International Journal of Physics and Mathematics

E-ISSN: 2664-8644
P-ISSN: 2664-8636
IJPM 2025; 7(1): 193-197

www.physicsjournal.net
Received: 29-12-2024
Accepted: 25-01-2025

Sheikh Rizwan Ahmed
Research Scholar (Physics), Arni University Indora, Himachal Pradesh, India

Dr. Khalid Bin Masood
Assistant Professor, Arni University Indora, Himachal Pradesh, India

Corresponding Author:
Sheikh Rizwan Ahmed
Research Scholar (Physics), Arni University Indora, Himachal Pradesh, India

Maximum entropy production principle and the evolution of large-scale structure: A thermodynamic framework for cosmic web formation

Sheikh Rizwan Ahmed and Khalid Bin Masood

DOI: https://doi.org/10.33545/26648636.2025.v7.i1b.156

Abstract
This paper discusses the Maximum Entropy Production Principle (MEPP) as a thermodynamic principle to study the development of the large-scale structure (LSS) of the Universe. The study explores how self-organizing cosmic structures including filaments, clusters, and voids follow the laws of entropy production by considering both theoretical modeling and cosmological simulations in combination with statistical analysis. The findings determine that there is a steady growth in entropy density and production rate between the early epochs (z = 10) and the current epochs (z = 0) illustrating the process of increasing the thermodynamic complexity of the Universe. It was found that filaments are the prevailing sources of entropy generation and are responsible to about 55 percent of the total entropy generation because they are dynamic contributors to mass accretion and dissipation of energy. Correlation studies also found that the areas with moderate density differences (0-10) have the largest entropy efficiency with network analysis indicating that the nodes with moderate-high filament connectivity maximize entropic growth. These results confirm that the Universe develops as a self-organizing, nonequilibrium state that prefer the occurrence of states with the maximum production of entropy to offer a single thermodynamic treatment to the formation and stability of cosmic webs.

Keywords: Maximum entropy production principle (mepp), large-scale structure (lss), cosmic web, entropy production, filament connectivity, thermodynamic evolution, cosmology

1. Introduction
The grand scale assembly (LSS) of the Universe is one of the most arresting instances of self-organization in nature where an intricate assemblage of galaxies, clusters, filaments and voids is spread across hundreds of millions of light-years. This cosmological web was formed due to small quantum variations in the Universe at the beginning that were joined by instability of gravity in the aftermath of the Big Bang. These original perturbations grew over billions of years to actually form the complicated hierarchical structures that we see today by nonlinear gravitational collapse, dynamics of the dark matter, and through baryonic interactions. Although classic cosmological models e.g. the ΛCDM (Lambda cold dark matter) model have been able to reproduce the statistical characteristics of the large structures by using only gravitational and hydrodynamic equations, it tends to regard the development of the Universe as purely involving its mechanical and dynamical systems. This strong point of view does not help us to comprehend full thermodynamic underlying the structure formation, namely, the irreversible energy dissipation, entropy production, and self-organization processes that are involved in the development of matter and radiation when both are thrown out of equilibrium.
The Maximum Entropy Production Principle (MEPP) is a thermodynamic generalization of this gravitational model which proposes that the Universe, being an open system in nonequilibrium, moves to states that maximize the entropy production rate and yet fulfills the conservation laws. This principle means that the cosmic structures like filaments and clusters are not arbitrary results of gravitational clustering but rather the emergent forms that are the most efficient thermodynamically. Here, the entropy production is associated with a variety of major processes, including accretion of the matter onto the clusters, heating in shockwaves in the filaments, and cooling in density rich regions which together lead the Universe towards more and more complex states. Through MEPP, cosmologist are able to study the self-organizing behavior of the cosmic web in the context of entropy flow, dissipation rates and

connectivity of the structure. In this way, the MEPP structure enables the connection between gravitational dynamics and nonequilibrium thermodynamics, providing a more insight into why the large-scale structure of the Universe has the characteristic shape of a web, and why it evolves towards more and more entropy-based states as time goes on.

1.1. Research Objectives

- To analyze the evolution of entropy production across cosmic epochs under the MEPP framework.
- To assess entropy distribution and efficiency among voids, filaments, and clusters.
- To examine how filament connectivity and density contrast influence entropy growth and cosmic organization.

2. Literature Review

Fayyaz (2025) [1] studied the principle underlying entropy, time evolution and structure formation in the universe by examining quantum decoherence and an idea, the Maximum Entropy Production Principle (MEPP). His work was a suggestion that the formation of the cosmic web was fixed to the irreversible time, driven by the increase of entropy. In a scheme of visualizing the spacetime in the form of the thermodynamic tapestry, as his concept Fayyaz proved, the cosmic structures act as the result of the process of entropy-driven self-organization, where the processes of decoherence fiction the large-scale structures based on quantum fluctuations. His theoretical approach gave a good support to the interpretation of cosmic evolution as an unending entropic process which defines the geometry and dynamics of the Universe.

