
Cosmological Inflation: A Personal Perspective

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Summary. We present a brief review of Cosmological Inflation from the personal perspective of the author who almost 30 years ago proposed a way of resolving the problem of Cosmological Horizon by employing certain notions and developments from the field of High Energy Physics. Along with a brief introduction of the Horizon and Flatness problems of standard cosmology, this lecture concentrates on personal reminiscing of the notions and ideas that prevailed and influenced the author's thinking at the time. The lecture then touches upon some more recent developments related to the subject and concludes with some personal views concerning the direction that the cosmology field has taken in the past couple of decades and certain speculations some notions that may indicate future directions of research.

1 Introduction

The development of General Relativity and the possibility it offers to probe the issues of the overall geometry, topology and evolution of the Universe as a whole it is certainly one of the great achievements of human spirit and captured my own imagination when I first came across an article by G. Chasapis on the "Universe" in the Greek encyclopedia "Helios". Since then, the field of Cosmology has been for me an avocation of sorts, honed in time, as I pursued studies in physics first at the University of Thessaloniki, through courses offered by professors G. Contopoulos and S. Persides and then through a large number of discussions with my late roommate and fellow graduate student at the University of Chicago B. Xanthopoulos as well as from interactions with my late thesis advisor D. N. Schramm. Since this is a brief personal account and not a review, I would like to apologize in advance to many for the absence of a large number of important references and contributions to the subject.

Following the original cosmological models of Einstein, de Sitter, Lemaitre, Friedman and others and the discovery of the expansion of the Universe by Hubble, the next development came through the realization (Gamow, Alpher) that the present expansion of the Universe implies that at an earlier stage it should have been sufficiently hot for nuclear reactions to take place. This then,

supported by the discovery of the Cosmic Microwave Background (CMB) radiation, led to the development of Big Bang Nucleosynthesis (BBN) by Wagoner, Fowler & Hoyle [1] that still serves as a ruler against which all cosmological models have to be measured.

In the mid to late 70's, the subject of Cosmology was much less prominent than today, at least from the perspective of a graduate student, even one that specialized in astrophysics. The primary Cosmology text was Weinberg's book [2], wherein one could find the fundamentals of General Relativity and its application to relativistic objects, i.e. neutron stars and black holes, as well as the Universe itself. Its exposition of Cosmology provided, in addition to the general cosmological models, also the details of the thermal evolution of the universe and some of the open outstanding issues of standard cosmology namely the entropy (number of photons) per baryon $1/\eta$ in the cosmological fluid, and the issue of horizons.

The issue of the high value of $1/\eta$ ($\simeq 10^9$), compared to that found in a typical star ($\eta \simeq 1$), was given a prominent position both in [2] and also in Weinberg's, then new, more popular book "The First Three Minutes"[3]. Particular emphasis was given at the difficulty of producing such a large value for $1/\eta$ through dissipative processes given that the homogeneity and isotropy of the Universe that allows only for the effects bulk viscosity. However, as argued by the author, even this process could not add much more than a photon per baryon to the value of $1/\eta$.

2 The Cosmological Problems

At this point I would like to make a brief digression to outline the dynamics of the Universe and formulate the Cosmological problems of Horizon and Flatness. In my view, the root of both these problems, at least partially, lies in the fact that, in the system of units in which $h = c = 1$, the gravitational constant G has dimension of $(\text{mass})^{-2}$, the so-called Planck mass; this is the mass of particles for which the Schwarzschild and Compton lengths are equal, i.e. $2GM_P/c^2 = h/M_Pc$, or $G = hc/2M_P^2$ or $M_P = (hc/G)^{1/2} \simeq 10^{-5}$ gr. To this mass scale one can assign equivalent length, time and temperature scales of corresponding values $l_P \simeq 10^{-33}$ cm, $t_P \simeq l_P/c \simeq 10^{-43}$ sec and $T_P \simeq 10^{32}$ K.

2.1 Newtonian Cosmology

It is most amazing that the dynamics of the Universe as determined by the equations of General Relativity can be derived from purely Newtonian considerations. The facts that allow a Newtonian treatment of cosmology are that: (1) the Universe is homogeneous and isotropic, so any point can serve as the origin of a spherically symmetric coordinate system and (2) the property of the Newtonian potential that for a spherically symmetric matter distribution,

the dynamics of the matter within a volume of radius a is determined only by the matter interior to a . Therefore, for a homogeneous and isotropic distribution, such as that of the Universe, one can choose the radius a arbitrarily and study the dynamics this sphere, all matter exterior to a being irrelevant. The Hubble law indicating that velocities are proportional to the distance, then, guarantees that shells of different radii expand homologously and do not run onto each other.

