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BEYOND HEAT DEATH: A THERMODYNAMIC COSMOLOGY OF INFORMATION AND SELF-ORGANIZATION

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ABSTRACT

We propose a model of thermodynamic cosmology of self-organized complex systems in which the universe is described as a non-equilibrium thermodynamic system governed by the coupled dynamics of entropic dissipation, coherent information, and structural organization. Central to this framework is the introduction of a "counter-entropic self-organization potential," enabling the local emergence and stabilization of complex structures without violating the second law of thermodynamics. The universe thus exhibits a pseudo-dynamic character at local scales, marked by dissipative reorganization, while maintaining quasi-stationary behaviour on large scales. In this approach, time is interpreted as an emergent quantity arising from irreversible physical transformations, and information becomes a fundamental dynamic variable of cosmic evolution. The model is formalized as a non-linear dynamical system coupling entropy, information, and organization, inspired by non-equilibrium thermodynamics, information theory, and complex systems. Although exploratory and not yet validated by observational evidence, this theoretical construct opens an interdisciplinary perspective for the study of cosmic self-organization and the emergence of structures in the universe. If the description faithfully reflects the underlying physics, several implications naturally follow: the absence of a genuine thermodynamic heat death, cosmological self-organization and large-scale structure formation, dynamical transitions in cosmic evolution, the emergent origin of the arrow of time, an effective gravitational role of organization, a dynamical interpretation of dark energy, black holes as systems of information reorganization, and testable deviations from the standard cosmological model.

KEYWORDS

Thermodynamic Cosmology; Self-Organization; Emergent Time; Entropy; Information Theory; Emergent Gravitation.

INTRODUCTION

The observable universe exhibits a fundamental characteristic that spans all physical scales: the spontaneous emergence of organised structures within an environment that is, overall, subject to thermodynamic dissipation. From the formation of galaxies to the emergence of living beings, cosmic history seems marked by a constant tension between the increase of entropy and the local persistence of complex forms of organization.

Consequently, the existence of highly organised structures such as galaxies, constellations, stars, complex biological systems (both those discovered and those yet to be discovered) as well as complex networks, seems to highlight that, alongside global thermodynamic dissipation, local mechanisms of structuring and stabilisation are also at work far from thermodynamic equilibrium.

Within the framework of known standard cosmological models, the universe is generally described as an expanding system whose overall evolution is dominated by the increase of entropy (Tu et al., 2021), potentially leading to a final state of maximum dissipation known as "heat death" (Coule, 2003). Although this description is consistent with general relativity (Uzan, 2011) and classical thermodynamics (Wang, 2009). Several questions remain unanswered regarding the origin of complex structures, the maintenance of cosmic organization at different scales, and the fundamental role of information in the dynamics of the universe.

At the same time, advances in non-equilibrium thermodynamics, complex systems theory, statistical physics and information theory have profoundly changed our understanding of organised and complex phenomena at all levels (Kleidon, 2009). Recent studies on dissipative structures and self-organization have shown that open systems subjected to continuous flows of energy and matter can spontaneously generate highly ordered configurations far from thermodynamic equilibrium. From this perspective, entropy as a fundamental physical quantity, no longer appears solely as a principle of disorder, but also as an irreversible driving force for the transformation and reorganization of physical systems.

From this perspective, living organisms are probably one of the most remarkable manifestations of this dynamic. Biological organisms maintain, reproduce and locally increase their complexity whilst fully complying with the second law of thermodynamics (Sabater, 2022). Indeed, it has been shown that they do not eliminate entropy. Furthermore, they export more dissipation to their external environment in order to preserve their internal organization. In this respect, life appears to be a self-organised dissipative structure resulting from ongoing interactions between energy flows, coherent information and dynamic regulatory mechanisms.

This observation naturally leads to a deeper question: could the self-organization mechanisms observed in biological systems reflect a more general and fundamental property of cosmic evolution itself? In other words, are the organised structures observed at different scales of the universe (galaxies, galaxy clusters, constellations, stars, solar systems, etc.) merely the consequence of transient local fluctuations, or do they reflect the existence of a deeper informational thermodynamic dynamic capable of producing and maintaining local organization within a globally dissipative universe?

It is within this framework that the thermodynamic cosmology of self-organising complex systems proposed in this work is situated. The model regards the universe as a complex system out of equilibrium, whose evolution results from dynamic interactions between entropic dissipation, coherent information and structural organization. In this model, entropy provides the global irreversibility of physical transformations, whilst information and self-organization mechanisms allow the temporary emergence of stable structures at different scales of the cosmos.

The model proposed in this study is based on several fundamental assumptions: (i) time is regarded as an emergent quantity derived from the irreversible transformations of physical systems; (ii) the universe exhibits pseudo-dynamic behaviour locally and is quasi-stationary on a large scale; (iii) cosmic information is globally conserved; (iv) "anti-entropic" phenomena contribute to the emergence of organization; and finally, (v) black holes may play a role in thermodynamic and informational restructuring within the universe.
In this model, the universe is no longer viewed solely as an expanding geometric space, but also as a non-equilibrium thermodynamic system within which the following elements interact continuously: "entropic dissipation" ↔ "information"↔ "organization".

Life thus appears not as an exception to the laws of thermodynamics, but as a natural manifestation of the general dynamics of self-organization present in the cosmos.

To formalise these ideas, the model introduces a cosmological state space defined by several coupled dynamic quantities, notably functional entropy (S), coherent information (I), the global level of organization of systems (Ω), and the global information-energy of the cosmos (U). The evolution of these

quantities is described by a non-linear dynamical system inspired by non-equilibrium thermodynamics, information theory and self-organising complex systems.

The aim of this work is not to replace established cosmological models, but to propose a complementary conceptual and mathematical framework that allows us to explore the possible role of information, dissipation and self-organization in the evolution of the cosmos or the universe. This model thus opens up an interdisciplinary perspective linking cosmology, thermodynamics, information physics, complex systems and biology within a single overarching framework for structuring and understanding the universe.

I. General Development

1. Conceptual Foundations of the Model

1.1 The Universe as a Self-organising Complex System

In this model, the observable universe is not interpreted as a system evolving solely towards irreversible dissipation (heat death), but as a complex system out of equilibrium capable of generating order locally.

Entropy here is therefore no longer reduced to a simple measure of macroscopic disorder. It also becomes an indicator of state transformations and reconfigurations of the cosmic system (galaxy clusters, galaxies, constellations, the solar system, etc.).

Thus, cosmic evolution results from the constant interaction between two complementary dynamics: (i) dissipative processes associated with entropy production and (ii) "anti-entropic" mechanisms favouring the self-organization of physical systems.

This model builds on the theories of dissipative structures and non-equilibrium complex systems.

1.2 Time as an Emergent Quantity

In classical and relativistic physics, time is generally regarded as a fundamental coordinate used to describe the evolution of physical systems. However, several contemporary approaches in quantum gravity, non-equilibrium thermodynamics and information theory suggest that time may not be a primitive or fundamental quantity of the universe, but rather an emergent property resulting from the internal transformations of complex physical systems.

In the present model, time is not regarded as a fundamental entity independent of matter and energy. Rather, it emerges from the internal transformations of physical systems. Thus, the physical changes in any given physical system are primary, whilst time constitutes a derived quantity that allows these transformations to be measured. This perspective aligns with certain relational approaches to time in quantum gravity and certain thermodynamic interpretations of cosmic dynamics.

In this context, without physical transformation, the operational concept of time would lose all meaning and physical basis. This leads to the introduction of a new fundamental variable, denoted "Ξ", which denotes the overall transformational dynamics of a complex physical system.

The global transformational dynamics "Ξ" represents the sum of the physical transformations affecting a complex system. According to our model, it depends simultaneously on: entropic dissipation; informational variations; structural reorganizations; and energy exchanges.
We therefore define the global transformational dynamics as:

$$\Xi = \Xi(S, I, \Omega, E) \quad (1)$$

where: S (functional entropy of the system); I (informational content); Ω (overall level of organization); E (available energy)

(1) reflects the fact that, in this model, the evolution of a complex physical system depends not only on energy, but also on its degree of organization and its informational structure.

The variation in the overall transformational dynamics (Ξ) can be expressed as the sum of the thermodynamic (entropy), informational, organizational and energetic contributions. Combining this with (1), we obtain:

$$d\Xi = \alpha\, dS + \beta\, dI + \gamma\, d\Omega + \delta\, dE \quad (2)$$

where: α (entropic contribution); β (informational contribution); γ (organizational contribution); δ (energetic contribution).

This general equation thus describes time as a cumulative measure of irreversible physical transformations. From this perspective: thermodynamic phenomena; variations in information; structural reorganizations and energy redistributions all contribute jointly to the emergence of time.
Consider a perfectly invariant system such as:

$$dS = dI = d\Omega = dE = 0 \quad (3)$$

So:

$$d\tau = 0 \quad (4)$$

This result implies that, in the complete absence of physical transformation, no measurable time can emerge. Time thus becomes a physically undetectable quantity.

This conclusion is consistent with certain relational approaches to quantum gravity, according to which time has meaning only through interactions between physical systems.

a) Thermodynamic Origin of the Arrow of Time

The apparent direction of time naturally follows from the thermodynamic irreversibility defined by:

$$\frac{dS}{d\tau} \geq 0 \quad (5)$$

(5) means that the statistical increase in entropy imposes a preferred direction on physical transformations and thus defines the thermodynamic arrow of time. Consequently, time is not an absolute dimension, but a consequence of the irreversible evolution of complex systems.

b) Cosmological Application of Time

On a cosmic scale, universal time can be interpreted as the cumulative sum of the transformations affecting the universe as a whole:

$$\tau_{cosmos} = k \int d\Xi \quad (6)$$

or :

$$\tau_{cosmos} = k \int (\alpha dS + \beta dI + \gamma d\Omega + \delta dE) \quad (7)$$

Cosmic time thus becomes an emergent property of the overall dynamics of the cosmos. We experience time differently in one system compared to another.

1.3 Global Pseudo-steady-state Universe

The model we propose distinguishes between two levels of cosmological description of the universe. Firstly, on a local scale, the universe appears dynamic (observable cosmic expansion; star formation; galactic evolution; gravitational collapse; the emergence of life and the formation of black holes); and secondly, on a global scale, the fundamental content of the cosmos remains broadly conserved. This content comprises mainly: energy; information; physical correlations; and the fundamental structures of the universe.

