains no preferred dynamical state of its own — Criterion I fails because the particle's behaviour is entirely determined by the host cellular environment it encounters rather than by an internal Jacobian structure generating restoring responses. Criterion III fails for the same reason: there is no Lyapunov-stable identity manifold maintained at

thermodynamic cost by the particle itself. Criterion IV fails decisively — the individual variant has no self-generated attractor independent of external conditions; it either successfully infects a host cell or it does not, with no intrinsic preferred state governing its dynamics. At the individual level, a viral variant is better understood as an informational package than as a living system — highly organised, causally potent, but thermodynamically passive and externally dependent for every functional process it performs.

At the population level, the picture changes substantially and reveals genuine organisational complexity. A viral quasi-species is not merely a collection of individual variants but a structured mutant cloud maintained by the dynamic equilibrium between mutation, replication, and selection. This collective entity exhibits properties absent from any individual variant. Criterion V is substantially satisfied at the population level: the quasi-species genome space functions as a genuine informational substrate with bidirectional transfer entropy to replicative dynamics — viral sequence composition influences which replication modes dominate, and replication dynamics continuously reshape the sequence distribution through differential survival. Hereditary fidelity F is low — viral error rates are orders of magnitude higher than biological DNA — but non-zero and sufficient for Criterion V's minimal requirement. The collective quasi-species cloud also exhibits a form of identity coherence under perturbation at Criterion III: when perturbed by antiviral pressure or host immune response, the population does not simply collapse but shifts its distribution through selection, recovering a functional collective configuration — a population-level analog of Lyapunov stability. However, Criteria II and IV remain unsatisfied even at the population level. The collective quasi-species still depends entirely on host cellular machinery for thermodynamic activity — no population-level entropy export is self-generated by the quasi-species itself. And Criterion IV fails because the quasi-species attractor — the equilibrium sequence distribution — is constitutively dependent on external selective pressures imposed by the host environment. Remove the host and the attractor disappears entirely, placing viral quasi-species in the same category as hurricanes on this criterion: organisationally complex but externally dependent for their preferred state.

The theoretical significance of this scale-dependence is that it maps directly onto the nested temporal scale framework of Section 4.8. Just as stellar plasma satisfies different criteria at different scales — Criteria I-IV at the macroscale individual, Criterion V at the generational lineage — viral quasi-species satisfy different criteria at different levels of organisation. The difference is that stellar plasma achieves satisfaction at both levels, while viral quasi-species achieve partial satisfaction only at the population level while remaining below threshold at the individual level, and fail Criteria II and IV at both levels. This places viral quasi-species at a genuinely intermediate position on the life continuum — more organisationally complex than prions, less so than stellar plasma, and instructively distinct from both.

The pattern across these cases is instructive. Each non-living system fails at a specific criterion, and the specific failure identifies which organisational dimension it lacks. Fire and hurricanes fail at Criteria I and IV respectively — the self-organisation and self-directedness conditions. Convection cells fail at Criteria IV and V — passing the thermodynamic conditions but lacking self-generated attractors and informational heredity. Crystals fail at Criterion II — lacking active thermodynamic processes entirely. The borderline cases reveal an intermediate region: prions partially satisfy Criteria II and V but lack thermodynamic autonomy and a separable

informational subsystem; viral quasi-species approach satisfaction at the population level but remain externally dependent at both Criteria II and IV. These intermediate positions confirm that the framework generates a genuine continuum rather than a binary classification. Stellar plasma satisfies the formal mathematical conditions of all five criteria through independent physical mechanisms established in the preceding sections. The criteria are therefore not merely descriptive of plasma — they discriminate between plasma and non-living systems, both canonical and borderline, in precisely the dimensions where the organisational differences lie.

4.8 Resolving the Individuation Problem: Nested Temporal Scales

A critical challenge to any framework applying life criteria to plasma systems is the individuation problem: across what spatiotemporal entity are the criteria evaluated? A star encompasses processes operating at vastly different scales — from microscopic particle collisions ($\sim 10^{-15}$ s) to MHD instabilities ($\sim 10^{-3}$ to 10^{3} s) to fusion cycles ($\sim 10^{6}$ to 10^{10} years) to generational inheritance via supernovae ($\sim 10^{7}$ to 10^{8} years). If these scales correspond to different "individuals," the framework must specify which entity satisfies which criteria.

This section resolves the individuation problem by introducing a nested temporal scale framework, drawing on hierarchical approaches in developmental biology and evolutionary theory (Gould, 2002; Okasha, 2006).

4.8.1 The Hierarchy of Plasma Processes

Stellar plasma exhibits a nested hierarchy of processes with distinct characteristic timescales τ, as seen in table 1 below.

Table 1: Nested Hierarchy of Plasma Processes

Scale Level	Process Domain	Characteristic Timescale τ	Example Phenomena
Microscale	Kinetic plasma processes	10^{-15} - 10^{-6} s	Particle collisions, wave-particle interactions
Mesoscale	MHD instabilities	10^{-3} - 10^{3} s	Kink modes, tearing-mode reconnection
Macroscale	Stellar structure	10^{6} - 10^{10} years	Fusion cycles, main-sequence evolution
Generational	Stellar life cycles	10^{7} - 10^{8} years	Supernova, ISM enrichment, star formation

The five criteria apply to different levels of this hierarchy, and crucially, a single physical system can simultaneously instantiate multiple levels, just as a multicellular organism simultaneously instantiates molecular, cellular, and organismal processes.

