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Thermodynamics and Cosmology

I. Prigogine[1]

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A new type of cosmological history which includes large-scale entropy production is proposed. These cosmologies are based on a reinterpretation of the matter-energy stress tensor in Einstein's equations. This modifies the usual adiabatic energy conservation laws, thereby leading to a possible irreversible matter creation. This creation corresponds to an irreversible energy flow from the gravitational field to the created matter constituents. This new point of view results from the consideration of thermodynamics of open systems in the framework of cosmology. It appears that the usual initial singularity is structurally unstable with respect to irreversible matter creation. The corresponding cosmological history therefore starts from an instability of the vacuum rather than from a singularity. The universe evolves through an inflationary phase. This appears to be an attractor independent of the initial vacuum fluctuation.

Very few physical theories are in such a paradoxical situation as are those in cosmology today. On the one hand, our universe is characterized by a considerable entropy content, mainly in the form of the blackbody radiation. On the other hand, the classical Einstein equations are purely adiabatic and reversible, and consequently can hardly provide, by themselves, an explanation relating to the origin of cosmological entropy.

On the contrary, matter constituents may be produced quantum mechanically in the framework of Einstein's equations. The energy of these produced particles is then extracted from that of the (classical) gravitational field (Brout *et al.*, 1978, 1979*a*,*b*, 1980). But these semiclassical Einstein's equations are adiabatic and reversible as well, and consequently also unable to provide the entropy burst accompanying the production of matter.

The aim of the present work is to overcome this problem. We propose a phenomenological macroscopical approach allowing for both particles

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[1]Center for Studies in Statistical Mechanics, University of Texas, Austin, 78712, and Free University of Brussels, Belgium.

and entropy production in the early universe. We shall show that thermodynamics of open systems (Prigogine, 1947; see also Prigogine and Geheniau, 1986; Geheniau and Prigogine, 1986), as applied to cosmology, leads very naturally to a reinterpretation in Einstein's equations of the matter stress-energy tensor.[2] This would take into account both matter and entropy creation on a macroscopic level. With this in view, we extend the concept of adiabatic transformation from closed to open systems. This will apply to systems in which matter creation occurs.

This consideration leads to an extension of thermodynamics as associated with cosmology. Traditionally, in addition to the geometrical state of the universe, the two physical variables describing the cosmological fluid are the energy density ρ and the pressure p. Einstein's equations are then solved assuming an equation of state $\rho=\rho(p)$. In our case however, a supplementary variable, the particle density n, enters naturally into the description. This leads to an enlargement of traditional cosmology, which shall be presented here. An important conclusion is that, in these circumstances, creation of matter can only occur as an irreversible process, corresponding to an irreversible transfer of energy from the gravitational field to the created matter. It is quite satisfactory that this irreversible creation of matter generates cosmological entropy. This process follows the second law of thermodynamics and therefore appears to be thermodynamically possible.

Moreover, it is shown that the big-bang singularity of traditional cosmology is structurally unstable with respect to irreversible matter creation. A cosmology which includes such a phenomenon starts from an instability (Gunzig and Nardone, 1982, 1984; Biran *et al.*, 1983) of the Minkowski vacuum and no longer from a singularity. We specify these properties in the framework of a simple phenomenological model of irreversible particle production. This model provides a cosmological history which evolves in three stages: first, a creation period which drives the cosmological system from an initial fluctuation of the vacuum to a de Sitter space. This de Sitter space exists for the decay time of its constituents. Finally, a phase transition turns this de Sitter space into a usual Robertson–Walker (RW) universe, which extends to the present. Entropy creation occurs only during the two first cosmological stages, while the RW universe evolves adiabatically on the cosmological scale.

A fundamental fact is that the de Sitter regime appears as an attractor whose parameters are independent of the characteristics of the initial fluctuation. This implies, in turn, that all the physical parameters characterizing

[2]Recently (Prigogine and Geheniau 1986; Geheniau and Prigogine, 1986) have considered the problem of a redefinition of matter-density and pressure in the stress tensor. To some extent, the present work continues this attempt.

the present RW stage are independent of this initial fluctuation. In particular, the specific entropy per baryon S depends only on two characteristic times of the theory: the creation period time τ_c and the de Sitter decay time τ_d.

It can be noticed that this cosmological model is not part of traditional cosmology, which leads to entropy-conserving evolution throughout the whole cosmological history.

