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Inflationary Universe without GUTs

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The existence of a primordial inflationary era is unavoidable due to the puzzling nature of semiclassical gravitation, regulated by Einstein's equations and the laws of quantum mechanics. This interaction appears to be controlled by a mass-dependent effective gravitational coupling constant. The latter undergoes an unexpected transition from a classical gravitational attractive to an antigravitational repulsive regime when the corresponding mass of a quantum matter field passes through a definite threshold. This induces in turn a gravitational, spontaneously broken symmetry phenomenon responsible for the presence of an unusual non-Minkowskian ground state: the inflationary de Sitter space-time. This then acquires the status of the primordial cosmological vacuum, the generic configuration of our cosmological history.

The inflationary idea[2] appears to be the only mechanism that offers the possibility of success in confronting such problems as (besides others) (a) causality, horizons, and flatness linked with the big-bang cosmological genesis. We intend to show in this paper that the usual GUT premises of the inflationary scenarios may be completely relaxed without affecting the unfolding of the inflationary phenomenon: indeed, the latter reveals itself to be a necessary response to the quantum nature of matter fields in the presence of classical gravitational interaction. We shall exhibit a mechanism that not only avoids a big-bang-like cosmogenesis, but also promotes the de Sitter exponential expansion era to the status of the ground state of the self-consistent semiclassical gravity. Self-consistency here refers to any cooperative mechanism that leads to the simultaneous production of both a large-scale (cosmological) classical gravitational field as well as quantum massive material particles in a feedback interplay regulated by Einstein's equations (Gunzig and Nardone, 1984a, 1987; Brout *et al.*, 1978, 1979b,

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[2]See, e.g., Linde (1984) for a review of this concept.

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1980; Vilenkin, 1982, 1983). The de Sitter expansion acquires a self-consistent character only if the mass of its constituents is bounded below by the threshold mass $m_{\rm th} = (288\pi^2)^{1/2} m_{\rm PL}$, where $m_{\rm PL}$ denotes the Planck mass (Brout *et al.*, 1979a; Gunzig and Nardone, 1987); the inflationary era appears in this way as the primordial vacuum, the unavoidable generic configuration of our cosmological history. Our results show indeed that the "bare" classical Einstein gravitational coupling constant κ is "dressed" due to the SC mechanism by the particles mass when in the presence of a quantum massive field (Gunzig and Nardone, 1984b). The resulting *effective* gravitational interaction is then regulated by an effective $\kappa_e(m)$ mass-dependent coupling constant. The amazing feature lies in the fact that the latter changes its sign, thereby causing an effective antigravitational repulsive interaction when the corresponding de Sitter particle mass exceeds precisely the above-mentioned self-consistent existence threshold $m_{\rm th}$. This effective repulsive effect prevents the reannihilation of these virtual pairs, populating the Minkowskian background, having a mass above this threshold $m_{\rm th}$: hence, the fall of the false semiclassical Minkowskian vacuum, unable to sustain such fluctuations.

This effective gravitational interaction induces in turn a spontaneously broken symmetry mechanism associated with a gravitational effective potential which regulates the matter-gravitational self-consistent dynamics (Gunzig and Nardone, 1985, 1987): as soon as $\kappa_e(m)$ controls the repulsive interaction, this potential minimum stability point falls below the Minkowskian level; the corresponding new stable configuration appears to be nothing but the inflationary, spatially flat de Sitter space-time provided that the mass m of its massive constituents exceeds $m_{\rm th}$. The occurrence of such a peculiar situation in which a curved, nonempty space-time acquires the ground-state status of the semiclassical gravitational theory provokes at first glance a fundamental inquiry: indeed, from where and how does the energy-momentum of this nontrivial ground state come? The answer lies in a very puzzling property of gravitation: the repulsive character of the semiclassical gravitational interaction controlled by $\kappa_e(m > m_{\rm th})$ gives rise to this nontrivial vacuum, whereas the reverse sign of the bare classical attractive gravitational constant permits a cooperative particle-curvature production without any external global energy need (Brout *et al.*, 1978, 1979b, 1980; Gunzig, and Nardone, 1984a; Vilenkin, 1982, 1983); this intriguing possibility results from the following very unique circumstance: the matter-gravitational system contains an available intrinsic degree of freedom—the large scale curvature—which enables such a self-consistent mechanism; more precisely, it represents a negative energy reservoir from which the matter-gravitational system is able to extract the positive energy required to convert virtual particles into real ones at the expense of curving space–time. The energy is hence extracted from the geometrical background and this process occurs thereby without any global violation of energy-momentum conservation. Not only does this self-consistent program enable us to solve the energy-origin enigma for the nontrivial ground state (as there is globally no energy at all!), but furthermore its unique dynamical realization is the inflationary de Sitter space–time itself (Brout *et al.*, 1979a; Gunzig and Nardone, 1985). Moreover, since this ground state is being populated by massive particles interacting repulsively through $\kappa_e(m > m_{\text{th}})$, the latter induces not only the appearance of a non-Minkowskian vacuum, but also justifies its exponential expansion behavior. The order of magnitude of m_{th} leads one (Gunzig and Nardone, 1987; Casher and Englert, 1981) to conceive them as mini black holes. Consequently, the inflationary de Sitter stage lasts the quantum black-hole evaporation time. This decay process gives rise to the same consequences as those resulting from the release of the energy associated with the null Higgs field in the framework of Guth's traditional inflationary conjecture: in both cases the inflationary driving mechanism disappears and the inflationary expansion stops (no longer either negative pressure or cosmic repulsion) and an enormous amount of energy and entropy is then released.