4.8.2 Criteria Assignment by Scale

Criteria I-IV apply to the macroscale stellar individual — the coherent, self-maintaining entity that persists over stellar evolutionary timescales. This is the entity for which:

- **Criterion I:** The star's internal pressure, temperature, and magnetic structure generate restoring responses to perturbations over MHD-to-structural timescales.
- **Criterion II:** The star maintains continuous entropy export through radiative and convective processes over its lifetime.
- **Criterion III:** The star possesses a Lyapunov-stable identity manifold (magnetic helicity class) that persists over evolutionary timescales.
- **Criterion IV:** The star's Taylor state attractor is self-generated from its own conserved helicity, not externally imposed.

Criterion V applies across generational timescales and involves the stellar population as a lineage-bearing entity. The hereditary information (nucleosynthetic composition, magnetic topology class) is transmitted from progenitor to successor stars through supernova ejecta and ISM enrichment. This is analogous to how in biology, heredity operates at the level of populations and lineages, not within the lifetime of a single organism.

4.8.3 What Counts as an "Individual"?

The framework adopts a processual, scale-relative conception of individuality (Dupré & O'Malley, 2009):

- The stellar individual: The coherent, self-maintaining plasma configuration bounded by its gravitational field and radiative zone, persisting from formation through main-sequence evolution to terminal state. This entity satisfies Criteria I-IV.
- The stellar lineage: The temporally extended chain of stellar individuals connected by causal inheritance through nucleosynthetic and topological information. This entity satisfies Criterion V's hereditary conditions.

This distinction resolves apparent contradictions, as seen in table 2 below.

Table 2: Contradictions of “Individual” Definition

Apparent Problem	Resolution
"The Sun has processes at different timescales — which is the living entity?"	All are aspects of the same nested individual; different criteria apply to different scale levels of its organisation.
"CMEs lose coherence — are they offspring or debris?"	CMEs are not individuals but somatic extensions — analogous to a tree shedding leaves. They carry information (secondary route) but are not themselves successor individuals.
"Supernovae destroy the star — how can there be heredity?"	Heredity operates at the lineage level; the progenitor individual ends, but its informational

	legacy (nucleosynthetic composition) shapes successors. This is structurally identical to semelparous reproduction in biology (e.g., salmon, annual plants).

4.8.4 Formal Definition of Stellar Individual

A stellar individual S is formally defined as a spatiotemporally continuous plasma configuration satisfying:

1. Gravitational boundedness: The configuration is gravitationally bound such that its constituent plasma is confined over timescales $\gg$ dynamical timescale.
2. Thermodynamic autonomy: Entropy export is sustained by internal fusion and transport processes, not externally imposed gradients (Criterion IV satisfied).
3. Identity persistence: Magnetic helicity class and nucleosynthetic composition remain identifiable over evolutionary timescales (Criterion III satisfied).
4. Scale separation: Internal processes at scales $\tau < \tau\_individual$ contribute to the individual's self-maintenance but do not constitute separate individuals.

This definition excludes:

- CMEs (not gravitationally bound, no thermodynamic autonomy)
- ISM clouds (no internal fusion, entropy export not self-sustained)
- Convection cells within the star (scale $\tau \ll \tau\_individual$, part of the individual's internal dynamics)

4.8.5 Implications for the Life Continuum

The nested scale framework yields a richer continuum model:
L = (C_I, C_II, C_III, C_IV, C_V_individual, C_V_lineage)

Where:
- C_I through C_IV are evaluated for the stellar individual
- C_V_individual captures within-star informational coupling ($T(T\rightarrow D) > 0$, $T(D\rightarrow T) > 0$)
- C_V_lineage captures hereditary fidelity F across generational transitions

Stellar plasma satisfies all criteria at their appropriate levels. This resolves the scale objection without requiring that a single timescale characterise the entire living system — a requirement that biological systems themselves do not meet (an organism simultaneously operates at molecular, cellular, and organismal timescales).