The universe is therefore, in this respect, pseudo-stationary, that is to say, dynamic in its local configurations and quasi-stationary in its global structure. This approach allows us to envisage a universe in constant transformation without imposing a definitive disappearance of cosmic organization, as certain cosmological models suggest.

The model proposed here is based on a set of thermodynamic and informational variables describing the overall state of the cosmic system or the universe, notably the total energy-information (U); the total physical energy (E); the cosmic information content (I); the functional entropy (S); the "anti-entropic potential" or "dissipative self-organization potential" (Φ); the overall level of organization (Ω); the emergent evolution parameter or emergent time (τ); the self-organization coefficient (α); the dissipative coefficient (β); the organizational efficiency (γ); and the thermodynamic flux (J).

This model posits that the universe cannot be described solely by classical physical energy, but by a generalised quantity combining energy, information and organization known as "global energy-information".

a) Total Energy-information

In this model:

$$U \neq \text{simple mechanical energy}$$

but:

U = energy content + informational structure

The central quantity of the model is defined by:

$$U = E + \lambda I + \mu\Omega \quad (8)$$

where: E (total physical energy); I (information content); Ω (level of cosmic organization); λ and μ are coupling coefficients.

(8) expresses a thermodynamic unification between: energy, information and organization. Consequently, the overall content of the cosmos is thus described as a dynamic energy-information structure. The universe is not reducible to raw energy; organization and information also have a physical reality that must be taken into account.

b) Global Conservation of the Cosmic System

The evolution of the universe is described by:

$$\frac{dU}{d\tau} = \frac{dE}{d\tau} + \lambda\frac{dI}{d\tau} + \mu\frac{d\Omega}{d\tau} \quad (9)$$

But the model assumes that the total energy-information of the cosmos is conserved:

$$\text{If U is conserved, then } \frac{dU}{d\tau} = 0 \quad (10)$$

So:

$$\frac{dE}{d\tau} + \lambda\frac{dI}{d\tau} + \mu\frac{d\Omega}{d\tau} = 0 \quad (11)$$

This relationship reflects an overall balance between: energy dissipation; informational reorganization; and structural emergence.

1.4 The "Anti-entropic Principle" or the "Potential for Dissipative Self-organization" and the Emergence of Complex Structures

The model introduces an anti-entropic principle, also known as the "dissipative self-organization potential", which describes the existence of natural self-regulatory mechanisms capable of locally slowing down dissipation, maintaining complex structures and promoting the emergence of higher levels of organization.

This principle does not violate the laws of classical thermodynamics as described. Rather, it corresponds to self-organization phenomena observed in open systems out of equilibrium. That is to say, the greater the coherent information, the stronger the organization and the greater the self-organising capacity; thus, the anti-entropic potential is defined by:

$$\Phi \propto I\Omega \quad (12)$$

Conversely, the greater the entropic dissipation, the more difficult self-organization becomes; the "anti-entropic potential" is therefore defined as follows:

$$\Phi \propto \frac{1}{S} \quad (13)$$

Consequently, the anti-entropy potential is then expressed as:

$$\Phi = \gamma\frac{I\Omega}{S} \quad (14)$$

where γ represents the system's organizational efficiency.

(14) implies that S > 0. Under this condition, it represents a regime in which: (i) dissipation directly controls self-organization and (ii) saturation effects are neglected.

However, if: S→0 so $\frac{1}{S} \to \infty$ which would result in: (i) a physical discrepancy; (ii) numerical instability; and (iii) an unrealistic explosion of the entropy potential.

Therefore, to ensure that S > 0, one would need to write $(1 + S)$ as if S→0 so $\frac{1}{1+S}$ does not tend towards infinity.

(14) is then written as:

$$\Phi(I, \Omega, S) = \eta\frac{I\Omega}{1+S} \quad (15)$$

Generally speaking:

$$\eta\frac{I\Omega}{1+S} \to \gamma\frac{I\Omega}{S} \text{ si } S \gg 1 \quad (16) \text{ with } \gamma \equiv \eta$$

Φ increases when: coherent information increases; structures become more organised; and dissipation remains under control. The "anti-entropy potential" thus represents a system's capacity to maintain or generate organization.

Consequently, Φ must satisfy several conditions:

$\frac{\partial\Phi}{\partial I} > 0$: the more information there is within a system, the more efficient the organizational mechanisms become.

$\frac{\partial\Phi}{\partial\Omega} > 0$: a more organised structure is better able to resist dissipation.

$\frac{\partial\Phi}{\partial S} < 0$: when the total dissipation entropy "S" becomes very large, structures become unstable, correlations break down and organization is gradually destroyed.

In our model, Φ is a term that competes with the total dissipation of the cosmos in local and large scale. It describes the effective capacity of the cosmos to transfer energy and information locally into stable organization, despite the global thermodynamic irreversibility of the cosmos imposed by the second law of thermodynamics.

1.5 Level of Organization and Dynamics of the Cosmic Order

In our model, Ω represents the overall level of organization of a complex system, which is a fundamental quantity of the model. This quantity serves to link cosmology, thermodynamics, life, information and the complexity of a system.

Consequently, the model implicitly suggests that the universe evolves not only through the redistribution of energy, but also through a transformation of its level of organization.

Thus, Ω does not represent a simple geometric order (Ω ≠ simple geometric order), but rather the structural capacity of a system to maintain dynamic coherence.

In other words, Ω measures the organised complexity of a system; the stability of interactions within a system; the degree of internal coherence of a system; a system's capacity for self-regulation; and informational integration within any system at both local and global levels.

For example, consider a primordial homogeneous plasma (low Ω); a galaxy (higher Ω); a living organism (very high Ω); and consciousness (even more complex and higher Ω). The level of organization depends on: information, internal correlations, and the coherence of interactions.

Hence:

$$\Omega = \frac{I_c}{S} \quad (17)$$

where: Ic (coherent information) and S (dissipative entropy).

(17) implies that an organised system possesses a great deal of coherent information, but relatively little destructive dissipation. Furthermore, an organised system must possess available energy (E).

(17) can then be written as:

$$\Omega = \frac{EI_c}{S} \quad (18)$$

Similarly, (18) does not indicate how the organization evolves, grows or shrinks, nor how it behaves over time. To do this, we need to construct a dynamic equation of the form $\frac{d\Omega}{d\tau}$.

Therefore: $\frac{d\Omega}{d\tau} = \frac{d}{d\tau}\left(\frac{EI_c}{S}\right)$

so:

$$\frac{d\Omega}{d\tau} = \frac{S\frac{d(EI_c)}{d\tau} - EI_c\frac{dS}{d\tau}}{S^2}$$

and:

$$\frac{d\Omega}{d\tau} = \frac{S\left(I_c\frac{dE}{d\tau} + E\frac{dI_c}{d\tau}\right) - EI_c\frac{dS}{d\tau}}{S^2}$$

we get:

$$\frac{d\Omega}{d\tau} = \frac{I_c}{S}\frac{dE}{d\tau} + \frac{E}{S}\frac{dI_c}{d\tau} - \frac{EI_c}{S^2}\frac{dS}{d\tau}$$

The approximation of organizing and destructive phenomena leads to the formulation of the dynamic equation governing the evolution of organization:

$$\frac{d\Omega}{d\tau} = \alpha\Phi(S, I, \Omega) - \beta S \ (19)$$

Where αΦ denotes the self-organising contribution; βS denotes the entropic dissipative contribution.

The behaviour of the system depends on the ratio between organization and dissipation:

- if $\alpha\Phi > \beta S$, as the organization (Ω) grows, complex structures begin to emerge;
- if $\alpha\Phi < \beta S$, Ω then decreases; disorganization prevails;
- if $\alpha\Phi = \beta S$, Ω is zero, then equilibrium is achieved and the system reaches a pseudo-steady state.

This equation constitutes the fundamental dynamic equation of the model.

1.6 Local Entropic Dynamics

According to this model, the local evolution of entropy is described by:

$$\frac{dS}{d\tau} = \sigma - \Phi \ (20)$$

where σ represents entropy production and Φ represents the "anti-entropy" contribution.

The fundamental entropy balance resulting from the competition between irreversible entropy production (σ) and "counter-entropic reorganization" (Φ), the latter being fuelled by coherent information and the self-organization of the cosmic system. Entropy is therefore not interpreted as a mere increase in disorder, but as a dynamic transformation of physical configurations.

- **The relationship between entropy and organization**

The relationship between entropy and organization can be expressed using the following classical entropy equation:

$$S = k_B \ln W \ (21)$$

where k_B is the Boltzmann constant and W represents the number of accessible microstates.

Within the framework of this model, this relationship is given a broader interpretation, namely that entropy (S), no longer represents mere disorder but rather the transformation of physical configurations.
In this model, entropy is regarded as a measure of dynamic transition rather than a mere indicator of the degradation of a physical system.

1.7 Pseudo-stationary Dynamics of the Universe

Our model posits that the universe is neither perfectly static nor in a state of perpetual divergent expansion.

The universe exhibits local dynamics superimposed upon a global equilibrium that is quasi-stationary. This means that: (i) the overall average state of the universe or cosmos remains relatively stable, and (ii) local fluctuations give rise to the observable evolution.

Thus, the observable cosmological evolution is represented by the equation:

$$a(\tau) = a_0(1 + \epsilon f(\tau)) \ (22)$$

Where a(τ) represents the apparent factor of cosmic evolution (expansion/contraction/overall evolution of the universe) or the observable macroscopic state of the cosmic system; a_0 represents the quasi-stationary global state or the global average state of the universe; εf(τ) describes local fluctuations and dynamics; ε measures the relative amplitude of local fluctuations relative to the average cosmic state.

Therefore:

$$\varepsilon = \frac{\text{amplitude of local fluctuations}}{\textit{overall average}}$$

The parameter a_0 is derived from the steady-state point of the overall system.

1.7.1 Fundamental Condition of the Quasi-steady-state Regime

From (20):

$$\frac{dS}{d\tau} = \sigma - \Phi(I, \Omega, S) \ (20)$$

And :

if $\sigma \gg \Phi$: dominant dissipation (disorganization; instability; heat death);
if $\Phi \gg \sigma$: explosive growth of physical structures (organizational instability; dynamic divergence);
but if $\sigma \approx \Phi$ so $\frac{dS}{d\tau} \approx 0$: the total entropy of the cosmos varies little; the overall average state of the universe remains stable. Under these conditions, only local fluctuations persist. Therefore, $\varepsilon \ll 1$.

