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A Dark Energy Hypothesis XI—Information Theory and Evolution

James Togeas

Division of Science and Mathematics, University of Minnesota, Morris, USA
Email: togeasjb@morris.umn.edu

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Abstract

In a Dark Energy Hypothesis, dark matter transforms continuously into dark energy, which is known as the dark matter/dark energy dynamic. The dynamic is studied under the rubric of information theory. The study leads to a prediction of the mass of a dark matter particle. Although the dynamic is evolutionary, it is quasi-static. Information theory divides cosmological evolution into two eras, an early one in which information is produced and a later in which it is lost.

Keywords

Information Theory, Entropy, Dark Matter, Dark Energy

1. Introduction

A brief presentation of information theory appeared in a DEH X [1]. The goal of this paper is to develop the ideas that appeared in that paper. To that end, it presents three tools for the development before proceeding to numerical work followed by a prediction and two interpretations. The first tool is a brief summary of the DEH formalism that should suffice for reading this paper; a full development of the formalism is in a DEH IX [2]. This paper concludes with a brief summary.

2. Dark Matter/Dark Energy Dynamic in a DEH

Total energy U is conserved in a DEH:

$$U = U_\lambda + F(dm) + F(b) = \frac{\Gamma}{\kappa} \tag{1}$$

The terms after the first equal sign are dark energy, the Helmholtz free energy of dark matter, and the Helmholtz free energy of baryonic matter. Γ is the conserved cosmological length, 6.32×10^{24} m = 204 Mpc, and κ is the Einstein gravitational constant, $8\pi G/c^4 = 2.076 \times 10^{-43}$ m·J^{-1}. The baryonic term is constant at 5% of the whole. Hence the sum of the dark energy and dark matter terms is constant at 95% of the whole:

$$U_\lambda + F(dm) = 0.95\frac{\Gamma}{\kappa} \tag{2}$$

The dark matter/dark energy dynamic is that of dark matter continually transforming into dark energy:

$$\Delta U_\lambda = -\Delta F > 0 \tag{3}$$

This will be the point of departure for studying cosmological evolution in terms of information theory.

However, there are other useful relationships to be noted here. The dynamic can be represented in terms of dimensionless quantities since Equation (2) can be written as

$$\frac{\lambda\Gamma}{\kappa} + \frac{\chi(dm)\Gamma}{\kappa} = \frac{0.95\Gamma}{\kappa} \tag{4}$$

In Equation (4) λ is the dark energy parameter

$$\lambda = \frac{\cosh(\eta) - 1}{6\eta^2} \tag{5}$$

where η is the conformal time, and $\chi(dm)$ is the dark matter parameter. The former is related to cosmic time, t, and the scale factor "a" by $a\mathrm{d}\eta = c\mathrm{d}t$. It follows that Equation (2) and inequality (3) become

$$\lambda + \chi(dm) = 0.95 \,\&\, \mathrm{d}\lambda = -\mathrm{d}\chi(dm) > 0 \tag{6}$$

A typical use of these ideas would be to start with the widely held idea that the cosmos in the present epoch is 70% dark energy and 25% dark matter. In a DEH that means that λ = 7/10—the dark energy parameter defines a cosmological epoch. From Equation (5) the conformal time is η = 5.571, which leads to the current value of the scale factor and age of the universe:

$$a = \frac{\Gamma}{6}(\cosh(\eta) - 1) \,\&\, ct = \frac{\Gamma}{6}(\sinh(\eta) - \eta) \tag{7}$$

According to a DEH the age of the universe in this epoch is t = 14.0 Gyr. Equation (7) means that space in a DEH is hyperbolic.

The cosmological entropy is the last feature of a DEH required for turning to information theory; it derives from dark energy:

$$S = \frac{U_\lambda}{T} \tag{8a}$$

Except for the earliest universe, the temperature will be that of the cosmic microwave radiation, in which case

$$S = C(\eta\lambda)^2 \tag{8b}$$

with

$$C = 5.142 \times 10^{65}\ \mathrm{J \cdot K^{-1}}$$

The entropy depends on time only and hence increases monotonically as time elapses.