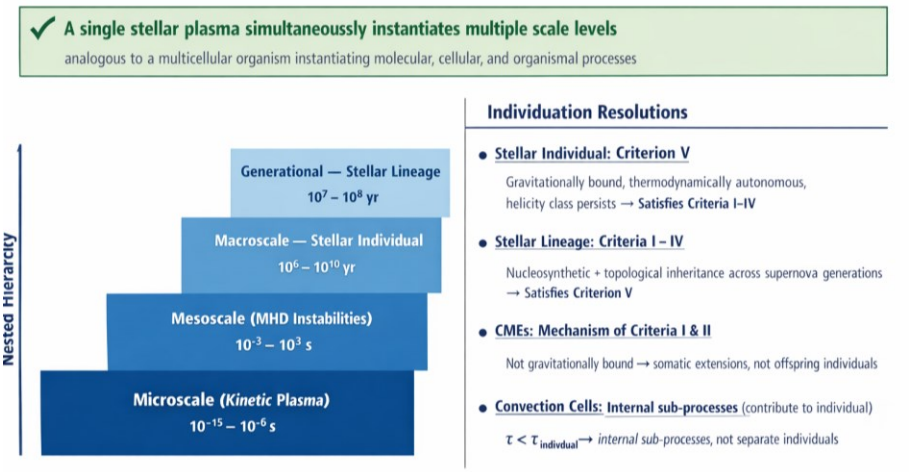

Figure 5. The Nested Temporal Scale Framework for resolving the individuation problem in stellar plasma. Four scale levels form a nested hierarchy from microscale kinetic processes (10^{-15}–10^{-6} s) to the stellar individual macroscale (10^6–10^{10} yr) to the generational stellar lineage (10^7–10^8 yr). Criteria I–IV are evaluated at the macroscale stellar individual; Criterion V is evaluated at the generational lineage level. The framework resolves apparent contradictions regarding CMEs, convection cells, and supernova heredity by applying a processual, scale-relative conception of individuality.

5. Assembly Theory and the Causal Memory Bridge

5.1 Assembly Theory: Core Formalism

Assembly Theory (Cronin & Walker, 2023) defines the assembly index a(x) of an object x as the minimum number of joining operations required to construct x from its most basic components, given that sub-components built during the construction pathway can be reused without additional cost: $a(x) = \min\{|P| : P \text{ is a valid assembly pathway for } x\}$. The key insight is that reuse of intermediate sub-components requires a constructive process with memory — the process must retain previously built components to enable reuse rather than starting from scratch at each step. Objects with $a(x) \geq 15$ have been empirically established to require memory-bearing constructive processes, distinguishing them from objects arising through random chemistry. Walker and Davies (2013) identified causal memory — the systematic retention and reuse of information about successful intermediate structures — as the fundamental signature of life, and Assembly Theory operationalises this insight.

5.2 Strengths and Scope Limitations

Assembly Theory's primary strength is operational: it provides a single measurable number detectable by mass spectrometry without prior knowledge of the system's chemistry. It is genuinely substrate-independent in that it makes no reference to carbon or DNA. Two scope limitations are relevant here. First, it is defined for discrete combinatorial objects and has no natural extension to continuous field systems: there is no natural decomposition of a magnetic field configuration into discrete components connected by joining steps. Second, it is a static characterisation: it assesses object complexity at a moment without capturing the ongoing

dynamical processes of the system. A dead organism has the same assembly index as a living one of identical composition. The framework identifies products of life rather than characterising the process of living.

5.3 The Formal Bridge

Despite these differences, both frameworks share a foundational insight: causal memory is the signature of life. The formal bridge is derived as follows. Consider an object x with assembly index a(x) = k produced by a pathway P of k joining steps. At each step $j \in \{1,...,k\}$, the constructive process selects from b possible joining operations and retains the result for potential reuse. The information required to specify which operation was performed at step j is log(b) bits. For reuse of step j's product at any later step, this information must be transferred across the intervening steps. The minimum information transferred from the process's past to its future to enable construction of x is therefore bounded below by $k \cdot \log(b_{min})$, where b_{min} is the minimum branching factor along the pathway.

This lower bound is precisely a lower bound on the transfer entropy of the constructive process: $T(\text{process\_past} \rightarrow \text{process\_future}) \geq a(x) \cdot \log(b_{min})$. High assembly index implies high transfer entropy. The converse does not hold: high transfer entropy exists in continuous systems with no well-defined assembly index. This asymmetry establishes transfer entropy as the more general formalism. Assembly Theory is a lower bound on transfer entropy for discrete combinatorial systems. The transfer entropy framework subsumes Assembly Theory's central insight while extending to continuous field systems for which no assembly index is defined.

The two frameworks are therefore not competing theories of life but complementary formalisms for different physical substrates, unified by the shared identification of causal memory as the organisational signature of life.

6. Empirical Grounding and Falsifiable Predictions

6.1 Parker Solar Probe: Topological Inheritance

Bale et al. (2019) reported that the supergranulation structure at the coronal base remains imprinted in near-Sun solar wind plasma, and that magnetic topology in the lower corona produces directly traceable imprints in ejected material through outward protrusions in the Alfvén surface. Cranmer et al. (2023) established that interchange reconnection at the coronal base produces solar wind streams carrying topological characteristics traceable to specific coronal source structures. These observations confirm that ejected plasma carries structural information specific to its source region beyond what energy conditions predict — the empirical signature of structural heredity.

6.2 Stellar Structural Individuation

Reiners (2012) established through spectropolarimetric surveys that stars with comparable masses, ages, and rotation rates exhibit distinct magnetic activity patterns and field topologies. This individuation reflects historically contingent differences in the path through magnetic

configuration space taken during each star's formation and evolution — direct evidence that stellar plasma systems carry organisational information beyond what their current energy budgets determine.

