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Equation of State for the Information Fluid in Entropy-Based Cosmology

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Abstract: This paper investigates the application of entropy-based frameworks to cosmology by extending the concept of entropy beyond its thermodynamic definition to include informational contributions. We introduce a novel 'information fluid', whose dynamics are described by a Chaplygin gas equation of state, providing a unified description of dark matter and dark energy.

Keywords: information fluid; chaplygin gas; dark components of the universe

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Nature may be fundamentally based on information and amenable to a mathematical description in terms of statistical concepts [1–3], with entropy playing a central role. Even the Universe itself exhibits an apparent horizon endowed with entropy, drawing a close analogy with black-hole thermodynamics (see the recent review on entropic cosmology [4]). The entropic language enables a unified modeling of diverse physical systems [5, 6], in which information-related terms can be explicitly incorporated into physical equations. This viewpoint is particularly compelling given that probability distributions in quantum mechanics are represented by wavefunctions [7], and that even consciousness has been conjectured to possess quantum origins [8].

In this paper, we employ an entropic framework in cosmology to investigate the structure of the equation of state governing the dark sector of the Universe.

When all interactions within a physical system are taken into account, its total entropy, \mathcal{S}_{tot} , which may represent a globally conserved quantity in the Universe [9], is expected to approach zero. For any physical object, or for the finite Universe as a whole, \mathcal{S}_{tot} may be symbolically decomposed into thermodynamic (\mathcal{S}), gravitational (\mathcal{G}), informational (\mathcal{I}), and quantum (\mathcal{H}) contributions [10, 11]:

$$\mathcal{S}_{\text{tot}} = \mathcal{S} + \mathcal{G} + \mathcal{I} + \mathcal{H} \approx 0. \quad (1)$$

This linearized relation should be interpreted as an effective entropy-balance condition rather than an exact microscopic identity. The second law of thermodynamics, commonly used to define the arrow of time, is usually formulated solely in terms of the increase of thermodynamic entropy \mathcal{S} .

Treating the entropy components in Equation (1) on equal footing may appear problematic, since informational entropy is dimensionless, whereas thermodynamic entropy conventionally carries Boltzmann's constant. This distinction, however, is largely conventional. In physical laws, Boltzmann's constant appears only in combination with temperature, allowing thermodynamic entropy to be reformulated in dimensionless form. Within this perspective, thermodynamic entropy can be interpreted as a Shannon-type quantity measuring information stored in microscopic degrees of freedom, such as atomic configurations [12–14]. Accordingly, all entropy contributions in Equation (1) are understood in dimensionless units, with Boltzmann's constant effectively absorbed into the definition of temperature. This viewpoint reinforces the correspondence between entropy in statistical mechanics and in information theory [15].



The condition (1) also suggests a form of information quantization [16], analogous in spirit to the discreteness of microscopic degrees of freedom in quantum theory. This analogy with electric charge quantization should not be interpreted literally; rather, it reflects the expectation that information is fundamentally encoded in discrete microscopic structures, potentially associated with Planck-scale physics or holographic bounds. Within this perspective, matter fields behave as particle-like carriers of information during measurement processes, with bits intrinsically associated with particle configurations. Matter may therefore be viewed as information encoded in quantum fields through their microscopic states.

As the Universe evolves, increasingly complex particle structures emerge, enhancing the capacity to store information and thereby increasing thermodynamic entropy. In this sense, the matter energy density, which quantifies thermodynamic information content, need not remain strictly conserved from an informational perspective during cosmological expansion. Within the framework of Equation (1), the Big Bang may then be interpreted not as a singular state, but rather as the onset of the generation and growth of thermodynamic entropy together with its compensating negative counterparts. At this initial stage, thermodynamic entropy was minimal because no complex particle structures yet existed to encode information.

To satisfy (1) while preserving the second law of thermodynamics for \mathcal{S} , the standard definitions of \mathcal{G} , I , and \mathcal{H} appear to require the presence of negative contributions, in analogy with ideas encountered in holography, gravitational thermodynamics, and quantum-information approaches to spacetime [17–19]. Allowing for such negative components implies that thermodynamic entropy may locally decrease. This behavior can be primarily attributed to gravity, which aggregates matter through attractive interactions and thereby reduces thermodynamic entropy. Consequently, gravitational entropy, characterizing the degrees of freedom of the free gravitational field [20–23], may be converted into thermodynamic entropy. By contrast, quantum measurements and information acquisition are inherently irreversible processes. Within the framework of Equation (1), this irreversibility suggests that the conversion of \mathcal{G} into \mathcal{S} is effectively unidirectional, thereby shaping the observed arrow of time.