One can, hence, write the equations of motions of a sphere of arbitrary radius a simply using the total energy integral, E , namely

$$\frac{1}{2}\dot{a}^2 - \frac{GM}{a} = \frac{1}{2}\dot{a}^2 - \frac{4\pi G\rho}{3}a^2 = E \quad \text{or} \quad H^2 = \frac{\dot{a}^2}{a^2} = \frac{2E}{a^2} + \frac{8\pi G\rho}{3} \quad (1)$$

It is instructive to compare this equation the the corresponding Einstein equation for a homogeneous and isotropic Universe of spacial curvature $k = 1, 0, -1$ corresponding to a closed, flat or open Universe:

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G\rho}{3} \quad (2)$$

The role of the energy is played by the spatial curvature, $-k$, indicating that in a closed Universe ($k > 0$, $E < 0$) the radius of the sphere reaches a maximum while in flat and open universes it can reach infinity.

The solution of this equation requires an assumption about the variation of the density with time (or with a); this can be obtained from the conservation of energy, which reads $\rho \propto a^{-3}$ for pressureless matter and $\rho \propto a^{-4}$ for radiation while for temperature implies $T \propto 1/a$.

The only difference between the Newtonian and Einstein version of Cosmology becomes apparent only by differentiating Equations (1) or (2) taking into account the relation between ρ and the pressure P from local energy conservation (Eq. 8 below) to obtain the corresponding force equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(3P + \rho) . \quad (3)$$

This equation incorporates the contribution of pressure to the gravitational force, as it should, since pressure is energy density and all energy gravitates. The presence of this term, significant in the radiation era, has been verified by comparing the outcome of BBN to observation[5].

2.2 The Horizon Problem

The finite age of the Universe $t_U \simeq 1.4 \times 10^{10}$ yr $\simeq 5 \times 10^{17}$ sec, along with the finite speed of light indicate that light signals since the creation of the Universe have traveled a distance $R_H \simeq ct_U \simeq 10^{28}$ cm. One can now estimate the size of R_H at the time its age was t_P and its temperature T_P , by scaling R_H by the ratio of the CMB temperatures at the two epochs, namely

$R_P \simeq R_H(3\text{K}/10^{32}\text{ K}) \simeq 10^{-3}\text{ cm}$. This size is 30 orders of magnitude larger than the horizon size at that time $ct_P \simeq l_P$, indicating that the Universe at that time comprised $\sim 10^{90}$ causally disconnected regions, all of which must have had approximately the same temperature since the Cosmic Microwave Background (CMB) appears to be quite uniform across the observed Universe. This constitutes the Horizon problem. More formally, the size of the horizon must take into account the fact that the photon signal co-moves with the expanding Universe and it is thus given by

$$S_H = a(t) \int_0^t \frac{cdt}{a(t)} \quad (4)$$

One can see that for a power-law expansion rate $a(t) \propto t^p$ with $p < 1$ (as is the case for a radiation ($p = 1/2$) or matter ($p = 2/3$) dominated Universe) the horizon size is just a multiple of ct_U . However, for $p \geq 1$ the integral is dominated by the lower limit and the horizon diverges at $t \rightarrow 0$.

2.3 The Flatness Problem

For a given value of the ratio $H \equiv \dot{a}/a$, Equation (1) defines a characteristic value of the density $\rho_c = 3H^2/8\pi G$, i.e. the density for which the explosion energy E is equal to zero, and use it to define the ratio of the density to the critical one as $\Omega = \rho/\rho_c$. We can now divide Eq. (1) by \dot{a}^2 to obtain

$$1 - \Omega = \frac{2E}{\dot{a}^2} = -\frac{k}{(Ha)^2} \quad (5)$$

Applying the above relation at two different values of a and the corresponding values of Ω we obtain

$$\Omega_1 - 1 = \frac{\dot{a}_0^2}{\dot{a}_1^2}(\Omega_0 - 1) \quad (6)$$

One can now see that if the present value $|\Omega_0 - 1| \simeq \mathcal{O}(1)$, then, given that in standard cosmology $a(t) \simeq K t^{1/2}$, $\dot{a}_0^2/\dot{a}_1^2 \simeq t_1/t_0$; since $t_0 \simeq 10^{17}$ sec, at an earlier epoch with $t_1 \ll t_0$, $\Omega_1 \rightarrow 1$. If, in particular we set $t_1 \sim t_P \sim 10^{-43}$ sec, $t_1/t_0 \simeq 10^{-60}$, i.e. under Standard Cosmology, at the Planck time, the radiation density was equal to the critical density to within 1 part in 10^{60} !

3 Phase Transitions, Baryogenesis

The focus placed by Weinberg on the value of η helped galvanize a couple of fellow graduate students including myself to take an independent look at this parameter in search for mechanisms that could account for its value. As far as I can now recall, our first attempt was to use Weinberg's prescription of bulk viscosity[4] but dare to consider its application to much higher temperatures

and include much more massive particles than had been considered till then. However, we soon realized that no matter what the temperature and the particle masses, this process could add but a small number of photons per baryon in the cosmological fluid.