The model thus asserts that:

$$\varepsilon \ll a_0$$

This implies observable local dynamics and global stability of the cosmic system. It is a system in non-equilibrium equilibrium.

According to this model, the condition ε≪1 reflects the fact that local dynamic fluctuations remain small compared to the mean cosmological state a_0. This property results from the dynamic thermodynamic equilibrium between entropic production (σ) and self-organization mechanisms (Φ):

$$\sigma \approx \Phi(I, \Omega, S)$$

leads to a quasi-stationary state of the universe in which global variations in the cosmic system remain limited, whilst locally dissipative and organizational fluctuations persist, giving rise to complex structures.

1.7.2 The Cosmological Role of Black Holes

In standard cosmology, black holes are primarily described as extreme gravitational objects characterised by an event horizon and a high concentration of energy (Cohen et al., 1999). In this model, they take on a more general thermodynamic function.

In this model, black holes are interpreted as regions of informational compression, energetic restructuring and thermodynamic transition. They are therefore not merely dissipative objects, but operators that transform the informational energy content of the cosmos.

Our model suggests that black holes participate in cosmic recycling mechanisms enabling the local reconfiguration of energy and information. This hypothesis partially aligns with certain contemporary issues related to the black hole information paradox (Bekenstein, 2004) and holographic approaches (McFadden & Skenderis, 2010).

Black holes are described as operators of energy and information transformation:

$$\mathcal{B}(U_i) = U_f$$

or

$$\mathcal{B}(E_i, I_i) = (E_r, I_r)$$

where $\mathcal{B}$ (thermodynamic operator associated with the black hole); U_i (incident state); U_r (restructured state); E_i (incident energy); I_i (incident information); E_r (restructured energy) and I_r (restructured information).

A more explicit expression is given as follows:

$$E_i + I_i \rightarrow E_r + I_r \ (23)$$

(23) states that energy is conserved, that information is not destroyed, and that physical configurations undergo a restructuring.

In our model, the black hole appears as a mechanism of transition that is both thermodynamic and informational. In other words: matter + incoming information → cosmic reconfiguration. The incident energy E_i (matter, radiation, information) undergoes a profound transformation to give rise to a new energy configuration E_r.

Thus, black holes could represent regions of extreme local restructuring of the universe (Ω). We can therefore write:

$$\Omega_r = f(\Omega_i, S, \Phi) \ (24)$$

This model also posits that; cosmic information content is linked to Shannon's statistical entropy via the relationship by:

$$I = -\sum_i p_i \ln p_i \ (25)$$

where p_i represents the probability of the accessible states of the cosmic system.

(25) formalizes the interdependence between information, structure and the distribution of physical states.

The model thus adopts an informational interpretation of cosmic organization. It imposes a global conservation of cosmic information, such that:

$$\frac{dI}{d\tau_{global}} = 0 \text{ (26)}$$

despite local transformations (gravitational collapse; energy dissipation and thermodynamic transitions).

This hypothesis is consistent with certain modern formulations of the black hole information problem.

1.8 Life as an Organised Dissipative Structure

Living organisms are complex thermodynamic structures, endowed with the ability to generate local order, maintain the informational coherence of the complex system, and delay their own internal entropy. Cellular ageing thus reflects a gradual breakdown of this thermodynamic and informational stability. Consequently, living organisms are not an anomaly in the laws of physics, but rather the natural expression of the dynamics of cosmic self-organization.

2. Mathematical Development of the Thermodynamic Cosmological Model of Self-Organizing Complex Systems

The model we propose can be reformulated within the formal framework of non-equilibrium thermodynamics, non-linear dynamical systems and variational field theory.

The aim here is to demonstrate, through a mathematical approach, that organization does not constitute a violation of the second law of thermodynamics, but rather emerges from a dynamic equilibrium between three interdependent poles: dissipation, information and self-organization.

2.1 Cosmological State Space

In our model, the cosmological state space refers to a multidimensional space structured by thermodynamic, informational and organizational variables, which describe the overall state of the cosmic system. Each point in this space corresponds to a possible configuration of the universe, whilst cosmic evolution manifests itself as a dynamic trajectory, governed by the interaction between entropic dissipation, coherent information and self-organization mechanisms.

The global cosmological state is defined by:

$$X(\tau) = (U(\tau), S(\tau), I(\tau), \Omega(\tau)) \text{ (27)}$$

In (27), the parameter τ is conceived as an emergent quantity arising from physical transformations. It does not correspond to an absolute or fundamental time. In other words: (i) systems do not move through a pre-existing time, (ii) it is the accumulation of physical transformations that gives rise to observable time.

Thus:

$$\tau = \tau(S, I, \Omega, E) \text{ (28)}$$

Here, time appears as an emergent function, dependent on several fundamental dimensions: entropy, information, organization and energy exchanges. It is no longer a pre-existing absolute framework, but a dynamic outcome produced by the interaction of these processes.

Thus, a distinction should be made between: (i) the mathematical parameter of evolution, denoted by λ, which serves solely to parameterise the differential equations:

$$\frac{dX}{d\lambda} = F(X) \text{ (29)};$$

(ii) the emergent physical time, defined by: $\tau = \tau(S, I, \Omega, E)$ (28);

with: $d\tau = (\partial\tau/\partial S)\, dS + (\partial\tau/\partial I)\, dI + (\partial\tau/\partial\Omega)\, d\Omega + (\partial\tau/\partial E)\, dE$

let's define: $\alpha = \partial\tau/\partial S$; $\beta = \partial\tau/\partial I$; $\gamma = \partial\tau/\partial\Omega$ et $\delta = \partial\tau/\partial E$

This gives us: $d\tau = \alpha\, dS + \beta\, dI + \gamma\, d\Omega + \delta\, dE$ (30)

In (30), λ is defined as an abstract mathematical parameter, whilst α, β, γ and δ represent positive constants. The parameter τ, meanwhile, corresponds to the actual physical time.

If the physical transformations of the system cease, then:

$$dS = dI = d\Omega = dE = 0 \text{ (31)}$$

so: $d\tau = 0$ (32)

(32) implies that, without physical transformation, no measurable time emerges. This conclusion is consistent with several contemporary approaches, such as relational quantum gravity (Rovelli, 2008), the thermodynamics of time (Donoghue & Menezes, 2020), emerging models of time in quantum cosmology (Bojowald, 2012), as well as informational interpretations of time (Gómez & Jimenez, 2020).

From a cosmological perspective, τ is not merely an external clock. It constitutes the cumulative measure of the irreversible transformations of the cosmos. In this view, entropy provides direction, information organizes the coherence of the system's evolution, organization stabilises certain configurations, and time emerges as the dynamic result of all these processes.

Starting from the cosmological state space;

the state space becomes:

$$\mathcal{E} \subset \mathbb{R}^4 \text{ (33)};$$

cosmic evolution thus corresponds to a trajectory:

$$X: \mathbb{R}^+ \to \mathcal{E} \text{ (34)};$$

the principle of energy-information conservation posits:

$$\frac{dU}{d\tau} = 0 \text{ (10)}$$

with:

$$U = E + \lambda I + \mu\Omega \text{ (08)}$$

Therefore:

$$\frac{dE}{d\tau} + \lambda\frac{dI}{d\tau} + \mu\frac{d\Omega}{d\tau} = 0 \text{ (11)}$$

(11) states that any local increase in organization or information necessarily involves a redistribution of energy. The cosmic system is thus locally dissipative, as every structural change requires an expenditure of energy, but globally conservative, since the totality of these exchanges maintains the energy balance of the cosmos.

2.2 Coupled Non-linear Dynamics of the Model

The model is formulated as a coupled differential equation system (Arévalo et al., 2012). The general dynamic model becomes:

$$\begin{cases} \frac{dS}{d\tau} = \sigma - \Phi(I, \Omega, S) \\ \frac{dI}{d\tau} = \gamma\Omega - \delta SI \\ \frac{d\Omega}{d\tau} = \alpha\Phi(I, \Omega, S) - \beta S\Omega \end{cases} \quad (35)$$

where: σ>0 represents the entropic production; Φ is the "anti-entropic potential"; and α, β, γ, δ are positive constants.

(35) constitutes a non-linear dissipative dynamical system.

2.3 Analysis of cosmological steady states

Steady-state conditions verify: $\frac{dS}{d\tau} = \frac{dI}{d\tau} = \frac{d\Omega}{d\tau} = 0$ (36)

We get: $\sigma = \Phi$ (37)

and: $\gamma\Omega = \delta SI$ (38)

as well as: $\alpha\Phi = \beta S\Omega$ (39)

substituting Φ into (39) gives:

$$\alpha\eta\frac{I\Omega}{1+S} = \beta S\Omega \text{ (40)}$$

and if Ω≠0, then (40) becomes:

$$\alpha\eta I = \beta S(1+S) \text{ (41)}$$

(41) represents the mathematical condition for a self-organising pseudo-stationary universe.

2.4 Local Stability Analysis

We're setting up:

$$X = \begin{pmatrix} S \\ I \\ \Omega \end{pmatrix} \text{ (42)}$$

and the dynamic system:

$$\frac{dX}{d\tau} = F(X) \text{ (43)}$$

where:

$$F(X) = \begin{pmatrix} F_1(S, I, \Omega) \\ F_2(S, I, \Omega) \\ F_3(S, I, \Omega) \end{pmatrix} \text{ (44)}$$

Thus: F_1 describes the evolution of entropy; F_2 describes the evolution of information; and F_3 describes the evolution of organization.

From (35):

$$\begin{cases} \frac{dS}{d\tau} = \sigma - \Phi(I,\Omega,S) \\ \frac{dI}{d\tau} = \gamma\Omega - \delta SI \\ \frac{d\Omega}{d\tau} = \alpha\Phi(I,\Omega,S) - \beta S\Omega \end{cases}$$

we get directly:

- For the entropy function F_1

Entropy naturally increases through heat dissipation: +σ; but organization locally reduces this dissipation: -Φ

Therefore:

$$F_1(S,I,\Omega) = \sigma - \eta\frac{I\Omega}{1+S} \text{ (45)}$$

or

$$F_1(S,I,\Omega) = \sigma - \Phi(I,\Omega,S) \text{ (45')}$$

(45) reflects the difference between entropic production and the anti-entropic effects associated with organising processes.