3. Statistical Thermodynamics

Suppose that the thermodynamic system consists of N atoms at volume V and energy U. Its entropy in the microcanonical ensemble is

$$S = k_B \ln(W) \tag{9}$$

The thermodynamic state consists of W microstates, which is the number of ways of distributing the total energy U among the N atoms at the given volume V. All microstates of the ensemble have the same N-particle energy and are equally probable of being the state in which the N atoms find themselves. In this case, the probability that a particular state is occupied is just $P = 1/W$, so W, sometimes called the complexion, is the number of states compatible with N, V, and U.

4. Information Theory

Equation (9) provides a nice point of departure for explaining Brillouin's concept of information [3]. Suppose that the system is isolated and at equilibrium with entropy at its maximum value:

$$S_0 = k_B \ln(W_0)$$

Since all microstates are equally probable, the observer is in a state of complete ignorance about the microstate of the system, which is to say totally without information. However, as the system was evolving towards equilibrium it was in a lower entropy state

$$S_1 = k_B \ln(W_1)$$

Since

$$S_1 < S_0 \quad \text{then} \quad W_1 < W_0$$

It follows that information exists in this thermodynamic state:

$$S_1 = S_0 - I$$

$$\Delta S = S_0 - S_1 = k_B \ln\left(\frac{W_0}{W_1}\right) = \underset{\sim}{I} > 0$$

The points to be made are that the maximum entropy state has no information associated with it, that information reduces entropy, and, conversely, an increase in entropy destroys information. Brillouin writes (p. 160) that "entropy is a measure of the lack of information". Application of information theory to cosmology will qualify his dictum. In this example, the information has the units of entropy, but henceforward will be a dimensionless quantity.

The unit of information will be the bit, n, more fully the binary unit of information:

$$W = 2^n$$

Hence

$$S = k_B n \quad \text{where} \quad \ln(2) = 1\,\text{bit}$$

Despite replacing W by n, Brillouin's argument that the maximum entropy state contains no information still holds. As will be seen, Shannon's theory of information embodies that idea.

To introduce that theory, let N be the number of dark matter particles and n the number of bits of dark energy. Introduce the *ansatz* that one dark matter particle is equivalent to one bit of dark energy, that the dark matter/dark energy dynamic in informational terms is simply the transformation of a particle of dark matter into a bit of dark energy, that in effect, a dark matter particle is bit of dark matter information. This means that the total number of bits of information is a constant:

$$\Omega = N + n = \text{constant}$$

In analogy to Equations (3) and (6),

$$\mathrm{d}n = -\mathrm{d}N > 0$$

Then the information I is

$$I = \Omega i \tag{10}$$

where i is Shannon's measure of information. This is a two-parameter problem, dark matter and dark energy: let $p = n/\Omega$ be the fraction of the parameter space occupied by dark energy and $P = N/\Omega$ the fraction occupied by dark matter. Shannon's measure of information is

$$i = -\left[p \ln p + P \ln P\right] \tag{11}$$

Figure 1 is a graph of i vs. p. Shannon's measure is the average information per bit; multiplying by the total number of bits gives the total amount of information. Brillouin derives this formula on p. 5 of his book. The maximum value of the measure is for $p = P = 1/2$, in which case $i = \ln 2 = 1$ bit.

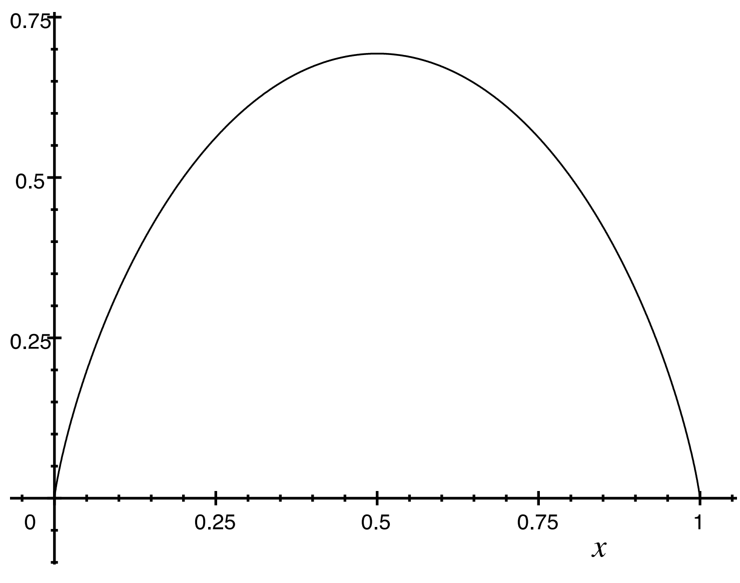

Figure 1. Shannon's measure of information.