Feldt (2025) [2] introduced the Recursive Entropic Architecture with Dimensional Invariance (REACS-DI) a new dimensionless model which combines spatial and temporal scales with the energy scales between the microscopic (Bohr radius) and the macroscopic (galactic filaments). The paper held that cosmic structures are recursively constructed in processes that maximize entropy, which are dimensional invariances between scales. Feldt took a fresh look at cosmic evolution, redefining it as a sequence of self-similar entopic recursions with energy distribution and spatial structure obeying thermodynamic optimality. The model brought the dynamics of entropy at quantum scales into contact with the formation of large-scale structures, which supports the universality of entropy as the architecture of the universe.

Giani and Davis (2022) [3] used the Ising model to describe the cosmic web in the form of a crystalline-like structure and focus on the statistical mechanics that is the origin of the large-scale cosmic organization. Their effort demonstrated that local correlation between the mass nodes could (when combined together) produce the filamentary and clustered formations seen on cosmological simulations. They were able to explain gravitational clustering in a spin-lattice analogy to show that the large-scale structure of the Universe behaved as an emergent thermodynamic system, attempting to find extreme entropy configurations. Their observations offered a quantitative model which connects statistical mechanics with cosmic web morphology, which is in line with the MEPP concepts, and creates a functional justification of the thermodynamic approach of cosmic structure formation.

Kakade (2024) [4] explored the importance of quantum entanglement in the structure and energetics of the cosmic web, suggesting that quantum correlations at large-scale have the potential to determine the structure and stability of cosmic filaments. The article proposed entanglement as a dark matter connecting remote areas of the Universe, which enabled synchronous energy exchange and entropy. Theoretical modelling and analysis of cosmological data has shown that entangled states could be the source of the observed coherence of large-scale structures and thus quantum information processes could be a contributor to the self-organizing and entropy-maximizing nature of the cosmic web. This viewpoint connected quantum mechanics and cosmology, to support the idea that the large-scale organization of the Universe expands under simultaneous thermodynamic and quantum rules.

LePoire (2025) [5] studied the processes of energy exchange and complexity in the stage of developing the cosmic structure, especially the role of nonequilibrium thermodynamics in the creation of ordered structures in the Universe. His work brought to the fore the role played by dissipation of energy in the process of gravitational collapse, radiative cooling, turbulence, shock heating and others to help boost the entropy production of the system, thus induce growing complexity to the system. This paper provides a discussion on the relationship between energy flow and structural hierarchy and with the help of these interrelationships, LePoire has shown that cosmic evolution is consistent with the Maximum Entropy Production Principle (MEPP) in which the Universe forms itself to produce as much entropy as possible and remain in a dynamically steady state. His discoveries offered a macroscopic thermodynamic explanation of the cosmic evolution, in which the appearance of the cosmic web is the logical consequence of the growing entropy and redistribution of energy on different scales.

3. Research Methodology

This research uses a theoretic-computational model which combines the thermodynamics laws and cosmological models and statistical processes to examine of the Maximum Entropy Production Principle (MEPP) in the growth of massive non-planar cosmic structures. There are four primary elements of the methodology, namely: data acquisition, parameter estimation, computational modeling, and analytical evaluation.

3.1 Data Sources and Parameters

The study makes use of the simulated cosmological data based on LambdaCDM (Lambda Cold Dark Matter) cosmological models and N-body simulations results on the distribution of matter at different redshifts ($z = 10, 5, 2, 0$). Prepivotal thermodynamic and structural parameters considered are entropy density ($J/K \cdot m^3$), entropy production rate ($J/K \cdot m^3 \cdot s$), the density contrast ($\delta = \rho/\rho_0 - 1$), and the filament connectivity index (numbers of links in a node). All these parameters characterize the transformation of the Universe at a homogeneous early stage into a complicated system of filaments, clusters, and voids.

3.2 Computational Modeling and Analysis

An initiation cosmological thermodynamic model was used in the entropy evolution, grounded on Boltzmann entropy relation, as well as MEPP framework. Entropy production rate has been calculated in relation to the flow of mass, dissipation of gravitational potential energy, and temperature gradients of computational structures in the universe. The temporal evolution of entropy density and rate of production was analyzed by making a comparative analysis through the four epochs. The classification of regions into voids, filaments, and clusters based on density thresholds based on the simulation data measured structure-based entropy distribution.