Si $F_1 > 0 \rightarrow$ entropy increases and if $F_1 < 0 \rightarrow$ organization counterbalances dissipation.

- For the informational function F_2

Information increases with organization: +γΩ, but decreases when dissipation breaks down correlations: -δSI

Therefore:

$$F_2(S,I,\Omega) = \gamma\Omega - \delta SI \text{ (46)}$$

(46) highlights that organization generates coherent information, whereas entropic dissipation leads to the destruction of information. In other words, organization produces coherence, whilst entropy acts as a force of disintegration that destroys it.

- For the organizational function F_3

Organization grows thanks to the anti-entropic potential: +αΦ, but dissipation destroys structures: -βSΩ

Therefore:

$$F_3(S,I,\Omega) = \alpha\eta\frac{I\Omega}{1+S} - \beta S\Omega \text{ (47)}$$

or

$$F_3(S,I,\Omega) = \alpha\Phi(I,\Omega,S) - \beta S\Omega \text{ (47')}$$

(47) represents the growth of the organization through self-organization and its breakdown through dissipation. Consequently, if $F_3 > 0$, structures emerge; if $F_3 < 0$, disorganization prevails.

The functions F_1, F_2, F_3 in our model can be used to describe couplings, study equilibria, analyse stability and detect organizational transitions. These functions act as the laws of evolution of the cosmic system in our model.

Local stability is determined by the Jacobian matrix:

$$J = \begin{pmatrix} \frac{\partial F_1}{\partial S} & \frac{\partial F_1}{\partial I} & \frac{\partial F_1}{\partial \Omega} \\ \frac{\partial F_2}{\partial S} & \frac{\partial F_2}{\partial I} & \frac{\partial F_2}{\partial \Omega} \\ \frac{\partial F_3}{\partial S} & \frac{\partial F_3}{\partial I} & \frac{\partial F_3}{\partial \Omega} \end{pmatrix} \text{ (48)}$$

- **Partial derivatives**

For F_1 :

$$F_1 = \sigma - \eta\frac{I\Omega}{1+S} \text{ (45)}$$
$$\frac{\partial F_1}{\partial S} = \eta\frac{I\Omega}{(1+S)^2} \text{ (49)}$$
$$\frac{\partial F_1}{\partial I} = -\eta\frac{\Omega}{1+S} \text{ (50)}$$
$$\frac{\partial F_1}{\partial \Omega} = -\eta\frac{I}{1+S} \text{ (51)}$$

For F_2 :

$$F_2 = \gamma\Omega - \delta SI \text{ (46)}$$
$$\frac{\partial F_2}{\partial S} = -\delta I \text{ (52)}$$
$$\frac{\partial F_2}{\partial I} = -\delta S \text{ (53)}$$
$$\frac{\partial F_2}{\partial \Omega} = \gamma \text{ (54)}$$

For F_3

$$F_3 = \alpha\eta\frac{I\Omega}{1+S} - \beta S\Omega \text{ (47)}$$
$$\frac{\partial F_3}{\partial S} = -\alpha\eta\frac{I\Omega}{(1+S)^2} - \beta\Omega \text{ (55)}$$
$$\frac{\partial F_3}{\partial I} = \alpha\eta\frac{\Omega}{1+S} \text{ (56)}$$
$$\frac{\partial F_3}{\partial \Omega} = \alpha\eta\frac{I}{1+S} - \beta S \text{ (57)}$$

The steady state $(S^{\backslash *}, I^{\backslash *}, \Omega^{\backslash *})$ checks:

$$\sigma = \frac{\eta I^{\backslash *}\Omega^{\backslash *}}{1+S^{\backslash *}} \text{ (58)}$$
$$\gamma\Omega^{\backslash *} = \delta S^{\backslash *} I^{\backslash *} \text{ (59)}$$
$$\frac{\alpha\eta I^{\backslash *}\Omega^{\backslash *}}{1+S^{\backslash *}} = \beta S^{\backslash *}\Omega^{\backslash *} \text{ (60)}$$

and so:

$$\alpha\eta I^{\backslash *} = \beta S^{\backslash *}(1+S^{\backslash *}) \text{ (61)}$$

(61) constitutes the fundamental condition for steady-state self-organization in our model.

Similarly, the Jacobian matrix is:

$$J = \begin{pmatrix} \eta\frac{I\Omega}{(1+S)^2} & -\eta\frac{\Omega}{1+S} & -\eta\frac{I}{1+S} \\ -\delta I & -\delta S & \gamma \\ -\alpha\eta\frac{I\Omega}{(1+S)^2} - \beta\Omega & \alpha\eta\frac{\Omega}{1+S} & \alpha\eta\frac{I}{1+S} - \beta S \end{pmatrix} \text{ (62)}$$

At the stationary point, the last term simplifies considerably. $\alpha\eta\frac{I}{1+S} - \beta S = 0$ (63)

Indeed: $\alpha\eta I^{\backslash *} = \beta S^{\backslash *}(1+S^{\backslash *})$ (61)

so: $\frac{\alpha\eta I^{\backslash *}}{1+S^{\backslash *}} = \beta S^{\backslash *}$ (64)

which implies: $\frac{\partial F_3}{\partial \Omega}|_{*} = 0$ (65)

The stationary Jacobian becomes:

$$J^{\backslash *} = \begin{pmatrix} A & B & C \\ D & E & F \\ G & H & 0 \end{pmatrix} \text{ (66)}$$

with:

$A = \frac{\eta I^{\backslash *}\Omega^{\backslash *}}{(1+S^{\backslash *})^2} > 0$; $B = -\frac{\eta\Omega^{\backslash *}}{1+S^{\backslash *}} < 0$; $C = -\frac{\eta I^{\backslash *}}{1+S^{\backslash *}} < 0$; $D = -\delta I^{\backslash *} < 0$; $E = -\delta S^{\backslash *} < 0$;

$F = \gamma > 0$; $G = -\frac{\alpha\eta I^{\backslash *}\Omega^{\backslash *}}{(1+S^{\backslash *})^2} - \beta\Omega^{\backslash *} < 0$; $H = \frac{\alpha\eta\Omega^{\backslash *}}{1+S^{\backslash *}} > 0$

The equity values satisfy:

$$\det(J^{\backslash *} - \lambda I) = 0 \text{ (67)}$$

which leads to: $\lambda^3 + a_1\lambda^2 + a_2\lambda + a_3 = 0$ (68)

where $a_1 = -\mathrm{Tr}(J^{\backslash *})$; a_2 = 'sum of the principal minors' and $a_3 = -\det(J^{\backslash *})$.

2.5 General Stability Condition (Routh–Hurwitz criterion) (Chakraborty & Burikham, 2026)

For a cubic system: $\lambda^3 + a_1\lambda^2 + a_2\lambda + a_3 = 0$ (69)

Local stability requires: $a_1 > 0$; $a_2 > 0$ (70); $a_3 > 0$ and above all: $a_1a_2 > a_3$ (70')

These conditions ensure that $\Re(\lambda_i) < 0$, which ensures local stability. The system becomes stable when: (i) the entropic destruction of information is sufficiently pronounced, (ii) the self-organization mechanisms remain moderate, and (iii) positive feedback does not take over. In other words: $\delta S^{\backslash *}$ et $\beta S^{\backslash *}$ must prevail γ and $\alpha\eta$.

Thus, dissipation dampens fluctuations; the organization remains bounded and cosmological structures persist without divergence. This describes a self-organising pseudo-stationary universe.

2.6 Unstable Conditions

A dynamic system is unstable if at least one of its eigenvalues has a strictly positive real part: $\Re(\lambda_i) > 0$. In particular, it occurs when the following condition is met: $a_1 \cdot a_2 < a_3$ or when a coefficient changes sign, thereby altering the internal balance of the parameters.

This situation results in: excessive amplification of self-organising mechanisms; too rapid a growth in coherent information; and insufficient dissipation of fluctuations.

In other words, if: $\alpha\eta \gg \beta$ or if $\gamma \gg \delta S^*$, then self-organization becomes explosive and the system departs from its steady state.

2.7 Oscillation Conditions

Oscillations occur when the eigenvalues become complex:

$$\lambda_{1,2} = p \pm i\omega \quad (71)$$

with: $\omega \neq 0$

This requires cross-feedback between: entropy (S); information (I); and organization (Ω).

In our model, these couplings are contained in: J (B,C,D,F,G,H). Oscillations occur when: γ, α, η become comparable to the dissipative terms: δ, β. Under these conditions, we can conclude that: (i) organization produces information; (ii) information reinforces organization; and (iii) entropy periodically destroys this coherence. The system then enters a cycle of oscillation:

(disorder→organization→saturation→dissipation→re-organization).

2.8 Hopf transition

The most important case is the Hopf bifurcation (Chakraborty et al., 2021). It appears when: $\Re(\lambda_{1,2}) = 0$; $\Im(\lambda_{1,2}) \neq 0$. This can be written as: $\lambda_{1,2} = \pm i\omega$ (72)

The system shifts from a stable equilibrium to self-sustained oscillations when the organising feedbacks exactly offset the dissipation: $\gamma\alpha\eta \approx \beta\delta S^*$. This condition marks a critical transition, indicating a change in the dynamic regime. It reflects the emergence of an oscillatory state in which steady-state equilibrium is replaced by a regular alternation between organization and disorganization.

Within the framework of our approach, this transition enables us to model: cosmological oscillations; cycles of vacuum organization; order/disorder alternations; and large-scale periodic structures.

These phenomena, although fundamental to understanding universal dynamics, will be discussed in greater detail later in this work.

2.9 Possible Configurations of the Model

Our model exhibits four fundamental dynamic regimes: (i) when it is stable, that is, when the real part of the eigenvalues is negative ($\Re(\lambda_i) < 0$), the universe behaves like a stationary self-organising system; (ii) in an unstable regime, when $\Re(\lambda_i) > 0$, there is explosive growth of structures; (iii) the oscillatory regime, characterised by a non-zero imaginary part ($I(\lambda_i) \neq 0$), corresponds to cosmological cycles and, finally, (iv) the Hopf critical regime, defined by $\Re(\lambda) = 0$, marks a dynamic transition.

The model predicts three major phenomena: organizational transitions in complex systems, structural oscillations and cosmological bifurcations. The cosmos thus becomes a dynamic system where cosmic evolution can be formalised as:

$$\text{'cosmic evolution'} = (F_1, F_2, F_3) \quad (73)$$

In other words, the constant interplay between dissipation, information and self-organization dictates the evolution of the cosmos.