With respect to the dark matter/dark energy dynamic, $P > 1/2$ corresponds to dark matter dominance and hence is conveniently designated as the early universe, and $P < 1/2$ the late universe. Evolution occurs from left to right in Figure 1. By Equation (6), $p = \lambda/0.95$ and $P = \chi(dm)/0.95$.

5. Numerical

The goal here is to generate some numbers and then discuss their significance. First consider the two extreme points in Figure 1. When $\lambda = 0$, $p = 0$, and $S = 0$, meaning that there is no dark energy; $P = 1$ and $N = \Omega$—it's the beginning of evolution when there is only dark matter and $I = 0$. Dark matter disappears when $\lambda = 0.95$ and $p = 1$; by Equation (5) this occurs at the conformal time $\eta = 6.033$ and by Equation (7) at $t = 22.5$ Gyr. At this point $\Omega = n$ and entropy has attained its maximum value of $S = k_B\Omega$ with $I = 0$ once again, consistent with Brillouin's analysis.

Calculating intermediate points is easy once the total number of bits is known, but that's easy too. The entropy when $p = 1$ is given by Equation (8b) with $\lambda = 0.95$ and $\eta = 6.033$. Then $\Omega = S/k_B = 1.223 \times 10^{90}$.

For intermediate points: 1) choose p; 2) $n = p/\Omega$; 3) $\lambda = 0.95p$; 4) Equation (5) gives η; 5) Equation (7) gives t; and 6) Equation (8b) gives S. Table 1 gives a sample of results.

Table 1. Evolution and information.

p	I/Ω	t (Gyr)	$n/10^{89}$	$N/10^{89}$	S (J·K^{-1})/10^{66}
0	0	0	0	12.23	0
1/4	0.562	1.91	3.06	9.17	0.404
1/2	ln(2)	7.35	6.12	6.12	2.85
3/4	0.562	14.4	9.17	3.06	8.18
1	0	22.5	12.23	0	16.9

If $t = 0$ seems an unsatisfactory starting point because that is the time of the big bang and there can be no material content of any kind, then an acceptable starting point should be $t = 3$ minutes. However, this corresponds to $\eta = 6.75 \times 10^{-5}$, $\lambda = 1/12$, and $S = 1.63 \times 10^{55}$ J·K^{-1}; on the scale of other entropies, this is $S = 0$. The difference between $t = 0$ and t = 3 minutes in this context is unimportant.

The present epoch is $\lambda = 7/10$ with $p = \lambda/0.95 = 0.737$ and $t = 14.0$ Gyr.

6. A Prediction and Interpretations

Predicting the mass of a dark matter particle.

The Helmholtz free energy for dark matter is

$$F(dm) = M(dm)c^2 = m(dm)c^2 N(dm)$$

where $m(dm)$ is the mass of a single particle, at this point in time unknown, and

$N(dm)$ is the number of dark matter particles. In the formalism of a DEH, the total dark matter mass is

$$M(dm) = \frac{\chi(dm)\Gamma}{\kappa c^2}$$

Then $m = M/N$ is the mass of a single particle. Both N and M vary, but they vary in proportion such that their ratio is constant, which is readily demonstrated as follows. For any epoch P,

$$\frac{M}{N} = \frac{M}{P\Omega} = \frac{0.95\Gamma}{\Omega\kappa c^2} = \text{constant}$$

With $\kappa c^2 = 1.886 \times 10^{-26}$ m·kg^{-1} and numbers given above,

$$m = 2.63 \times 10^{-40} \text{ kg},$$

This is the mass of an axion-like particle but does not establish that it is an axion. It is a candidate for the mass of a dark matter particle.

In a DEH IV [4], a prediction of the same quantity using the Born-Einstein method of fluctuations, but not information theory, gave $m = 1.54 - 2.63 \times 10^{-40}$ kg, for a nice consistency. A topic in DEH V [5] was the possible interaction of dark matter with hydrogen in a state of recombination, an example of dark matter/baryonic matter interaction: the result was that there would be no interaction if $m > 10^{-36}$ kg. The search for an empirical value by observational cosmologists is intense but so far unavailing [6] [7].

A quasi-steady state.