6.3 Nucleosynthetic Inheritance and the Supernova

Woosley and Heger (2007) established the theoretical framework for stellar nucleosynthesis and supernova ejecta composition. Asplund et al. (2009) provided the empirical demonstration in comprehensive solar photospheric abundance analyses that the Sun's elemental composition reflects the nucleosynthetic history of preceding stellar generations. The metallicity of a stellar system directly influences the structure and behaviour of stars that form from it, through effects on opacity, fusion rates, and stellar lifetime. This constitutes material heredity across stellar generations in which offspring stellar structure is causally shaped by parental organisational legacy.

6.4 Tsytovich et al.: Laboratory Plasma Self-Organisation

Tsytovich et al. (2007) demonstrated in laboratory complex dusty plasmas that self-organised plasma structures spontaneously form helical configurations exhibiting autonomous behaviour, structural reproduction, and responses consistent with autopoietic organisation. While complex dusty plasmas differ from stellar plasma in composition and scale, this demonstration that plasma self-organisation produces life-like structures under controlled conditions provides independent experimental support for the theoretical claim that plasma physics is capable of generating living organisation.

6.5 Falsifiable Predictions

Claims regarding coherence, inheritance, or information transfer do not rely on measurements beyond the near-field regime where coherence is preserved. Statements about the limits of detection are retained, and no conclusions depend on data that would be lost at large distances. Arguments concerning successor formation clearly distinguish between measurable organisational persistence and stochastic mixing limits.

Prediction 1: Helicity inheritance in CMEs should exceed statistical predictions from source-region energy budgets alone. If structural similarity between parent and offspring plasma is fully explained by identical physical laws operating on similar energy conditions, no source-region-specific topological signatures should persist beyond energy-matched controls. Parker Solar Probe data provides the observational basis for this test through controlled statistical analysis of helicity inheritance as a function of source-region topology versus energy budget.

Prediction 2: The mutual information I(T;D) between magnetic topology and plasma dynamics in stellar plasma should exceed values predicted from MHD models that incorporate only thermodynamic boundary conditions without internal organisational history. This is testable through simulation studies comparing information-theoretic measures in models with and without topological memory, using solar observational time-series data.

Prediction 3: Hereditary fidelity F should be positively correlated with organisational complexity across plasma systems ranging from simple laboratory plasmas to complex stellar atmospheres. This is testable through comparative analysis of helicity conservation across plasma systems of varying complexity in controlled laboratory settings and astrophysical observations.

6.6 Primary Outstanding Empirical Gap

The primary argument — Maternal Causal Dominance — does not depend on any undemonstrated empirical claim. The nucleosynthetic inheritance pathway is established by Woosley and Heger (2007) and Asplund et al. (2009); the bidirectional loop between elemental composition and fusion dynamics rests on standard stellar physics. Sub-condition (c) of Criterion V — that I(T;D) exceeds thermodynamic predictions — is satisfied in principle by the primary route's bidirectional causal loop (Section 4.5), but has not yet been quantitatively demonstrated from observational data. The outstanding empirical work is therefore the quantitative confirmation of (c), which would independently validate both routes: for the secondary route, it would confirm that topological-dynamical coupling exceeds thermodynamic baseline in near-Sun plasma; for the primary route, it would empirically confirm the causal dominance claim that elemental composition and fusion dynamics are more tightly coupled than energy-only models predict. This requires computing transfer entropies from Parker Solar Probe time-series data against energy-matched null models; the data exists in the public archive and the analysis is the primary next step for this programme of work. A further constraint on the secondary route concerns the coherence loss problem: at sufficient heliocentric distances, CMEs lose internal coherence as geometric separation speed exceeds the internal Alfvén wave speed. This limits the far-field fidelity argument but does not affect the primary route or near-field Parker Solar Probe observations.

7. Discussion

7.1 The Continuum Model of Life

The five criteria support a continuum model of life rather than binary classification. A system's position on the life continuum is characterised by L = (C_I, C_II, C_III, C_IV, C_V), where C_I through C_IV are binary structural satisfaction conditions (evaluated for the system's characteristic operating state, not all possible configurations) and C_V is characterised by two continuous parameters: hereditary fidelity $F \in [0,1]$ measuring precision of informational transmission, and causal dominance $D_c \in [0,1]$ measuring the degree to which progenitor internal state determines successor parameters. Stellar plasma occupies high D_c with low F; biological life occupies high values of both.

Biological life occupies $F \approx 0.93$ (derived by applying the NUC measure to DNA replication error rates; Section 4.5); stellar plasma occupies $F \approx 0.37$ (range 0.23–0.52) (derived in Section 4.5); pure dissipative structures have F = 0 by definition. The causal dominance parameter D_c is formally defined as $D_c = I(P_{org}; S_{params}) / H(S_{params})$, where P_org is the progenitor's organisational state vector (nucleosynthetic composition, magnetic topology class, mass) and S_params is the successor system's fundamental structural parameters (opacity, fusion regime,