The study and validation of this system require establishing the conditions for the existence, uniqueness and convergence of the proposed cosmological model. To this end, the system is reformulated within the standard framework of non-linear dynamical systems, allowing for rigorous analysis and integration into the general theory of complex systems.

For that, the system is defined as follows:

$$\frac{dX}{d\tau} = F(X) \quad (43) \text{ with : } X = (S, I, \Omega) \in \mathbb{R}^3$$

$$\text{and } F(X) = \begin{pmatrix} \sigma - \frac{\eta I\Omega}{1+S} \\ \gamma\Omega - \delta SI \\ \frac{\alpha\eta I\Omega}{1+S} - \beta S\Omega \end{pmatrix} \text{ where: } \alpha, \beta, \gamma, \delta, \eta, \sigma > 0 \quad (74)$$

2.10 Availability of Solutions in the Local Area

According to the Cauchy–Lipschitz (or Picard–Lindelöf) theorem, the problem:

$$\frac{dX}{d\tau} = F(X), X(0) = X_0 \quad (75)$$

admits a unique local solution if: (i) F is continuous and (ii) F is Lipschitz locally.

- **Continuity check**

The components of F are:

$$\begin{cases} F_1 = \sigma - \dfrac{\eta I\Omega}{1+S} \\ F_2 = \gamma\Omega - \delta SI \\ F_3 = \dfrac{\alpha\eta I\Omega}{1+S} - \beta S\Omega \end{cases} \quad (76)$$

These functions are rational-polynomial.

The only possible singularity occurs at: $1 + S = 0$; that is to say: $S = -1$. Or physically: $S \geq 0$ (because entropy is positive).

So, in the physical realm: $\mathcal{D} = \{(S, I, \Omega) \in \mathbb{R}^3 \ ; \ S \geq 0\}$, the functions F_1 F_2 and F_3 are continuous.

Therefore: $F \in C^0(\mathcal{D})$ (77)

- **Lipschitz condition check**

A function is locally Lipschitz if : $\| F(X) - F(Y) \| \leq L \| X - Y \|$ on any compact (Zhao et al., 2010). However, all the partial derivatives of F exist and are continuous for $S > -1$.

So: $F \in C^1(\mathcal{D})$ and any function C^1 is locally Lipschitz.

Thus, the system has a single local solution for any initial condition:

$X_0 = (S_0, I_0, \Omega_0)$ with $S_0 > -1$ and physically: $S_0, I_0, \Omega_0 \geq 0$ (78)

- **Global prevalence**

Local existence does not guarantee that a solution exists for all values of $\tau \to \infty$. We must show that the trajectories remain bounded.

- **Positivity of solutions**

We first show that the positive real domain is invariant: $S \geq 0, I \geq 0, \Omega \geq 0$

For $= 0$: $\frac{dS}{d\tau} = \sigma - \eta I\Omega$. As $\sigma > 0$, the flow generally moves towards: $S > 0$ (79);

For $= 0$: $\frac{dI}{d\tau} = \gamma\Omega \geq 0$; so: $I(\tau) \geq 0$ (79');

For $\Omega = 0$: $\frac{d\Omega}{d\tau} = 0$; so: $\Omega(\tau) \geq 0$; Therefore: $\mathbb{R}^3_+$ is invariant (79'').

The solutions remain physically valid.

- **Boundedness condition**

To ensure the survival of the species, we must prevent: $\| X(\tau) \| \to \infty$ in a finite time.

Let us consider:

$$U = S + I + \Omega \quad (80)$$

So:

$$\frac{dU}{d\tau} = \frac{dS}{d\tau} + \frac{dI}{d\tau} + \frac{d\Omega}{d\tau} \quad (80')$$

Substituting (80') with their expressions, we obtain:

$$\frac{dU}{d\tau} = \sigma - \frac{\eta I\Omega}{1+S} + \gamma\Omega - \delta SI + \frac{\alpha\eta I\Omega}{1+S} - \beta S\Omega \quad (81)$$

So:

$$\frac{dU}{d\tau} = \sigma + \gamma\Omega - \delta SI - \beta S\Omega + (\alpha - 1)\frac{\eta I\Omega}{1+S} \quad (81')$$

- **Fundamental condition for dissipation**

If $\alpha < 1$ in (81'): so $(\alpha - 1)\frac{\eta I\Omega}{1+S} < 0$ (82).

This means that the dissipative terms become dominant: -δSI, -βSΩ, and prevent divergence.

Thus: U(τ) remains bounded. Under these conditions: α<1 constitutes an important sufficient condition for global stability and global existence.

- **Condition for asymptotic convergence**

Convergence means: $X(\tau) \to X'^{*}$ when: $\tau \to \infty$ where X'^{*} is a steady state (83). According to the Lyapunov method

$$\text{Let us consider: } W(X) = \frac{1}{2} \| X - X'^{*} \|^2 \quad (84)$$

$$\text{So: } \frac{dW}{d\tau} = (X - X'^{*}) \cdot F(X) \quad (85)$$

Asymptotic convergence is achieved if : $\frac{dW}{d\tau} < 0$ in the vicinity of X'^{*}.

That is exactly the same as imposing: $\Re(\lambda_i) < 0$ for all eigenvalues of the Jacobian. Thus, asymptotic convergence corresponds to local stability.

- **Analytical convergence criterion**

According to Adolf Hurwitz's criterion:

for $\lambda^3 + a_1\lambda^2 + a_2\lambda + a_3 = 0$ (86), we must have: $a_1 > 0, a_2 > 0, a_3 > 0, a_1 a_2 > a_3$

so: $X(\tau) \to X'^{*}$

The mathematical conditions translate to: (i) if $F \in C^1$ there is a regular cosmic dynamic; (ii) if there is positivity, then entropy and organization are physically admissible; (iii) if $\alpha < 1$, then self-organization is limited; (iv) if δ and β are sufficiently large, then there is stabilising dissipation; finally, if the Hurwitz criterion is satisfied, then the system's fluctuations are damped.

In general: we can conclude that the system has a unique local solution for any initial physical condition. It has a bounded global solution if dissipative mechanisms dominate the organising feedbacks. Finally, convergence towards an organised cosmological state occurs when Hurwitz's stability conditions are satisfied.

The model mathematically describes a non-equilibrium universe that can converge towards stable self-organised structures without violating the global increase in entropy (S>0).

3. Variational formulation of model

In this model, the variational formulation should not be interpreted as a classical mechanical Lagrangian formulation. It falls within the framework of non-equilibrium thermodynamics of complex self-organising systems.

The model's dynamical space is the space of informational thermodynamic states $\mathcal{E} \subset \mathbb{R}^4$ defined by $X = (U, S, I, \Omega)$. Cosmological evolution corresponds to a trajectory: $X(\tau) = (U(\tau), S(\tau), I(\tau), \Omega(\tau))$ within this thermodynamic space.

The fundamental principle of the model is based on the idea that the evolution of the cosmos is governed by a dynamic interplay between: dissipation, information and organization.

In this context, the quantity:

$$\Phi(S, I, \Omega) = S - \kappa I - \mu\Omega \quad (87)$$

does not represent a mechanical Lagrangian in the sense of classical analytical mechanics. It represents a generalised non-equilibrium thermodynamic potential that measures the overall state of dissipation and organization of the cosmic system.

Thus, the term "S" reflects the irreversible dissipative tendency; the term "-κI" represents the structuring effect of coherent information; and the term "-μΩ" reflects the organizational stabilisation of cosmological structures.

The associated variational principle:

$$\delta \int \Phi \, d\tau = 0 \quad (88)$$

should therefore not be interpreted as a principle of least action in the mechanical sense. Rather, it expresses the idea that the cosmic system evolves towards thermodynamic trajectories that optimise the balance between dissipation, informational coherence and organization.

The variation occurs along thermodynamic trajectories: $X(\tau) = (S(\tau), I(\tau), \Omega(\tau))$ in state space.

In our model, entropy is not a mechanical coordinate; it's does not represent an inertial velocity; cosmological dynamics are not conservative dynamics.

The system evolves according to irreversible thermodynamic flows characterised by: entropic production; information exchanges; and dissipative self-organization mechanisms.

Thus, the evolution equations:

$$\begin{cases} \frac{dS}{d\tau} = \sigma - \Phi(I, \Omega, S) \\ \frac{dI}{d\tau} = \gamma\Omega - \delta S I \\ \frac{d\Omega}{d\tau} = \alpha\Phi(I, \Omega, S) - \beta S\Omega \end{cases} \quad (35)$$

are interpreted, in our model, as coupled thermodynamic flux equations, rather than as equations of motion in the mechanical sense.

Consequently, the classical Euler–Lagrange equations:

$$\frac{d}{d\tau}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}_i}\right) - \frac{\partial \mathcal{L}}{\partial q_i} = 0 \quad (89)$$

are not used here in their usual inertial interpretation.

The variational principle must be understood as a generalised thermodynamic principle of dissipative relaxation, akin to irreversible thermodynamics; dissipative structures as described by Ilya Prigogine (Prigogine, s. d.); non-equilibrium self-organising systems and modern thermodynamic variational formulations.

Cosmological evolution thus appears as an irreversible process of dissipative self-organization in which entropy provides the temporal direction; information structures correlations and organization stabilizes certain configurations of the cosmos. Finally, time itself emerges from this accumulation of irreversible transformations.

4. Generalisation of Cosmic Information Entropy

Informational content is defined by Shannon's entropy (Shanon, 1948) :

$$I = -\sum_i p_i \ln p_i \quad (90)$$

where p_i represents the probability of a cosmological microstate.

The level of organization becomes: $\Omega = \chi \frac{I_c}{S}$ (91); where I_c denotes coherent information; S denotes entropic dissipation. Thus, high informational coherence increases organization, whereas excessive dissipation destroys structure.

However, in the previous global formulation, the thermodynamic variables S, I and Ω describe average effective quantities characterising the system's overall cosmological state. The model will enable the study of fundamental self-organization mechanisms, steady states, dynamic bifurcations and the emergence of time.

Furthermore, within the framework of cosmic information entropy, a strictly global description becomes insufficient when one wishes to take into account: spatial inhomogeneities; thermodynamic gradients; information correlations; dissipative flows; and the local emergence of cosmological structures.