The connection between information and the energy components of the Universe can be explored using Landauer’s principle, which states that each bit of information corresponds to a definite amount of energy. This principle has been experimentally verified for both classical and quantum entropies [24,25] and applies universally to all forms of information in nature [9]. Consequently, any change in an observer’s information, even in a thought experiment, must involve energy exchange within the vacuum and should be incorporated into cosmological equations [26]. Although information transfer and energy transfer may appear unrelated, there are strong indications of a deep connection between them: for a broad class of classical communication tasks, a quantum system’s ability to transmit a unit of classical information is equivalent to its ability to transmit a unit of energy in a thermodynamic process [27].

The existence of multiple entropy components suggests the presence of distinct forms of energy in the Universe, each characterized by its own equation of state. We therefore hypothesize that, in addition to ordinary matter, an “information fluid” permeates the Universe and contributes to the dark sector. To uncover the structure of the equation of state of this information fluid, we analyze simplified information-transfer processes in a finite-Universe model. Determining this equation of state requires going beyond conventional thermodynamics, since not all forms of information (such as entanglement or cognitive processes) can be reduced to particle configurations.

The constancy of the total entropy of the finite Universe, the entropy balance condition (1) implies that within a region of radius R the rate of change of total entropy satisfies

$$\dot{\mathcal{S}}_R \Big|_{R \rightarrow R_U} \rightarrow 0, \quad (2)$$

where R_U denotes the radius of the observable finite Universe.

Assuming that the entropy of a moving boundary is proportional to its velocity [28], the entropy rate can be estimated as

$$\dot{\mathcal{S}}_R \sim \frac{v}{R}, \quad (3)$$

where v is a characteristic information-transfer velocity. The change in \mathcal{S}_R can then be approximated as proportional to the flux of matter entropy S_m through the surface area $A = 4\pi R^2$ of the region [29–31]:

$$\dot{\mathcal{S}}_R = \frac{S_m}{V} Av, \quad (4)$$

where $V = 4\pi R^3/3$.

To justify relation (4) in a cosmological context, in the present work, the Hubble horizon $R_H = 1/H$ is adopted as the effective thermodynamic screen. Unlike the future event horizon, the Hubble horizon is locally defined and

directly associated with the apparent horizon, making it suitable for local thermodynamic considerations. Near the de Sitter limit, both horizons asymptotically coincide, so the qualitative late-time behavior remains unchanged.

To model the entropy \mathcal{S}_H , we employ the holographic principle, which is widely used in thermodynamic analyses in field theory. Within this approach, the entropy associated with the Hubble horizon is given by the Bekenstein–Hawking formula (see the review [32]):

$$\mathcal{S}_H = \frac{A}{4G} = \frac{\pi}{GH^2}, \quad (5)$$

where G is the gravitational constant. In Equation (4), it is natural to set $v = c = 1$, where c denotes the speed of light, since a finite Universe must possess a universal maximum speed for information propagation that is shared by all observers.

For the Hubble sphere, one may further associate the temperature [33]

$$T_H = \frac{1}{2\pi R_H} = \frac{H}{2\pi}. \quad (6)$$

More generally, for a dynamical spacetime one may use the Hayward-Kodama surface gravity [34], which modifies the horizon temperature by terms involving \dot{H} . In the quasi-de Sitter regime relevant for late-time cosmology, these corrections remain subleading and do not alter the qualitative derivation of the effective equation of state presented below.

Using the classical Gibbs-Duhem relation,

$$\rho + p = T_H \frac{S_m}{V}, \quad (7)$$

where ρ and p denote the energy density and pressure of matter, respectively, Equation (4) can be rewritten as

$$\dot{A}_H = 4G(\rho + p) \frac{A_H}{T_H}, \quad (8)$$

which reduces to the standard cosmological acceleration equation [35,36],

$$\dot{H} = -4\pi G(\rho + p). \quad (9)$$

Expressing $(\rho + p)$ using the matter energy-momentum conservation equation,

$$\dot{\rho} + 3H(\rho + p) = 0, \quad (10)$$

and integrating, one also recovers the Friedmann equation, with the cosmological constant appearing naturally as an integration constant.

In the present framework, this derivation should not be interpreted as an independent proof of emergent gravity or a derivation of gravitational dynamics from first principles. Rather, it demonstrates a thermodynamic consistency relation within the standard Friedmann–Robertson–Walker cosmological framework, showing that the entropy-flow approach is compatible with the conventional cosmological equations.