The dark matter/dark energy dynamic viewed in terms of information theory is evolutionary, but is also similar to a steady-state model. At $t = 0.840$ Gyr, the number of dark particles falls to $N = 1 \times 10^{90}$, and falls to $N = 1 \times 10^{89}$ at $t = 19.8$ Gyr. In other words, $N \approx 10^{89}$ for 84% of the dynamic's lifetime. Hence, the large-scale structure provides a quasi-steady state for evolution of cosmological structures. The controlling factor here is the relative insensitivity of Shannon's measure of information to the change of time:

$$0 \le i \le \ln(2)$$

Evolution of information.

Evolutionary history in a DEH separates into two large eras, the early universe in which information is produced and the late universe in which it is lost. In other words, an era of building up is followed by an era of breaking down. This is readily seen by a simple application of the chain rule.

$$\frac{\mathrm{d}S}{\mathrm{d}\eta} = \frac{\mathrm{d}p}{\mathrm{d}\eta}\frac{\mathrm{d}I}{\mathrm{d}p}\frac{\mathrm{d}S}{\mathrm{d}I} > 0$$

The inequality is just the second law of thermodynamics. But

$$\frac{\mathrm{d}p}{\mathrm{d}\eta} > 0$$

is just the dark matter/dark energy dynamic. Hence,

$$\frac{\mathrm{d}I}{\mathrm{d}p}\frac{\mathrm{d}S}{\mathrm{d}I}>0$$

From Figure 1 it is evident that $\mathrm{d}I/\mathrm{d}p > 0$ for the early universe, and hence $\mathrm{d}S/\mathrm{d}I > 0$, meaning that as entropy increases, information increases. Then for the late universe, $\mathrm{d}I/\mathrm{d}p < 0$ and hence $\mathrm{d}S/\mathrm{d}I < 0$, meaning that information is lost as entropy increases. The information is about a combination of dark matter and dark energy. Brillouin's dictum that entropy is a measure of the lack of information applies to the late universe, but in the early universe it is a measure of the presence of information.

Shannon's measure of information is at the root of this evolution. The cosmos is like a mountain climber whose route is dictated by the second law, that he will ascend the early universe slope and descend on the late universe slope. Table 1 illustrates this route. The simplicity of this result should not undermine its efficacy. The information increase in the early universe corresponds to interpreted observations on the backward light cone, viz., the emergence of galaxies and galactic clusters from a uniform background. It corresponds to the early universe's predominance of dark matter, which is the "adhesive" that binds these structures together, to build up earlier and forestall breaking down later.

Although Shannon's measure is symmetrical with respect to the dark energy parameter, λ it is asymmetrical in time as Table 1 shows, with the early universe persisting for 7.35 Gyr and the late universe for 15.1 Gyr. Doubtless the reason is that the expansion rate is greater in the early universe than in the late:

$$\frac{\mathrm{d}a}{\mathrm{d}t}=\frac{c\sinh(\eta)}{\cosh(\eta)}$$

For small values of the conformal time, $\mathrm{d}a/\mathrm{d}t \to 2c/\eta$ and for large values $\mathrm{d}a/\mathrm{d}t \to c$. Thus, for example, at $t = 3$ minutes, $\eta = 6.75 \times 10^{-5}$, $\mathrm{d}a/\mathrm{d}t = 3.0 \times 10^{4}c$.

Finally, it is to be noted that the increase of information with entropy applies only to gravity in the early universe. Chemistry is unaffected; chemical entropy depends on the electromagnetic force as governed by quantum mechanics.

7. Summary

This paper presents cosmological evolution as interpreted by information theory. Shannon's measure, with its small range of variability, plays the decisive role. It means that for most of the range of the dark matter/dark energy dynamic, the cosmological background is practically unchanging as cosmological structures come-to-be and pass away. It provides a quantitative distinction between the eras of building up and breaking down, with the former occupying about one-third of the dynamic and the latter two-thirds. The predicted value of a dark matter particle is an invariant of the model. All of this occurs in the context of increasing cosmological entropy. The idea of cosmological entropy is developed in a DEH VIII [8], where the cosmological second law is defined in terms of the Hubble expansion, that is, that the scale factor "a" must always increase in time, at least in the $k = 0$ and -1 spaces. In a DEH, it is easy to rewrite the scale factor as an entropy and to cast the second law in its traditional entropic language.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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