Indeed, cosmic information and structural organization are not uniformly distributed throughout the observable universe. Information entropy must therefore be interpreted as a spatially distributed quantity.

The model's variables thus become continuous thermodynamic fields:

$$S = S(x^\mu), I = I(x^\mu), \Omega = \Omega(x^\mu) \quad (92)$$

$x^\mu = (x^0, x^1, x^2, x^3)$ refers to the actual coordinates of the emerging space-time.

In this ongoing expansion: $S(x^\mu)$ represents the local density of information entropy; $I(x^\mu)$ describes the local density of informational coherence, and Ω (x^μ) represents the local level of cosmic organization.

The cosmos can then be interpreted as a non-equilibrium thermodynamic system within which structures emerge from dissipative self-organization processes.

This generalisation naturally leads to the introduction of diffusion and thermodynamic transport terms into the dynamical equations:

$$\begin{cases} \frac{\partial S}{\partial \tau} = D_S \nabla^2 S + \sigma - \frac{\eta I \Omega}{1+S} \\ \frac{\partial I}{\partial \tau} = D_I \nabla^2 I + \gamma \Omega - \delta S I \\ \frac{\partial \Omega}{\partial \tau} = D_\Omega \nabla^2 \Omega + \frac{\alpha \eta I \Omega}{1+S} - \beta S \Omega \end{cases}$$

where D_S represents entropic diffusion; D_I the dissemination of information and D_Ω organizational dissemination.

These equations (93) simultaneously describe: the propagation of thermodynamic fluctuations; information exchange; dissipative mechanisms; and the local emergence of self-organised structures.

From this perspective, the universe no longer appears as a mere passive space containing matter, but as a complex non-equilibrium thermodynamic system in which cosmic organization emerges dynamically from the interactions between dissipation, information and structuring.

This continuous formulation constitutes a natural extension of the global model and paves the way for a thermodynamic description of cosmological structures, spatial correlations and large-scale self-organization phenomena.

5. Continuous Formulation and Field Equations of this Model

The model presented is formulated here using a global approach with effective thermodynamic variables. A continuous generalization in the form of a non-equilibrium thermodynamic field theory can be considered to introduce: spatial gradients; diffusion phenomena; local dissipative structures; and a possible geometric emergence of space-time. This extension will be the subject of further developments.

II. Dimensionless Formulation, Physical Calibration, Advanced Model Analysis, Possible Observational and Theoretical Predictions of the Model

Modern cosmology goes beyond purely geometric and energetic approaches to include thermodynamics and information theory. In this context, the universe is seen as a non-equilibrium system where entropy (S), coherent information (I), and organization (Ω) interact. The thermodynamic cosmological model proposed here highlights different regimes: dominant dissipation, quasi-stationarity, and self-organization, as well as the possibility of oscillatory cycles linked to Hopf bifurcations.

Here, we present a dimensionless formulation of the model, its physical calibration based on reference cosmological quantities (Bekenstein entropy, Landauer's principle, observed entropy of the universe), and an advanced analysis of the dynamic regimes.

Phase portraits and steady-state conditions show that this approach generalizes classical thermodynamics while paving the way for complex self-organized regimes.

1. Dimensionless Formulation of the Model

In order to reduce the number of independent parameters and to identify the fundamental mechanisms governing cosmological dynamics, the system is reformulated in a dimensionless form.

Let: S_c (characteristic entropy); I_c (characteristic information); Ω_c (characteristic level of organization); and t_c (characteristic time).

We introduce the reduced variables:

$$s = \frac{S}{Sc}, i = \frac{I}{Ic}, \omega = \frac{\Omega}{\Omega_c}, \tau = \frac{t}{t_c}$$

The counter-entropic potential or dissipative self-organization potential:

$$\Phi = \frac{\gamma I \Omega}{s+\eta} \quad (94)$$

is then written:

$$\varphi = \frac{i\omega}{s+\varepsilon}, \varepsilon = \frac{\eta}{Sc} \quad (95)$$

The d (93) ı (35) becomes (96):

$$\begin{cases} \frac{ds}{d\tau} = a - \frac{bi\omega}{s+\varepsilon} \\ \frac{di}{d\tau} = c\omega - di \\ \frac{d\omega}{d\tau} = \frac{ei\omega}{s+\varepsilon} - fs\omega \end{cases}$$

where a, b, c, d, e, f are dimensionless constants. This formulation makes it possible to study the universal properties of the model independently of the chosen physical units.

- **Physical dimension of the model's variables**

Table I. Physical Units of the Model Variables.

S	Functional entropy	$J \cdot K^{-1}$
I	Consistent information	bit
Ω	Overall level of organization	Without dimension
E	Physical energy	J
U	Global energy-information	J
Φ	Anti-entropy potential	$J \cdot K^{-1} \cdot s^{-1}$
J	Entropic production	$J \cdot K^{-1} \cdot s^{-1}$
t	Physical time	s
τ	Reduced time	Without dimension
η	Entropic regularization parameter	$J \cdot K^{-1}$
α	Informational coupling	s^{-1}
β	Dissipation coefficient	s^{-1}
γ	Organizational effectiveness	Without dimension

The table I above ensures the dimensional consistency of the whole model.

- **Demonstration of the Steady State**

The steady state is defined by the simultaneous cancellation of the time derivatives:

$$\frac{dS}{d\tau} = 0, \frac{dI}{d\tau} = 0, \frac{d\Omega}{d\tau} = 0$$

We get successively:

- Entropic equation: $J = \Phi$
- Informational equation: $I^* = \frac{\alpha}{\beta}\Omega^*$
- Organizational equation: $\gamma\Phi = \beta S^*$

By replacing Φ, we get:

$$\gamma^2 I\Omega = \beta S^*(S^* + \eta) \quad (97)$$

This relationship constitutes the fundamental condition for the existence of a self-organized pseudo-stationary state.

- **Classical Thermodynamic Limit**

In the limit I→0, the counter-entropy potential disappears (Φ→0) and the system reduces to :

$$\frac{dS}{d\tau} = J, \frac{dI}{d\tau} = -\beta I, \frac{d\Omega}{d\tau} = -\beta S\Omega \quad (98)$$

Thus :

- $I \to 0$ (disappearance of coherent information)
- $\Omega \to 0$ (collapse of the organization)
- $dS/d\tau > 0$ (monotone growth of entropy)

The model matches the behaviour dictated by the second law of thermodynamics.

2. Physical Calibration of the Model

The physical calibration proposed in this study is not meant to tweak the model's parameters to match precise cosmological observations. Instead, it aims to anchor the characteristic physical quantities in orders of magnitude that are compatible with the fundamental principles of thermodynamics, information theory, and modern cosmology. In this way, it provides a coherent framework for the physical interpretation of dimensionless variables and dynamic regimes highlighted by the theoretical and numerical analysis of the model.

- **Bekenstein Entropy** (Bekenstein, 1974)

Defined by:

$$S_B = \frac{k_B c^3 A}{4G\hbar} (99)$$

Here, Bekenstein's entropy provides a fundamental limit on the maximum amount of information and entropy that can be contained in a given gravitational region. In our model, it serves as a natural benchmark to define the characteristic entropy scale S_c and connect the dimensionless variables to the constraints set by gravitational thermodynamics.

- **Landauer's Principle** (Bérut et al., 2012)

This principle is defined by:

$$E_L = k_B T \ln 2 (100)$$

This relationship establishes the link between the minimal energy associated with any irreversible information processing operation. This fundamental connection between energy and information explains the introduction of the coupling between the variables "I" and "S" in our model and provides a physical basis for the energetic interpretation of informational processes involved in cosmic self-organization.

- **Observed Cosmological Entropy**

$$S_{obs} \approx 10^{104} - 10^{106} k_B (101)$$

Estimates of the total cosmological entropy provide an observational limit that helps physically anchor the entropic variables of the model. They give a realistic ballpark for calibrating Sc and offer a consistency check between the theoretical predictions of the dynamic system and the thermodynamic constraints inferred from the observable Universe.

- **Cosmological Number of Self-organization**

$$N = \frac{\Phi}{J} (102)$$

The cosmological number of self-organization measures the competition between entropic dissipation and organization. It helps us to identify the different dynamic regimes of the model: dominant dissipation (N<1); pseudo-stationarity (N=1); and dominant self-organization (N>1).

3. Advanced Model Analysis

- **Numerical Simulations and Phase Portraits**

To explore the dynamic behavior of the proposed thermodynamic cosmological model, a series of numerical simulations was carried out based on the coupled differential system describing the interactions between functional entropy (S), coherent information (I), and the level of cosmological organization (Ω). The resulting trajectories were analyzed in different phase spaces to characterize the possible evolution regimes of the system.

The results are shown in Figure 1 as phase portraits in the planes (S, Ω), (S, I), and (I, Ω), as well as in the three-dimensional space (S, I, Ω).

- **Existence of a Stationary Attractor**

Phase portraits highlight the existence of a stationary equilibrium point called E*, which corresponds to a configuration where the effects of entropy dissipation are balanced by the mechanisms of informational structuring and self-organization. In the (S, Ω) and (S, I) planes, the trajectories gradually converge towards this steady state following damped spirals. This behavior is typical of a stable focus and confirms the results of the local analysis obtained from the system's Jacobian matrix.

The existence of this attractor shows that the model has an intrinsic self-regulation mechanism that prevents the dynamic variables from diverging. Initial disturbances are gradually absorbed by the system, which spontaneously returns to its equilibrium state. This result suggests that cosmological evolution can lead to a quasi-stationary regime where entropy continues to be produced while maintaining a non-zero level of information and organization.

- **Coupling Between Entropy and Information**

The phase portrait in the (S, I) plane reveals a complex interaction between entropic growth and informational processes. The spiral structure observed shows the existence of damped oscillations around the steady state. Coherent information doesn't decrease monotonically but goes through a series of successive adjustments before stabilizing.

This dynamic shows that information acts like a regulatory mechanism capable of locally modulating the effects of dissipation. So, the increase in entropy doesn't necessarily lead to the immediate destruction of the informational structure. On the contrary, some of this information remains preserved thanks to the feedback mechanisms built into the system.

This property is one of the fundamental elements of the model since information appears here as a dynamic variable that can directly influence the overall thermodynamic evolution.