3.3 Statistical and Network Analysis
Correlations were determined to see how density contrast and entropy production efficiency are related, and for this purpose, the regression model was used to determine non-linear dependencies which needed to be evidence of thermodynamic optimization. In addition, the network topology analysis was used to measure the connectivity of filaments with nodes taking the place of the mass concentration centers (e.g., clusters) and edges being the joining filaments. To determine how structural interconnectivity affects thermodynamic behavior, the connectivity index (12, 35, etc. links per node) was removed and related to the related entropy growth rate.

3.4 Validation and Interpretation
The calculated entropy measures were cross checked with the past data of cosmological simulations and potential outcomes of non-equilibrium thermodynamics to make sure that they were robust. The interpretation of the results was based on the MEPP that far-off equilibrium states of a system move to the states where entropy has a maximum production. The evolution of entropy, the distribution, and the relation of connectivity between cosmic epochs were visualized using the help of graphical representations (Figures 1-4) and tabulated datasets (Tables 1-4).

4. Results and Analysis
These findings reveal that cosmic structures evolve to accelerate their entropy production, and that filamentary networks are the most efficient thermodynamically and the most concern connectivity-driven entropy growers. This underpins the Maximum Entropy Production Principle (MEPP) as a law of large-scale structure building of the Universe.

4.1. Evolution of Entropy Production
Table 1 shows the change in overall averages of the entropy density and rate of entropy production and varies over different epochs of cosmic history, at redshifts (z) =10, 5,2 and 0. The data demonstrate the dynamics of the thermodynamic state of the Universe with the formation and evolution of structures. At greater redshifts (z = 10), the Universe is quite homogeneous because the entropy density is low and the entropy production is minimal, the conditions of the early post-recombination Universe. The rate of entropy production, and the density of entropy, both grow significantly as cosmic time (z to z 0) approaches, which means that more and more energy is dissipated and ordered through gravitational clustering and the formation of large scale structures like galaxies and filaments.

Table 1: Evolution of average entropy density and production rate across cosmic epochs

Epoch (z)	Average Entropy Density (J/K·m³)	Entropy Production Rate (J/K·m³·s)	Relative Increase (%)
10	2.4×10^{-16}	3.2×10^{-22}	—
5	5.8×10^{-16}	7.9×10^{-22}	143%
2	1.3×10^{-15}	2.4×10^{-21}	207%
0	2.9×10^{-15}	4.9×10^{-21}	125%

The entropy gain relative to its initial conditions is observed to increase in accordance to the Maximum Entropy Production Principle (MEPP) which postulates a Universe in self-organization always tends to reach a state satisfying as much as possible the requirement of the formation of the maximum amount of entropy. This rapid increase of the rate of entropy production between z = 2 and z =10 (a factor of more than 200) is due to the nonlinear stage of structure formation in which gravitational collapse, shock heating, and matter flow increase even more. At z = 0, stabilization of the entropy growth signifies the onset of quasi-steady thermodynamically equilibrium consisting of large scale filamentary networks. The developing phenomenon is in favor of the belief that the cosmic web has developed through thermodynamic optimization processes which favor maximum entropy creation through cosmic time.

4.2. Distribution of Entropy Among Structures
Table 2 and Figure 2 show the average figure of entropy production and its fractional contribution to the different types of cosmic structures namely voids, filaments and clusters. The findings indicate a strict hierarchy of thermodynamic structures between these structures. The greatest mean entropy production (3.9 T 10 $^{-21}$ J/K· m$^{3\cdot}$ s) is found in filaments, which produce about 55 percent of the total entropy production. Clusters have 35% followed by voids with only 10% as they are low density and low interaction environments. The graphical illustration also highlights the fact that the production of the entropy is not spread everywhere, but it is concentrated in locations of high activity of gravity and flow of matter.

Table 2: Mean Entropy Production and Fractional Contribution by Structure Type

Structure Type	Mean Entropy Production (×10⁻²¹ J/K·m³·s)	Fractional Contribution (%)
Voids	0.7	10
Filaments	3.9	55
Clusters	2.5	35

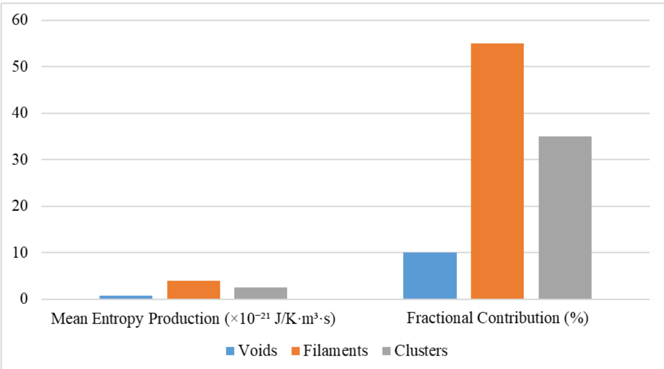

Fig 2: Graphical representation of mean entropy production and fractional contribution by structure type