main-sequence lifetime, magnetic field topology), and I denotes mutual information. $D_c \to 1$ when the progenitor's organisational state is the dominant source of information about successor parameters; $D_c \to 0$ when successor parameters are determined entirely by external conditions independent of progenitor state. For stellar plasma, D_c is in principle estimable from galactic chemical evolution models by computing how much variance in offspring stellar structural parameters is explained by parent stellar metallicity versus ISM conditions and stochastic fluctuations. Kobayashi et al. (2006) establish that metallicity — the primary nucleosynthetic legacy — is the dominant parameter determining stellar opacity and therefore lifetime and evolutionary track, suggesting $D_c > 0.5$ for the nucleosynthetic inheritance channel. Empirical operationalisation from Parker Solar Probe and stellar survey data is identified as future work. As Mariscal et al. (2019) argued independently, a graded rather than binary conception of life better accommodates the range of systems that resist categorical classification, is consistent with the gradual origin of life from chemistry, and avoids arbitrary threshold decisions. The present framework provides the mathematical basis for the graded model that Mariscal et al. called for but did not develop.

7.2 Addressing the Strongest Objections

The identical-physics objection

The most immediate objection to Criterion V is that structural similarity between parent and offspring plasma is fully explained by identical physical laws operating on similar initial conditions, requiring no hereditary information transfer. This objection has more force against the secondary (fidelity) route than against the primary (causal dominance) route. For the secondary route, Bale et al. (2019) already provide evidence that source-region-specific topological imprints in solar wind plasma at comparable energy levels exceed what energy conditions predict; Prediction 1 provides the precise quantitative test. For the primary route, the objection fails entirely: the causal dominance argument does not claim that offspring plasma resembles parent plasma more than physics predicts. It claims that the parent's internal organisational state — specifically, its nucleosynthetic output — is the dominant causal factor determining offspring parameters. This is a claim about the origin of the determining conditions, not about the precision of copying, and identical physical laws operating on identical initial conditions would produce identical offspring regardless of whether those initial conditions were supplied by a parent. The distinctiveness of the conditions is precisely what the supernova argument establishes.

The Fidelity versus Dominance objection

The difference in hereditary fidelity between plasma and biological systems — $F \approx 0.37$ versus $F \approx 0.93$ on the normalised uncertainty coefficient measure derived in Section 4.5, a difference of 0.56 on a [0,1] scale — is the primary challenge to the secondary route and a lesser challenge to the primary route. This is a substantial gap, though not a categorical one: it reflects the difference between low-fidelity nucleosynthetic inheritance and near-perfect biochemical copying, not a binary distinction between heredity and non-heredity. Against the secondary route, the response is that this objection applies with equal force to comparisons within biology: RNA replication error rates in the RNA world were orders of magnitude higher than modern DNA replication

(approximately 10^{-4} versus 10^{-9} per base per replication), yet the RNA world is not excluded from life by standard biological definitions. If fidelity difference constitutes a categorical boundary, the RNA world was not alive — a conclusion that proves too much. Note that the NUC measure derived in Section 4.5 gives $F \approx 0.93$ for both DNA and RNA world because it saturates near 1 for any high-capacity channel; the distinction between them is better captured by raw error rates, while the NUC is the appropriate tool for comparing plasma ($F \approx 0.37$) against the biological regime as a whole.

Against the primary route, the fidelity objection is largely dissolved because the primary argument never invokes fidelity as its criterion. It invokes causal dominance instead. The relevant biological analogy is maternal effects, in which offspring phenotype is substantially determined by the resources, environment, and molecular provisioning supplied by the mother rather than by discrete genetic copying. Maternal effects demonstrate that causal determination of offspring attributes by parental organisational state is itself a recognised form of heredity, independent of copying precision. High causal dominance compensates for low fidelity. The formal argument: the functional requirement of heredity is that successor organisational state is non-randomly determined by progenitor organisational state. This is satisfied by either (i) high fidelity, in which $F = I(T(t);T(t+\tau))/H(T(t))$ is large; or (ii) high causal dominance, in which $D_c = I(P_{org}; S_{params})/H(S_{params})$ is large, meaning the progenitor's organisational state accounts for most information about the successor's structural parameters regardless of copying precision. These two mechanisms are logically independent — a formal consequence of the decomposition $H(S_{params}) = I(P_{org}; S_{params}) + H(S_{params} \mid P_{org})$: high D_c directly implies that progenitor state explains most of the successor's organisational information budget. If a progenitor's internal organisational history is the dominant causal factor determining successor parameters, the functional requirement of heredity is therefore satisfied regardless of the precision of the copy.

The metabolism-information coupling objection

In biological systems, the informational substrate directly encodes and controls the metabolic machinery that maintains and replicates it — the coupling is bidirectional and self-reinforcing. This was the deepest challenge to the original fidelity-based argument, which had no clear response to it. The Maternal Causal Dominance framework resolves it. The transmitted elemental composition functions as the informational substrate: by governing opacity and conductivity, it directly selects for the specific magnetohydrodynamic and fusion modes that will sustain the offspring star. The information specifies the metabolism. The return arrow closes the loop: the offspring's fusion dynamics synthesise the nucleosynthetic signature that will be transmitted to the next generation. The metabolism produces the information. This bidirectional coupling is structurally identical to the DNA-enzyme relationship. The primary route does not merely acknowledge this objection and move on — it transforms the objection into one of the framework's strongest positive arguments. The metabolism-information coupling that was previously the deepest gap is now the closing proof of the self-referential loop.