The traditional Einstein equations

$$G_{\mu\nu} = \kappa T_{\mu\nu} \tag{1}$$

as applied to isotropic and homogeneous universes involve the macroscopic stress tensor $T_{\mu\nu}$, which corresponds to a perfect fluid. It is characterized by a phenomenological energy density ρ and pressure $\tilde{p}$ given by

$$\rho = T_0^0 \qquad \text{and} \qquad \tilde{p}\delta_j^i = T_j^i \tag{2}$$

In addition to the Einstein equations (1), we use the Bianchi identities

$$G^{\mu}_{\nu;\mu} = 0$$

which, for homogeneous and isotropic universes, lead to the well-known relation

$$d(\rho V) = -\tilde{p}\, dV \tag{3}$$

In traditional cosmology, this equation is used to describe an adiabatic evolution for a closed system (any arbitrary comoving volume V) and one then interprets $\tilde{p}$ as the true thermodynamic pressure.

On the contrary, in the presence of matter creation, the appropriate analysis is performed in the context of open systems (Prigogine, 1947; Glansdorff and Prigogine, 1971). In this case, the number of particles N in a given volume V is not fixed to be constant. In the case of adiabatic transformation ($dQ = 0$), the thermodynamic energy conservation law reads

$$d(\rho V) + p\, dV - \frac{h}{n}\, d(nV) = 0 \tag{4}$$

where $n = N/V$ and $h = \rho + p$ is the enthalpy per unit volume. In such a transformation, the "heat" received by the system is entirely due to the change of the number of particles. In our cosmological context, this change is due to the transfer of energy from gravitation to matter. Hence, *the creation of matter acts as a source of internal energy.*

Correspondingly, the entropy change dS, which vanishes for adiabatic transformation in a closed system as is the case in traditional cosmology, for adiabatic transformation in open systems is given as follows:

$$T\, dS = \frac{h}{n}\, d(nV) - \mu\, d(nV) = T \frac{s}{n}\, d(nV) \tag{5}$$

where $\mu n = h - Ts$ is the chemical potential and $s = S/V$. Therefore, according to the second law of thermodynamics, the only particle number variations admitted are such that

$$dN = d(nV) \geq 0 \tag{6}$$

This inequality, in the present cosmological framework of open systems, implies that space-time can produce matter, while the reverse process is thermodynamically forbidden. The relation between space-time and matter ceases to be symmetrical, since particle production, occurring at the expense of gravitational energy, appears to be an irreversible process.

The relation (4) can be written in a number of equivalent forms, such as

$$\dot{\rho} = \frac{h}{n} \dot{n} \tag{7}$$

$$p = \frac{n\dot{\rho} - \rho\dot{n}}{\dot{n}} \tag{8}$$

or

$$p = -\frac{\partial e}{\partial v} \tag{9}$$

with the definitions

$$e = \frac{\rho}{n}, \qquad v = \frac{1}{n}$$

A dot denotes the derivative with respect to time. It is interesting to note that creation $\dot{\rho}$ and particle creation $\dot{n}$ determine the pressure p. As examples, note that

$$\rho = mn \rightarrow p = 0 \tag{10}$$

and furthermore,

$$\rho = aT^4, \qquad n = bT^3 \rightarrow p = \rho/3 \tag{11}$$

It is this thermodynamic analysis of open systems which provides the appropriate framework for cosmology in the presence of matter creation. This is realized owing to a reinterpretation of the pressure in the stress-energy tensor. More precisely, creation of matter corresponds to a supplementary pressure p_c, which must be considered as part of the phenomenological pressure $\tilde{p}$, as we may write (4) in a form similar to (3), namely

$$d(\rho V) = -(p + p_c)\, dV = -\tilde{p}\, dV$$

where p is the true thermodynamic pressure and

$$p_c = -\frac{h}{n}\frac{d(nV)}{dV} = -\frac{\rho + p}{n}\frac{d(nV)}{dV} \tag{12}$$

p_c is negative or zero depending on the presence or absence of particle production.

We shall now apply to cosmology these general considerations concerning open systems. In the case of an isotropic and homogeneous universe, we choose for V the value

$$V = R^3(\tau)$$

Then

$$p_c = -\frac{\rho + p}{3nH}(\dot{n} + 3Hn) \tag{13}$$

where $R(\tau)$ is the RW function, and $H = \dot{R}/R$ the Hubble function.