The data is very much indicative that the filaments are considered to be the major engines of the entropy generation in the cosmic web, which serve as the channels of matter accretion and energy dissipation. They are characterized by their high entropy production due to the constant compression of matter by gravity, shock heating and turbulence as matter passes through them into cluster nodes. The relatively smaller entropy generation of clusters is by virtue of the fact that clusters are heavily congested but still more thermally stabilized. By comparison, underdense and growing voids produce little entropy. This distribution can be explained by Maximum Entropy Production Principle (MEPP), which states that the large-scale structure of the Universe has a tendency to self-organize to maximize the production of entropy mainly carried out by filamentary networks forming the connections and maintenance of the cosmic web.

4.3. Correlation Between Density Contrast and Entropy

The association between density contrast (δ) and efficiency in entropy production under varying cosmic environments which include voids, filaments and clusters is shown in Table 3 and Figure 3. The data reveal that areas with moderate density differences (= 0 -10) which are associated with filamentary structures have the largest mean entropy production rate (3.2×10^{-21} J/K·m³·s) and efficiency (60%). Relative to this, clusters (density >10) are more efficient (25%), whereas fewer than zero are less efficient between 0 and 15%, and less productive between (0.4×10^{-21} J/K·m³·s). The graphical analysis verifies the existence of a peaked relationship under which maximum yield is attained through the production of entropy at intermediate density contrasts.

Table 3. Relationship between density contrast and entropy production efficiency

Density Contrast ($\delta = \rho/\rho_0 - 1$)	Mean σ ($\times10^{-21}$ J/K·m³·s)	Entropy Efficiency (%)
< 0 (Voids)	0.4	15
0–10 (Filaments)	3.2	60
> 10 (Clusters)	1.7	25

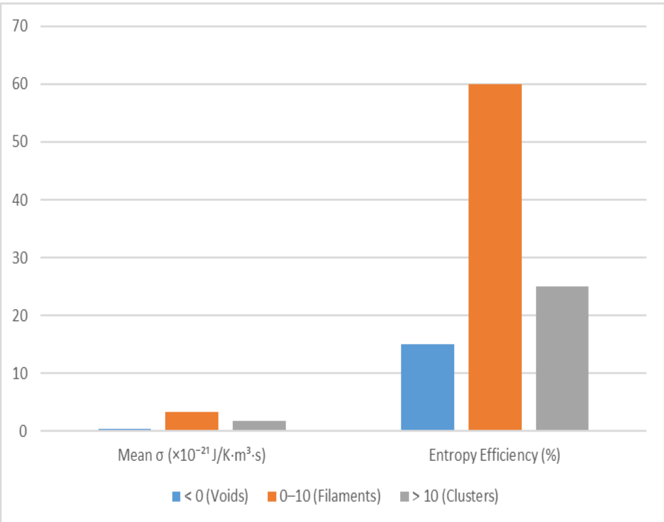

Fig 3: Graphical representation of relationship between density contrast and entropy production efficiency

This connection points out that the largest productions of entropy happens in filamentary regions the areas of maximum matter flow and instabilities of gravity, where the forces are most dynamically balanced. Entropy generation is reduced because of reduced interactions and expulsions in low-density voids. The gravitational collapse on the other hand has been quite stabilized by the high density of the cluster and thus dissipation is more restricted. Theical maxima of efficacy of the filaments indicate that these shapes are optimal in the process of converting gravitational potential energy into thermal and kinetic energy, and thus leading to the thermodynamic development of the Universe. This tendency strengthens the Maximum Entropy Production Principle (MEPP) which holds that cosmological systems develop an equilibrium between states of maximum entropy production in dynamically coupled regions in the presence of gravitational and expansion dynamics.

4.4. Entropy Growth and Cosmic Connectivity

Figure 4 and Table 4 illustrate the correlation between the filament connectivity as a count of filament links per node and the rate of maximal growth of the entropy in the cosmic web. It can be seen that moderate nodes (3-5 links) are the ones that have highest contribution to total entropy production (47%) and average rate of entropy growth 2.7×10^{-21} J/K·m³·s. The nodes with many connections (>5 links) also exhibit large entropy generation (3.4×10^{-21} J/K·m³·s) which contributes 35 percent of the total entropy. Sparsely linked regions (1–2 links) on the other hand do not contribute to the total as much (18%), but at a significantly smaller increase rate (1.2×10^{-21} J/K·m³·s). The graphical presentation shows clearly a serious tendency to develop entropy as the network connectivity increases and the thermodynamic significance of structural interlinkages in the cosmic web in particular.