We now proceed to the formal proof of these facts: first of all, the set of equations controlling the self-consistent matter-gravitational feedback production mechanism, as limited here for simplicity to spatially flat Robertson–Walker metrics:

$$ds^2 = e^{\Lambda(t)}(dt^2 - dx^2 - dy^2 - dz^2) \tag{1}$$

is provided by (Gunzig and Nardone, 1987)

$$3e^{-\Lambda}(\ddot{\Lambda} + \tfrac{1}{2}\dot{\Lambda}^2) = km^2\langle\psi^2\rangle^s \tag{2}$$

$$\langle\psi^2\rangle^s = e^{-\Lambda}\int_0^\infty \frac{k^2\,dk}{2\pi^2}\,[|\xi_k|^2 - \tfrac{1}{2}(k^2 + m^2\,e^{\Lambda})^{-1/2}] \tag{3}$$

$$\ddot{\xi}_k + (k^2 + m^2\,e^{\Lambda(t)})\xi_k = 0 \tag{4}$$

ψ stands here for a scalar quantum massive field whose quanta of mass m are self-consistently produced together with the cosmological classical field $\Lambda(t)$; the ξ_k are the eigenmodes corresponding to a plane-wave decomposition of the ψ-field, and $\langle\psi^2\rangle^s$ denotes its subtracted mean square value; a dot designates a derivative with respect to the conformal time t. As mentioned previously, it was proven that the unique solution to these equations (2)–(4)—i.e., the unique dynamical realization of the cosmological self-consistent concept—is provided by the inflationary de Sitter space, as long as κ_e corresponds to repulsive interaction (Gunzig and Nardone, 1985, 1987).

A WKB-like treatment of these equations (Gunzig and Nardone, 1987) gives rise to the following relation controlling the self-consistent dynamics:

$$R = -\kappa_e(m) \cdot (\Box R - \tfrac{1}{3}R^2 + R_{\alpha\beta}R^{\alpha\beta}) \tag{5}$$

where

$$\kappa_e(m) = \frac{\kappa}{2880\pi^2(1 - \kappa m^2/288\pi^2)} \tag{6}$$

It hence follows from equations (5) and (6) that the self-consistent dynamical behavior reduces to the trace of Einstein's equations, but with a mass-dependent effective coupling constant $\kappa_e(m)$; the mass m of the massive scalar quanta appears to be completely absorbed in a "dressing" of the bare gravitational coupling constant κ; moreover, the source of the scalar curvature R is provided by the combination of second-order invariants representing precisely the trace anomaly associated with the residual massless part of the scalar field (Gunzig and Nardone, 1984b, 1987). The cosmological self-consistent dynamics is therefore equivalent to a repulsive antigravitational interaction among massless particles, provided the mass m is greater than the threshold mass $m_{\text{th}} = (288\pi^2)^1 2^{/2} m_{\text{PL}}$. Thus, m_{th} is of the order of the Planck mass, which precisely divides the weak and strong interaction sectors in the grand unification scheme. Based on all these facts, an intriguing possibility would be that the creation of the universe, gravitation, and elementary particle physics are different facets of one and the same phenomenon.

The most revealing property of this self-consistent dynamics, when reexpressed in terms of the Hubble function H and the cosmic proper time τ, appears to be regulated (in the framework of the same WKB-like approach) by a dissipative conservation law, namely

$$\frac{d}{d\tau}\left(2\nu\dot{f}^2 + \frac{\mu}{2}f^2 + \frac{\nu}{6}f^6\right) = -12\nu f^2\dot{f}^2 = -3\nu\dot{H}^2 \tag{7}$$

in which $f = H^{1/2}$, a dot means $d/d\tau$, $\nu = \kappa/2880\pi^2$, and $\mu = 1 - \kappa m^2/288\pi^2$. The potential

$$V(f) = \frac{\mu}{2}f^2 + \frac{\nu}{6}f^6$$

hence plays the role of the effective gravitational potential characterizing the self-consistent problem; it obviously provokes a spontaneously broken symmetry behavior: when $m < m_{\text{th}}$, then μ is positive and the minimum of the potential $V(f)$ is located at $f = 0$, corresponding to the Minkowskian configuration; on the contrary, when $\kappa_e(m)$ corresponds to repulsive gravitational interaction—i.e., when $m > m_{\text{th}}$—a new stationarity point emerges, namely $H = f^2 = (-\mu/\nu)^{1/2}$; this then corresponds to the true self-consistent ground state of semiclassical gravity, which reveals itself to be the announced de Sitter space. Moreover, the dissipative term $-3\nu\dot{H}^2$ prevents classical oscillations around this ground state (Gunzig and Nardone, 1987). This formalism suggests a more general symmetry-breaking mechanism in which the gravitational field itself arises at the same time as the universe comes into existence.

In conclusion, it is the very presence of massive vacuum fluctuations, corresponding to $m > m_{\mathrm{th}}$, that implies inevitably that the primordial cosmological vacuum—the generic configuration of our cosmological history—is the inflationary de Sitter space, in complete agreement with results previously obtained. This primeval inflation sets up a cooperative matter-gravitational creation process and results from a spontaneously broken symmetry breakdown mechanism. Its self-consistent bootstrap-like character implies that the fundamental agent for symmetry breakdown is the creation of the universe itself!

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