To determine the equation of state of the information fluid, we consider the total information content within the Hubble sphere in a finite-Universe model. For the Hubble sphere, the entropy balance condition (1) implies

$$\mathcal{S}_H = -S_m, \quad (11)$$

where the negative sign reflects the compensating character of entropy contributions between the Hubble interior and the complementary degrees of freedom outside the horizon.

Using (5) and (6), one finds

$$\frac{\dot{\mathcal{S}}_H}{\mathcal{S}_H} \approx -\frac{\dot{T}_H}{T_H}. \quad (12)$$

In conventional fluids, the speed of sound is primarily governed by temperature. Assuming that the speed of sound in the information ‘medium’, introduced in Equation (3), satisfies the standard thermodynamic scaling relation $v^2 \sim T$, one obtains

$$\frac{\dot{T}}{T} \approx \frac{2\mathbf{a}}{v}, \quad (13)$$

where a denotes the effective acceleration associated with the information fluid.

Combining (12) and (13), the entropy-rate Equation (4) for the information component of the Universe can be rewritten as

$$\frac{P}{\rho_i} \sim -v^2, \quad (14)$$

where $P = F/A$ represents pressure, $F = \rho_i V a$ is the force, and ρ_i denotes the mass density associated with information. This result implies the pressure P of the information fluid is negative. A similar conclusion can be reached directly from the Friedmann equation, as the energy associated with an observer's total information increases with the expansion of the Universe [37].

The characteristic velocity in a fluid, the sound speed, is typically defined as: $v_s^2 = \partial p / \partial \rho$. From Equation (14), we therefore infer that the pressure of the information fluid obeys a Chaplygin gas-type equation of state:

$$P = -\frac{\Lambda}{\rho_i^\alpha}, \quad (15)$$

where Λ and α are positive constants.

Imposing energy-momentum conservation for the information fluid via (10), together with the equation of state (15), yields [38],

$$\rho_i = \left[\Lambda + \frac{D}{a^{3(1+\alpha)}} \right]^{1/(1+\alpha)}, \quad (16)$$

where a is the scale factor and D is an integration constant.

At intermediate stages of cosmological evolution, the effective equation of state of the information fluid becomes

$$\begin{aligned} \rho_i &\simeq \Lambda^{1/(1+\alpha)} + \frac{D}{(1+\alpha)\Lambda^{\alpha/(1+\alpha)}} a^{-3(1+\alpha)}, \\ P &\simeq -\Lambda^{1/(1+\alpha)} + \frac{\alpha D}{(1+\alpha)\Lambda^{\alpha/(1+\alpha)}} a^{-3(1+\alpha)}. \end{aligned} \quad (17)$$

This behavior corresponds to a mixture of an effective vacuum-energy component, $\Lambda^{1/(1+\alpha)}$, and a matter-like component obeying a soft equation of state,

$$P = \alpha \rho_i. \quad (18)$$

Cosmological models based on the Chaplygin gas equation of state (15) provide a unified description of dark matter and dark energy and successfully reproduce the observed expansion history of the Universe, including the transition from a decelerating to an accelerating phase [39]. Within the present framework, the information fluid reproduces the same qualitative behavior while providing an interpretation in terms of entropy and information balance. The inclusion of a Chaplygin gas component alongside ordinary matter [40] may therefore offer a phenomenological description of information-related contributions to the cosmic energy budget.

In conclusion, we have explored an entropy-based cosmological framework in which information-related contributions play a dynamical role in the evolution of the Universe. Assuming an effective balance among thermodynamic, gravitational, informational, and quantum entropy components, we derived an effective equation of state for an information fluid associated with the dark sector.

Using holographic and thermodynamic arguments applied to the Hubble horizon, we showed that the resulting information fluid naturally obeys a Chaplygin gas-type equation of state. The model provides a unified description of dark matter and dark energy and reproduces the transition from decelerated to accelerated cosmic expansion.

We emphasized that the entropy-balance relation should be interpreted as an effective macroscopic condition rather than a fundamental microscopic identity. Likewise, the thermodynamic derivation of the cosmological equations should be understood as a consistency correspondence within the standard cosmological framework rather than a derivation of gravitational dynamics from first principles. We also discussed the role of the Hubble horizon as a local thermodynamic screen and argued that the use of the more general Hayward-Kodama temperature does not qualitatively modify the main conclusions.

Future work should further investigate the microscopic origin of the entropy components, the role of quantum information and entanglement, and possible observational consequences of the information fluid for the dark sector and large-scale structure formation.

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Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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