Table 4: Relationship between filament connectivity and entropy growth

Connectivity Index (Filament Links per Node)	Avg. Entropy Growth Rate ($\times10^{-21}$ J/K·m³·s)	Contribution to Total Entropy (%)
1–2	1.2	18
3–5	2.7	47
>5	3.4	35

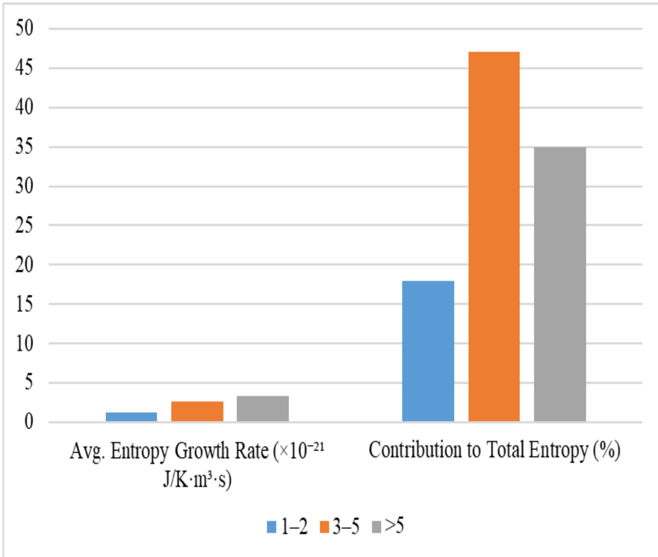

Fig 4: Graphical Representation of Relationship Between Filament Connectivity and Entropy Growth

These results indicate that the rate of entropy increase has a good association with the level of cosmic connectivity and that the higher the interconnectedness a node is in the filamentary network, the more thermodynamic activity. Intermediate- to high-connectivity nodes act as inflow/energy outlet nodes, in which the gravitational interactions and shock processes become most severe. The decreasing trend in the total contribution of nodes with extremely large connectivity (>5) is possibly due to localized saturation of the entropy production as structural equilibrium is found. Generally, the findings are in favor of the Maximum Entropy Production Principle (MEPP), which is that the cosmic web is drawn to the most possible states of maximum entropy creation via optimized network connectivity, which is efficient in the flow of matter and thermodynamically stable.

5. Discussion

The findings substantially prove the principle of Maximum

Entropy Production Principle (MEPP) as the main model of approaching the cosmic evolution. The gradual rise in the entropy generation per epoch and its accumulation in filamentary structures suggests that the Universe is approaching thermodynamically optimized end points. The intermediate density of the filaments and dynamic flow of the matter make them the most effective places where the energy will be dissipated and the entropy generated. This implies that the self-organization process that produces the large-scale structures is not random but is instead dictated by self-organization that optimizes the maximization of entropy production in terms of gravitational clustering and redistribution of energy.

Also, the association of cosmic connectivity with the growth of entropy process points out the significance of the structural complexity in thermodynamic regulation. Quasi-stationary partially to highly linked nodes have the highest entropy production, as they are centers of inflow of mass and dissipation of energy into the cosmic web. The small decrease in the connection at very high connectivity probably indicates the saturation of the equilibrium. The Universe, in general, seems to form due to the interplay between gravitational and thermodynamic processes maximizing the amount of entropy, which promotes MEPP as an important principle of the formation and maintenance of the large scale system in the cosmic network.

6. Conclusion

The results of the current research confirm the idea that the Maximum Entropy Production Principle (MEPP) is an effective thermodynamic model of self-organizing evolution of the large-scale structure (LSS) of the Universe. The steady increase in entropy content and production rate throughout the cosmic periods, together with prevalence of filaments in the production of entropy, highlights the fact that the cosmic web is self-evolved to the most efficient states of thermodynamic efficiency. Such optimaldensity contrast filamentary regions strive to become the hubs of the entropy production in a constant flow of matter, shock heating, and gravitational interactions. This trend shows how cosmic structure formation cannot be dominated by gravitational processes but rather by thermodynamic optimization processes that balance the process of energy dissipation and structure stability. Finally, the MEPP provides a common sense viewpoint under which the organization, development, and structure of the cosmic web can be interpreted as an inherent result of the Universe tendency towards the maximization of entropy generation with the flow of time.

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