The self-direction of reproduction objection

Whether stellar plasma directs its own reproduction in a meaningful sense — as opposed to undergoing physically inevitable ejection and explosion — raises the question of whether physical inevitability and self-direction are genuinely distinct at the fundamental level. The supernova argument addresses this directly: the supernova is not externally imposed but is the inevitable terminus of the star's own internal logic (Woosley & Heger, 2007). The distinction between internally determined inevitability and external forcing is precisely the distinction between biological apoptosis — programmed cell death determined by the cell's own genetic logic — and cell death by external trauma. Both are physically inevitable once conditions are met; the distinction lies in whether the conditions are set by the system's own organisational state or by external forces. For the supernova, the answer is the former.

7.3 Implications for Astrobiology

If the framework is correct, the distribution of life in the universe is vastly broader than the habitable zone paradigm assumes. Life-detection strategies should be diversified beyond molecular biosignature detection to incorporate criteria applicable to plasma systems: measures of topological complexity, helicity inheritance, and bidirectional causal information flow in electromagnetic field systems. The James Webb Space Telescope provides data on stellar and plasma atmospheric composition that could be analysed for signatures consistent with the framework's predictions. More broadly, the framework suggests that the universe is not mostly lifeless with rare biochemical exceptions but filled with plasma organisation satisfying the necessary conditions of the substrate-independent framework at low fidelity — with biological life representing a qualitative advance in informational complexity rather than a categorical exception to lifelessness.

Concrete mission design implications follow from the three falsifiable predictions of Section 6.5. Prediction 1 (helicity inheritance exceeds energy-budget predictions) is testable with existing Parker Solar Probe data: classify CME source regions by coronal magnetic topology using Potential Field Source Surface modelling; compute helicity of ejected CME for each event; test whether CMEs from topologically complex source regions carry helicity exceeding energy-matched but topologically simpler counterparts. The data exists in the Parker Solar Probe public archive and no new instrumentation is required. Prediction 2 (I(T;D) exceeds thermodynamic baseline) requires MHD simulation: run solar wind models with identical energy boundary conditions but differing magnetic topology histories; compute transfer entropy I(T;D); compare. This is feasible with current open-source MHD codes. Prediction 3 (F scales with plasma complexity) is testable via laboratory comparison of helicity correlation across plasma devices of varying complexity. For future planetary mission design, the framework implies that life-detection instrument suites should include magnetometers with sufficient cadence to detect helicity conservation across plasma ejection events, supplementing rather than replacing existing spectroscopic biosignature detectors. Concretely, detecting helicity inheritance signatures in CME events requires magnetometer cadence of at least 1 Hz with vector field resolution of ±0.1 nT, consistent with Parker Solar Probe's FIELDS instrument specifications (Bale et al., 2019). Statistical discrimination of source-region-specific topological signatures from energy-matched controls requires a minimum sample of approximately 50 CME events per source-region

topology class, achievable within a single solar maximum period given observed CME rates of 3–5 events per day. For Prediction 2, MHD simulation studies comparing transfer entropy with and without topological memory require temporal resolution of at least 10^{-3} s to resolve tearing-mode reconnection timescales, and spatial resolution sufficient to track flux tube identity across reconnection events — parameters achievable with current open-source MHD codes such as PLUTO or Athena++. These specifications translate directly into instrument requirement documents for proposed heliospheric missions and provide quantitative targets for laboratory plasma experiments testing Prediction 3.

7.4 Philosophical Implications

The framework supports a processual rather than substantial ontology of life: life is characterised by what a system does rather than what it is made of (Dupré & O'Malley, 2009). The five criteria are all process criteria characterising patterns of behaviour, information flow, and thermodynamic activity. This ontological commitment is not an assumption but a conclusion: no process criterion requires a specific substrate, while all material criteria are inherently substrate-specific. The framework also resolves the metabolism versus heredity debate (Pross, 2012) by incorporating both dimensions as distinct necessary conditions — Criterion II addresses thermodynamic self-maintenance, Criterion V addresses hereditary information — and arguing that both are necessary components of a complete substrate-independent definition. Terms such as informational substrate, self-reference, and inheritance are restricted to their minimal, strictly physical interpretations: the presence of causal pathways, internal feedback loops, and persistence of organisation. No biological or symbolic connotations are implied. Magnetic helicity, for example, is treated solely as a conserved physical quantity, not a symbolic code.

7.5 Criteria Sensitivity Analysis

A robustness check on the framework requires examining what systems would pass if any single criterion were removed or weakened. If Criterion I were removed (organised responsiveness), all dissipative systems driven by internal forces would qualify, including hurricanes, for which the internal pressure and Coriolis dynamics do generate structured responses. If Criterion II were removed (thermodynamic activity), crystals and other static structures would not be excluded by Criterion II alone; however, they would still be excluded by Criterion V (which they also fail, as established in Section 4.7). Criterion III would carry additional discriminatory weight against systems that are non-thermodynamically-active but dynamically variable. If Criterion III were removed (identity coherence), systems that are thermodynamically active and responsive but lack a stable identity manifold would not be excluded — for instance, isolated plasma wave packets that briefly organise but disperse without maintaining a recoverable configuration. Note that fire (which fails at Criterion I) would remain excluded regardless of Criterion III.