- **Emergence and Stabilization of the Organization**

The phase portrait in the (S, Ω) plane highlights the role of organization in cosmological dynamics. The trajectories converge to a finite value of Ω despite the continuous increase in entropy. This observation shows that organization doesn't disappear due to dissipative processes but tends toward a stable level determined by the balance between entropy production and "counter-entropy potential".

This behavior is consistent with Prigogine's theory of dissipative structures, which suggests that order can spontaneously emerge in open systems far from thermodynamic equilibrium. In the context of this model, organization appears as an emergent property resulting from the continuous coupling between information and dissipation.

- **Appearance of Limit Cycles and Hopf bifurcation**

The phase portrait in the (I, Ω) plane reveals the existence of more complex dynamic behavior. Besides the trajectories converging toward the steady state, we see the appearance of a closed orbit corresponding to a stable limit cycle. The presence of this structure is characteristic of a Hopf bifurcation. When self-organization mechanisms become strong enough to overcome dissipation, the steady state loses its stability and gives way to a self-sustained oscillatory regime.

In this regime, information and organization periodically change according to cycles of growth and decline. The system no longer reaches a fixed state but instead oscillates around an average configuration. This property suggests that some cosmological regimes could be marked by periodic alternations between phases of organization and phases of dissipation, paving the way for a cyclical interpretation of certain cosmic evolution processes.

- **Global Dynamics in Phase Space**

The three-dimensional representation of the system in the space (S, I, Ω) provides a concise view of all the dynamic interactions. The trajectories form a spiral structure that converges toward a central region of the state space. This geometry reflects the strongly coupled nature of the three key variables of the model and confirms that cosmological evolution results from a continuous interaction between dissipation, information, and organization.

The attractor observed in three-dimensional space is a sign of the system's overall stability. It shows that the negative feedback mechanisms in the model can keep excessive fluctuations in check and maintain a consistent dynamic over the long term.

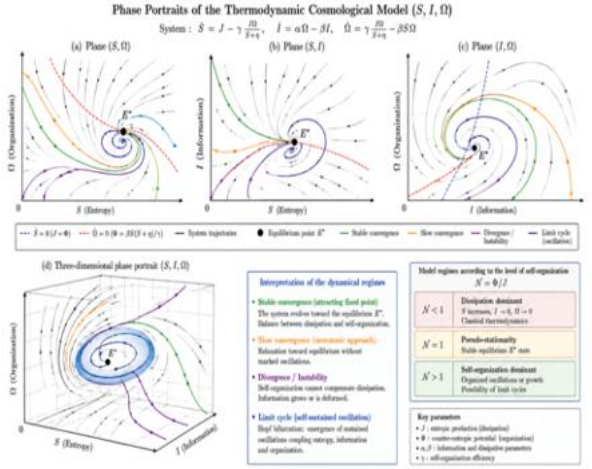

Figure 1. Phase portraits of the cosmological thermodynamic system in the (S, Ω), (S, I), and (I, Ω) planes, as well as in the three-dimensional (S, I, Ω) space. The trajectories illustrate different dynamic regimes: stable convergence, slow convergence, divergence, and limit cycles arising from a Hopf bifurcation.

All of the numerical simulations confirm the analytical predictions obtained earlier. Three fundamental dynamic regimes naturally emerge: (i) a regime dominated by dissipation characterized by entropic growth leading to the gradual loss of information and organization; (ii) a quasi-stationary regime where dissipative and organizing processes balance each other out; and (iii) an oscillatory regime associated with the appearance of limit cycles resulting from a Hopf bifurcation.

These results show that the growth of entropy does not necessarily mean moving toward thermal death. Under certain conditions, informational and organizational mechanisms can sustainably stabilize the system and allow complex, persistent structures to emerge. The proposed model thus provides a theoretical framework in which the universe can be seen as a non-equilibrium thermodynamic system capable of generating, maintaining, and renewing high levels of organization despite the fundamental irreversibility of physical processes.

1. Possible observational and theoretical predictions of the model

Within the framework outlined in this work, the universe is conceived as a non-equilibrium thermodynamic system governed by the coupled dynamics of entropy, coherent information, and organization. If this description faithfully reflects the underlying physics, a series of observational and theoretical implications naturally follow: the absence of a genuine thermodynamic heat death, cosmological self-organization and the emergence of large-scale structures, dynamical transitions in cosmic evolution, the emergent origin of the arrow of time, an effective gravitational role of organization, a dynamical interpretation of dark energy, black holes as systems of information reorganization, and testable deviations from the standard cosmological model.

○ Absence of a True Thermodynamic Heat Death

Unlike the standard scenario in which the universe evolves toward a state of maximal entropy and minimal structure, our model predicts the persistence of organized structures through the continuous action of the "counter-entropic potential"

$$\Phi = \frac{\eta I \Omega}{1+S}$$

As long as coherent information remains non-zero, organization is continuously regenerated despite the global increase of entropy. Consequently, the universe is expected to evolve toward a pseudo-stationary regime rather than an equilibrium state characterized by complete thermodynamic uniformity.

○ Cosmological Self-organization and Large-Scale Structures

In the reaction–diffusion formulation, our model naturally predicts the spontaneous emergence of organized spatial structures. The coupled diffusion of entropy, information, and organization can give rise to dissipative patterns analogous to those observed in non-equilibrium complex systems. Such mechanisms may contribute to the genesis of large-scale cosmological structures and provide a complementary pathway to the standard gravitational instability scenario.

○ Dynamical Transitions in Cosmic Evolution

The stability analysis predicts the presence of Hopf bifurcations that delineate stationary, oscillatory, and unstable regimes. This implies that the universe may experience critical organizational transitions throughout its evolution. Such transitions could manifest as successive epochs distinguished by varying degrees of large-scale coherence, rather than by a purely monotonic cosmological trajectory.

○ Emergent Origin of the Arrow of Time

Within this framework, time is not treated as a fundamental background parameter but rather emerges from irreversible thermodynamic transformations. Our model thus predicts that the cosmological arrow of time is intrinsically tied to the coupled evolution of entropy, coherent information, and organization. Irreversibility arises naturally from the dissipative dynamics, without the need for additional assumptions.

○ Effective Gravitational Contribution of Organization

If coherent information and organization possess an effective energetic content, they may contribute indirectly to the gravitational dynamics.

Although the present work does not formulate modified gravitational field equations, it suggests that future extensions may introduce an effective energy-momentum contribution associated with informational organization,

$$T_{\mu\nu}^{\text{eff}} = T_{\mu\nu}^{(m)} + T_{\mu\nu}^{(I)} + T_{\mu\nu}^{(\Omega)}.$$

Such an extension could provide an alternative framework for exploring part of the gravitational phenomena currently attributed to dark matter. In this model, gravity is not treated as a fundamental interaction of nature but as an emergent property arising from the non-equilibrium thermodynamic dynamics of complex systems. It results from the coupled redistribution of energy, coherent information, entropy, and organization. Space-time curvature is interpreted as the geometric manifestation of the thermodynamic constraints generated by this evolution, while dissipative self-organization continuously stabilizes cosmic structures without violating the global increase of entropy.

○ Dynamical Interpretation of Dark Energy

In the proposed approach, accelerated cosmic expansion does not necessarily rely on a strictly constant cosmological constant. Instead, the interplay between dissipative entropy production and organizational potential may generate an effective large-scale repulsive behavior.

Consequently, future developments of the model could predict slight deviations from the standard ΛCDM expansion history, potentially detectable by next-generation cosmological surveys.

○ Black Holes as Information Reorganization Systems

Our model suggests that black holes may fulfill a dual thermodynamic role: they remain regions of extreme gravitational confinement while simultaneously acting as efficient reorganizers of coherent information. This interpretation offers a fresh perspective on the black-hole information problem and may inspire future investigations into possible corrections to the thermodynamics of black-hole evaporation.

○ Testable Deviations from the Standard Cosmological Model

The present framework predicts that sufficiently precise observations could reveal measurable departures from the standard cosmological scenario. These include slight deviations from a strictly constant dark-energy equation of state, possible oscillatory signatures in the expansion history, organization-dependent corrections to large-scale gravitational dynamics, and non-equilibrium thermodynamic imprints in the evolution of cosmic structures. Quantifying these predictions will require dedicated numerical simulations and systematic comparison with cosmological observations.

III. Discussion

The proposed model sets up conceptual connections with several areas of contemporary theoretical physics while keeping its own identity. It fits within the framework of statistical thermodynamics by studying entropy, irreversibility, and systems out of equilibrium. (Goldstein & Lebowitz, 2004), as well as in the field of information theory (Gatenby & Frieden, 2007) by the role given to coherent information in the dynamics of the system. The most significant comparisons concern nonequilibrium thermodynamics (Kleidon, 2009), dissipative structures and self-organized complex systems, which highlight the emergence of collective behaviors resulting from the interaction between dissipation, feedback, and organization.

Conceptual analogies can also be drawn with certain contemporary approaches such as entropic gravity or informational formulations of cosmology. However, these correspondences should not be interpreted as formal equivalences. This model is primarily a thermodynamic approach to cosmological dynamics, where the key variables are entropy, coherent information, and organization. Finally, thermodynamic biology shows a strong connection, highlighting the continuity between cosmic organization and that of living systems, thereby confirming the interdisciplinary relevance of the model.

This approach is different from standard cosmological models that are mainly based on general relativity and the evolution of space-time metrics (Ellis, 2003). Here, cosmological dynamics is described as a nonequilibrium thermodynamic process governed by the interactions between entropic dissipation, coherent information, and self-organization mechanisms. Cosmological structures are interpreted as emergent dissipative configurations whose stability depends on the balance between these different processes. One of the main contributions of this theoretical framework lies in the explicit introduction of organization as an effective dynamic variable.

This formulation allows for the description of the emergence of complex structures as the result of nonlinear interactions between dissipation and information. From this perspective, galaxies, large-scale structures, or even biological systems can be seen as specific manifestations of general self-organization mechanisms observed in nonequilibrium systems.

The model also proposes a rethinking of cosmological time. Time is no longer seen as an external fundamental parameter, but as an emergent quantity linked to the accumulation of irreversible transformations in the system. This idea aligns with several contemporary approaches where temporality comes across as an emergent property connected to physical dynamics rather than an independent pre-existing framework. This approach paves the way for a cosmology of complex systems, creating a conceptual bridge between cosmology, nonequilibrium thermodynamics, information theory, and self-organization dynamics.