Because of the thermodynamic inequality (6), this extension of Einstein's equations to open systems now includes the second law of thermodynamics. This implies that, in the presence of matter creation, the usual Einstein equations

$$\kappa\rho = 3H^2 + \frac{k}{R^2}, \qquad \dot{\rho} = -3H(\rho + p) \tag{14}$$

become

$$\kappa\rho = 3H^2 + \frac{k}{R^2}, \qquad \dot{\rho} = \frac{\dot{n}}{n}(\rho + p) \tag{15}$$

with

$$\frac{\dot{S}}{S} = \frac{\dot{N}}{N} = \frac{\dot{n} + 3Hn}{n} \tag{16}$$

The corresponding new cosmologies are more general, because they involve three functions ρ, p, and n rather then ρ and p only. We have, for instance, a class of de Sitter spaces with $\dot{\rho} = \dot{n} = 0$, arbitrary pressure p, and $p_c = -h$.

Therefore our approach "rehabilitates" (for example) the de Sitter universe, which is now compatible with the existence of matter endowed with a usual equation of state. We may even consider classes of different de Sitter universes [see equations (10), (11)], such as "incoherent" de Sitter universes ($\rho = mn$, $n = \text{const}$, $p = 0$), or "radiative" de Sitter spaces ($T = \text{const.}$, $n = bT^3$, $\rho = aT^4$).

It has often been suggested that the expansion of the universe provides the arrow of time. A transition from an expanding universe into a contracting one would then invert the arrow of time. We do not confirm this idea, as the inequality (6) implies only that

$$\dot{n}+3Hn\geq 0 \tag{17}$$

which is compatible with $H\geq 0$, $H=0$ and $H\leq 0$. However, in the case of a de Sitter universe, in which $\dot{\rho}=0$, the relation (17) reduces to $H\geq 0$ by virtue of the relation (15).

Only an *expanding de Sitter universe is thermodynamically possible.* In our view, the arrow of time is provided by the transformation of gravitational energy into matter. In special cases, such as the de Sitter universe, this indeed prescribes an expansion of the universe.

Phrased alternatively: There are two types of situation given by the same Einstein equations. The empty universe with zero space-time curvature—the flat universe; and our universe, curved and populated. How does one differentiate between empty universe and material universe? The central quantity of the Einstein's equations, the energy, is of no use here. In fact, the two cases are both characterized by total zero energy. In the first, the zero result is the sum of two zero terms: that which characterizes the (zero) curvature of space-time, and that which characterizes the (absent) matter. In the second, it results from the sum of two terms of equal absolute value; one, negative, corresponds to the curvature of space-time, the other, positive, to its matter content. From the energetic point of view, therefore, the transition to the existence of the material universe is a gratuitous event. This, in itself, is hardly surprising: energy in physics does not provide the means to tell history; as far as energy is concerned, all histories possible are the same. Energy defines the invariant to which all evolutions must submit, but sheds no light on their temporal aspect, the difference they create between "before" and "after."

"Before" the transition to existence of its matter content, the entropy of the universe was zero. "After" this transition, it acquired a value which is the combined value of the entropy of the black holes created. The cost of the transition to existence of the universe is not energetic, therefore, but entropic. The narrative web which applies to the first instances of the universe is not, in the manner of the Einstein equations, determined by energy conservation, but by the irreversible growth in entropy defined by the second law of thermodynamics.

The main point is that the transformation of space-time into matter occurs irreversibly, the inverse transformation being impossible.

Indeed, a recent reinterpretation (Gunzig *et al.*, 1987) of Einstein's equations, characterized by a negative pressure term associated with particle production, has drastically altered the (ir)reversible character of these equations, even though the modification has consequences for only 10^{-37} sec! In spite of this, however, it enables us to express the evolution of space-time, in which particles are created, together with the growth of entropy, proportional to the number of these particles.

In the beginning, therefore, there was a gigantic entropic explosion, of such enormous size that the "thermal death" to which our universe was doomed according to 19th century physicists can, in comparison, be no more than a residual process. If the total matter of our present universe "disintegrated" into photons, the entropy of the universe would increase by only a few hundredths of a percent. Entropic irreversibility, which had always been associated with the end of all history, thus rids itself, here, of the negative sense bestowed on it in the 19th century, haunted, as it was, by the ideal of conservation. It translates into physical terms the realization of the arrow of time, which directs cosmological history, as it directs all physical processes. From this point of view, it can be said that "Time precedes existence."

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