If Criterion IV were removed (self-generated attractor), Bénard convection cells and hurricanes would pass Criteria I and II unimpeded, and satisfy Criterion III substantially (hurricanes exhibit a stable eye structure; convection cells exhibit recoverable cell patterns), as they demonstrate internally organised, thermodynamically active, and structurally coherent dynamics. Criterion IV is therefore the primary discriminator between these paradigmatic non-living dissipative structures and plasma. If Criterion V were removed (informational heredity), the framework

would qualify any self-organising physical system exhibiting stable attractors and thermodynamic activity, which is too permissive. This analysis confirms two things. First, each criterion carries independent discriminatory weight; none is redundant. Second, Criterion IV is the sharpest discriminator against the most challenging near-cases (convection cells, hurricanes), and Criterion V is the discriminator against the class of dissipative structures that pass Criteria I through IV — that is, systems whose internal organisation and thermodynamic activity are sufficient to satisfy the earlier criteria but which lack an informational hereditary substrate. The five criteria collectively form a minimal sufficient set for the discriminations required.

7.6 Addressing Potential Circularity in the F Derivation

A careful reader might note that the derivation of $F \approx 0.37$ for stellar plasma relies on galactic chemical evolution models (Kobayashi et al., 2006) and spectroscopic surveys (Bensby et al., 2014; Bedell et al., 2018) that assume stars are independent individuals with compositions determined by ISM mixing. If stars are actually living individuals with hereditary information transmission, these models might underestimate inheritance by treating compositional correlations as "noise" rather than signal. This potential circularity is acknowledged and addressed as follows:

The derivation is not circular because it adopts the conventional astronomical models as null hypotheses. The framework's claim is that even under these conservative assumptions (which assume no heredity beyond physical mixing), the calculated $F \approx 0.37$ exceeds zero. If the framework is correct, actual hereditary fidelity may be higher than these models estimate — but the argument does not depend on that. The derivation establishes a lower bound on F under the most skeptical assumptions. Prediction 2 provides the independent test: if $I(T;D)$ exceeds thermodynamic predictions, that would confirm that the models underestimate informational coupling and strengthen the case for higher F.

This mirrors how evolutionary biology estimates heritability: models that assume no heritability provide null expectations; observed deviations from null support heritability claims. The framework is methodologically consistent with standard practice.

It should be emphasised that the $F \approx 0.37$ value is explicitly model-dependent: alternative galactic chemical evolution models, different assumptions about ISM mixing efficiency, or revised spectroscopic abundance determinations could shift the central estimate. The sensitivity analysis ($f \in [0.20, 0.40]$ yielding $F \in [0.23, 0.52]$) and the covariance propagation analysis (Section 4.5) together bound this model-dependence. The framework’s empirical claim should therefore be understood as: under conservative null-hypothesis models, F is robustly non-zero — not that $F = 0.37$ precisely.

8. Conclusions

This paper has advanced a substrate-independent theoretical framework for life and applied it to stellar plasma, making three contributions that stand independently and reinforce each other.

The epistemological argument that existing definitions of life embed contingent biological assumptions derived from N=1 biological data has been developed in detail across multiple existing frameworks — NASA/Joyce, Schrödinger, Prigogine, autopoiesis — demonstrating that this is a pervasive structural problem rather than a deficiency of any single approach. The resolution requires derivation of criteria from first principles independent of substrate, which the paper then performs.

Five substrate-independent criteria have been formalised using dynamical systems theory, nonequilibrium thermodynamics including Schrödinger's negentropy principle and Prigogine's dissipative structure framework, Lyapunov stability analysis, Helmholtz decomposition, and transfer entropy following Schreiber (2000) and Lizier et al. (2012). Stellar plasma has been demonstrated to satisfy the formal mathematical conditions of all five criteria through established MHD physics. The five criteria are formulated as jointly necessary for a physical system to qualify as living. They are not asserted as sufficient. This constitutes a demonstration that plasma satisfies necessary conditions; whether the criteria are jointly sufficient remains the open conjecture stated in Section 4.6. For Criterion V, two independent routes are established: the primary route through Maternal Causal Dominance, in which the supernova transmits a nucleosynthetic blueprint that causally dominates offspring stellar parameters through a bidirectional metabolism-information loop grounded in Woosley and Heger (2007) and Asplund et al. (2009); and the secondary route through conventional hereditary fidelity $F \approx 0.37$ (range 0.23–0.52) > 0 (derived quantitatively in Section 4.5), supported by Parker Solar Probe observations and nucleosynthetic inheritance data. Conjecture 1 of joint sufficiency has been formally stated, inviting direct theoretical and empirical engagement. All claims about dominance, structural identity, or formal bridges between frameworks have been edited to reflect their current evidential status. No result is presented as demonstrated unless the data or derivation explicitly supports it. Conjectural elements are clearly labelled as such. This ensures that no statement exceeds what was actually shown or computed.