The analysis of the dynamic system highlights several possible evolution patterns. The analytical stability conditions show the existence of pseudo-steady states where the dissipative and organizing mechanisms partially balance each other out. The study of the eigenvalues of the Jacobian matrix also suggests the possibility of oscillatory regimes associated with Hopf-type dynamic transitions. These results indicate that the interaction between entropy, information, and organization can generate dynamics richer than what a purely dissipative description would predict.

In this context, the question of the Universe's thermodynamic future can be revisited. Classical thermodynamic models generally link the increase in entropy to a move toward a state of maximum equilibrium, marked by the gradual disappearance of usable gradients, referred to as 'heat death' (Graham, 2023). This model doesn't invalidate this fundamental principle, but it suggests that self-organization mechanisms could still exist locally as long as energy and information flows remain available. The presence of the anti-entropic potential introduced into the system mathematically reflects this possibility without challenging the overall increase in entropy.

The counter-entropic potential, or dissipative self-organization potential, is defined by the following relationship:

$$\Phi(I,\Omega,S) = \eta\frac{I\cdot\Omega}{1+S} \text{ or } \Phi(I,\Omega,S) = \frac{\gamma I\Omega}{S+\eta}$$

Where "I" represents coherent information, "Ω" the level of structural organization, "S" functional entropy, and η a coefficient of organizational efficiency. This expression reflects the cosmic system's ability to generate organization based on informational coherence and structural complexity, while being limited by overall entropic dissipation.

So, even in an overall dissipative universe, some regions can maintain or temporarily rebuild ordered structures. Thermal death no longer means a total end of all cosmic dynamics, but rather a state of high dissipation coexisting with local processes of thermodynamic and informational restructuring. The universe then takes on a pseudo-dynamic character on a local scale and a nearly stationary one on a large scale.

In this view, complex structures—galaxies, star systems, biological or organizational phenomena—aren't just temporary anomalies working against thermodynamics, but natural expressions of the self-organizing properties of systems out of equilibrium. Black holes also take on a new meaning: beyond their irreversible dissipative role, they can be seen as regions where information and thermodynamics are reshaped, capable of participating in the redistribution of the cosmos's energy and information configurations.

The future of the universe therefore appears as a continuous transformation process, where entropy enforces the overall irreversibility of evolution, while anti-entropy mechanisms allow the recurrent emergence of temporary organized structures. The universe no longer heads toward absolute stillness, but toward a dynamic state characterized by high overall dissipation along with ongoing processes of local reorganization. Thermal death becomes less of a final end and more of a transition to a cosmological regime dominated by persistent cycles of dissipation, restructuring, and self-organization.

The numerical simulations carried out in this study should be seen as a qualitative exploration of the model's behavior. They highlight the presence of stationary attractors, converging trajectories, and oscillatory patterns that match the analytical predictions. These results show that the coupling between entropy, information, and organization is enough to produce a variety of emerging behaviours within the dynamic system considered.

It's worth noting, though, that the parameters used in the simulations were chosen for illustrative purposes and aren't based on a calibration from cosmological observations. So, the attractors and oscillations we see should be viewed as plausible dynamic scenarios rather than precise predictions from the model. Likewise, the presence of periodic trajectories in some phase spaces hints at the possibility of oscillatory-type dynamic transitions, but at this stage, it doesn't formally prove the existence of a Hopf bifurcation in the strict mathematical sense.

Despite these limitations, simulations play an important role by showing that the coupling between entropy, information, and organization is enough to generate emergent behaviors that are missing from classical thermodynamic formulations. They thus provide a first level of internal validation of the model's consistency and identify several research directions that deserve further investigation. These include the full analysis of the eigenvalues of the Jacobian matrix, the determination of stability domains in the parameter space, the systematic study of bifurcations, as well as the physical calibration of the model based on constraints from observed cosmological entropy and the Bekenstein bound (Sachdev, 2015) and from Landauer's principle (Bérut et al., 2012).

So, the numerical results obtained shouldn't be seen as an empirical validation of the model but rather as a demonstration of its potential dynamic richness. They show that a theoretical framework based on the interaction between dissipation, information, and organization can generate a variety of regimes compatible with modern concepts of complex systems and non-equilibrium thermodynamics, paving the way for future theoretical and observational developments.

A particularly interesting interpretation of the model concerns the notion of a cosmological state space defined by the variables entropy (S), coherent information (I), and organization (Ω). In this framework, the evolution of the Universe can be represented as a trajectory within a three-dimensional phase space where different dynamic regimes correspond to distinct regions of stability, oscillation, or transition (Figure 2). The attractors identified suggest the existence of preferred cosmological states toward which the system spontaneously tends under the influence of interactions between dissipation and self-organization. This representation offers a unified view of cosmic evolution, in which observed structures are described not just by their energy content or geometry, but also by their position and dynamics within a thermodynamic and informational state space.

The evolution of the Universe is described as a dynamic path resulting from the interaction between entropic dissipation and self-organization mechanisms. The progression from a lightly organized primordial state to increasingly complex regimes illustrates the successive emergence of physical, astrophysical, and potentially biological structures. This depiction highlights the central role of information and organization in forming and temporarily stabilizing complex structures within a thermodynamically out-of-equilibrium universe.

Figure 2 also suggests that the overall increase in entropy does not rule out the existence of local mechanisms of restructuring and self-organization. The regions associated with bifurcations, attractors, and dynamic transitions reflect the possibility of coexistence between global dissipation and the local

emergence of order. Although this is a qualitative representation rather than a quantitative prediction, this visualization provides an intuitive framework for interpreting the model's results and highlights the importance of interactions between entropy, information, and organization in cosmological evolution.

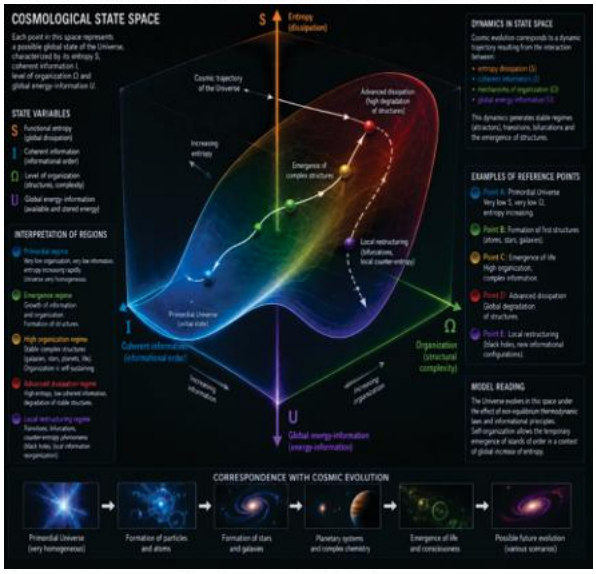

Figure 2: Summary of the Cosmological Model

Several aspects of the model remain exploratory. In particular, the physical interpretation of the counter-entropy potential, the extended conservation of energy–information–organization, the thermodynamic emergence of time, as well as the cosmological implications of self-organization mechanisms need further formalization. Some of the proposals put forward in this work should therefore be considered as research hypotheses rather than established results.

Future developments will need to focus in particular on a full analysis of stability regions, a systematic study of bifurcations, calibrating the model based on observational constraints, as well as identifying potential astrophysical signatures to compare theoretical predictions with observations. Special attention should also be given to making sure the proposed framework is compatible with relativistic descriptions of space-time and current cosmological observations.

So, the model should be seen as a developing theoretical framework whose main interest lies in exploring a cosmology based on the interactions between dissipation, information, and organization. More than an alternative to established cosmological models, it represents an attempt to bring together cosmology, nonequilibrium thermodynamics, information theory, and complex systems science, opening up new perspectives for studying the evolution of the cosmos.

If future theoretical advances succeed in establishing a covariant formulation and deriving explicit gravitational field equations, this framework could provide a unified thermodynamic perspective on several unresolved problems in modern cosmology—including the emergence of time, large-scale self-organization, dark matter, dark energy, and the black-hole information paradox.

CONCLUSION

The model of the thermodynamic cosmology of self-organized complex systems offers a theoretical framework in which the evolution of the cosmos is described by the dynamic interaction between entropy dissipation, coherent information, and self-organization. Unlike cosmological approaches that are mainly based on the geometric dynamics of space-time, our model views the universe as a non-equilibrium thermodynamic system whose structures emerge from feedback mechanisms between entropy production, information flows, and organizing processes.

Our model leads to a coupled nonlinear dynamic system whose fundamental mathematical properties have been studied. The analysis highlights the existence of self-organized quasi-stationary states of the universe, establishes local stability conditions based on the Routh-Hurwitz criterion, demonstrates the local and global existence of solutions under certain dissipative conditions, and reveals the possible emergence of oscillatory regimes associated with Hopf bifurcations.

The dimensionless formulation and the physical calibration based on Bekenstein entropy, Landauer's principle, and observed cosmological entropy also help to anchor the model within a framework that's compatible with the main principles of thermodynamics, information theory, and contemporary cosmology.

Numerical simulations confirm the existence of several fundamental dynamic regimes: a regime dominated by dissipation, a quasi-stationary regime characterized by a balance between dissipation and organization, and an oscillatory regime in which information, entropy, and organization evolve cyclically. These results suggest that the overall growth of entropy doesn't rule out the emergence or temporary maintenance of complex structures, and can even coexist with local self-organization mechanisms.

In this model, time no longer shows up as a fundamental parameter outside the physical system, but as an emergent quantity resulting from the accumulation of irreversible transformations. Entropy then gives the time direction, information shapes correlations, and organization stabilizes certain dissipative configurations. Cosmological structures can thus be seen as natural manifestations of out-of-equilibrium thermodynamic dynamics.

Nevertheless, the model should be seen as an exploratory approach, with several components still needing thorough formalization and empirical validation. Anti-entropy mechanisms, the expanded conservation of energy–information–organization, the thermodynamic interpretation of time, as well as potential links with cosmological observations, remain open questions. Future work will notably need to focus on the systematic study of bifurcations, a full analysis of the parameter space, comparison with observational constraints, and the search for astrophysical signatures that could test the model's predictions.

So, the model of thermodynamic cosmology of self-organized complex systems doesn't aim to replace established cosmological models, but rather offers a complementary conceptual framework to explore the combined role of entropy, information, and self-organization in the evolution of the cosmos. Its main contribution lies in opening up an interdisciplinary dialogue between cosmology, non-equilibrium thermodynamics, information theory, and complex systems science.

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