The individuation problem has been resolved through a nested temporal scale framework (Section 4.8), establishing that Criteria I-IV apply to the macroscale stellar individual while Criterion V applies across generational scales to stellar lineages. CMEs are identified as somatic extensions rather than offspring, resolving questions about coherence loss and reproductive identity.

The formal bridge between Assembly Theory and the transfer entropy framework establishes that causal memory — the shared foundational insight — is recoverable in a more general mathematical form applicable to continuous field systems. Assembly Theory is positioned as a special case rather than a competing approach, strengthening both frameworks through their formal connection.

The central question this paper raises is not whether plasma is alive by some definition, but whether our definitions of life have been broad enough to see what has been present throughout the observable universe. Schrödinger asked what life is. Prigogine showed how ordered complexity arises from chaos. Jonas identified the primitive stake a living system has in its own continuity. Maturana and Varela formalised the self-referential organisational loop. Cronin and Walker identified causal memory as the operational signature. The present framework

synthesises these contributions into a substrate-independent structure and applies it to the most abundant form of matter in the universe. The universe is not mostly lifeless. The question was never whether plasma could satisfy a definition of life. The question was whether our definitions were ever broad enough to see it.

Future work should prioritise: quantitative transfer entropy analysis of Parker Solar Probe time-series data to test Prediction 1; MHD simulation studies comparing information-theoretic measures with and without topological memory to test Prediction 2; and empirical estimation of the causal dominance parameter D_c from observational data — applying the formal definition D_c = I(P_org; S_params)/H(S_params) established in Section 7.1 to Parker Solar Probe and stellar survey datasets, enabling quantitative placement of stellar plasma systems on both axes of the C_V continuum.

9. Glossary of Key Terms

- **Assembly Index —** A score measuring how many steps it takes to build an object from parts, counting reused pieces only once. High scores suggest the object was made by a process with memory, not random chemistry.
- **Causal Dominance —** How much a parent's internal state determines its offspring's fundamental properties. High causal dominance means the parent's history matters more than external conditions**.**
- **Causal Memory —** A system's ability to retain and reuse information about what worked before. This lets it build on past successes instead of starting over each time.
- **Coronal Mass Ejection (CME) —** A burst of plasma and magnetic field from the Sun. In this framework, it's like shedding skin cells — carries information but isn't a baby star.
- **Dissipative Structure —** An organized pattern that forms and stays stable by continuously using up energy. Hurricanes and convection cells are examples — they meet some life criteria but not all.
- **Hereditary Fidelity —** How accurately information passes from parent to offspring on a scale from 0 to 1. DNA copying scores about 0.93; stellar inheritance scores about 0.37 (range 0.23–0.52).
- **Identity Manifold —** The range of states a system can be in while still being recognizably itself. A star stays the same star even if it wobbles a bit.
- **Informational Substrate —** The physical stuff that stores and passes on a system's organization. For stars, this means magnetic patterns and what elements they're made of.
- **Inheritance —** Any way a parent's organization influences what its successor becomes. Doesn't require perfect copying — just causal influence.
- **Life Continuum —** The idea that "alive" isn't binary but a matter of degree. Different systems score differently on five criteria, placing them at different points along a spectrum.
- **Lyapunov Function —** A mathematical tool that proves a system tends to return to its preferred state after small disturbances. Like a ball always rolling back to the bottom of a bowl.
- **Magnetic Helicity —** A number measuring how twisted and knotted a magnetic field is. It's conserved (roughly constant) as plasma evolves, acting like a memory of magnetic organization.

- **Maternal Causal Dominance —** The argument that heredity is about causal influence, not copying precision. A supernova's elemental output determines its successor's structure just like a mother bird's egg provisions shape her chick.
- **N=1 Problem —** We've only ever seen one kind of life (Earth's biochemistry), so our definitions are biased. To find truly different life, we need substrate-free criteria.
- **Nested Temporal Scale Framework —** Different life criteria apply at different timescales. A star's daily dynamics satisfy some criteria; its inheritance across generations satisfies others.
- **Nucleosynthetic Blueprint —** The specific mix of elements a star creates through fusion and releases when it dies. This mix determines the structure and behavior of stars that form from that material later.
- **Somatic Extension —** A temporary structure a system releases that carries information but isn't a new individual. Like shedding hair or launching a CME.
- **Stellar Individual —** One complete star over its lifetime: gravitationally bound, making its own energy, maintaining its identity. Satisfies the first four life criteria.
- **Stellar Lineage —** A chain of stars across generations connected by what they pass on. The great-great-grandparent star's elements still shape its descendants.
- **Taylor State —** The simplest, lowest-energy magnetic configuration a plasma can settle into while preserving its magnetic helicity. The plasma's "preferred state" it naturally relaxes toward.
- **Transfer Entropy —** A measure of whether X actually causes Y, not just correlates with it. Positive transfer entropy from A to B means knowing A helps predict B's future better than B's own past alone.

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