In search of other entropy producing processes I stumbled upon the idea of phase transitions and the entropy associated with the latent heat. Being aware that quarks were confined into baryons by a potential that grows (linearly) with distance, I considered that if this transition could be somehow delayed during the expansion of the Universe to densities lower than nuclear, the linear quark interaction could produce extremely large values of entropy *from the vacuum!* Because I considered such a situation rather contrived and poorly constrained, I suggested (in a publication[6] that received just a single citation[7]) that, even though there are overall no free quarks, it is possible that within a horizon volume there may be an excess of color, which would now interact via the quark linear potential with a similar color excess in an adjacent horizon volume. Assuming that the local color excess to be purely statistical, i.e. proportional to the square root of the particles within a given horizon volume, then one can calculate the amount of entropy produced as the universe expands. However, under these conditions the entropy thus released does not contribute significantly to $1/\eta$. Despite this fact, I was impressed by the possibility of energy production from the vacuum and thought it could have potentially significant consequences.

The issue of the value of $1/\eta$ was resolved in 1978 in an altogether different and far more subtle way (e.g. [8, 9] and others): The production of a large number of photons per baryon was supplanted by the production of a small excess of baryons over antibaryons in an originally symmetric cosmic fluid; this entailed invoking processes that violated baryon conservation, the CP symmetry and thermodynamic equilibrium. These processes were apparently possible within the context of Grand Unified Theories, i.e. theories that unified the strong with the weak and electromagnetic interactions at energies $\sim 10^{15}$ GeV.

While the issue of the photon to baryon ratio $1/\eta$ was resolved in principle as above, the issue of entropy production from the vacuum was still extremely appealing to me and my thought was that perhaps this could help resolve the remaining open cosmological problem, that of the Horizon.

4 Resolving the Horizon Problem

At the end of 1978 I got my PhD, left Chicago and spent the following year (1979) in the Greek military. Upon my discharge I returned to the US having been offered an NRC fellowship at GSFC by Floyd Stecker. On my way back to the US I spent a few days at Nordita in Denmark, where K. Sato had been also a visitor. He was very much interested in phase transitions in the early universe and we did discuss some of the issues of the quark - baryon one

outlined above with one of his comments being that he was interested “in a different type of phase transition”.

This last comment caught my attention enough to launch a (not so thorough, as it turned out) search for this different type of phase transition; the search produced only one relevant paper [10], which however involved the quark-baryon transition I was already aware of. At the same time, my interest in the horizon problem was rekindled by a paper by Brown & Stecker[11], which considered the intriguing and interesting possibility of a matter - anti-matter domain Universe produced by a phase transition-like violation of the CP symmetry with the order parameter taking randomly values of either -1 or $+1$ within each domain. The Horizon Problem is at the very heart of this proposal because the size of these domains is limited by the Horizon size at temperatures $\sim 10^{15}$ GeV, at which the baryon asymmetry is formed. In one of the references of [11] I found then a citation to [12] who discussed very much the same problem. The authors of [12] showed that because of the discrete nature of the CP-symmetry the corresponding phase transition produced a network of walls separating the two phases and that the wall network corresponds to a perfect fluid with equation of state $P = -2\rho/3$; this then leads to an expansion rate for the Universe $a(t) \propto t^2$ which, as discussed above can lead to domain sizes sufficiently large to avoid contradiction with observations on the existence of antimatter in space. This provided a resolution of sorts of the Horizon Problem, except for the fact that the resulting Universe would be very inhomogeneous due to the presence of these walls, in contradiction with observation.

At this point, I noticed a paper [15] discussing phase transitions within the context of Spontaneous Symmetry Breaking (SSB), a subject that had been extensively treated by [13, 14]. These are not unlike those discussed in [12] but the broken symmetries are not necessarily discrete and hence they do not have to lead to inhomogeneities. The work of [13] was very instructive: It showed that the energy stored in the self-interacting Higgs field ϕ , a fundamental ingredient of SSB, acts as a perfect fluid with an equation of state $P_v = -\rho_v$ with the vacuum expectation value of ϕ and the energy density ρ_v having the temperature dependence given in Fig. 1: (i) For $T > T_c$, $\langle\phi\rangle = 0$ and its energy density is $\rho_v \simeq a_{bb}T_c^4 = \text{constant} < \rho_r = a_{bb}T^4$ (ρ_r is the radiation energy density, a_{bb} is the black body constant). (ii) For $T < T_c$, $\langle\phi\rangle \neq 0$ and the energy density $\rho_v = \epsilon_v = a_{bb}T^4$ decreases with the temperature T but remains comparable to that of radiation ρ_r . This phase transition does not involve the confinement of quarks and does not suffer from the problems with that discussed earlier.

The effects of such a phase transition on the evolution of the Universe can be easily studied by considering that the total pressure and energy density consist of the sum of radiation and the vacuum, i.e. $P = P_r + P_v$ and $\rho = \rho_r + \rho_v$, with each obeying its own equation of state, i.e. $P_r = \rho_r/3$ and $P_v = -\rho_v$. The solution to Einstein’s equation

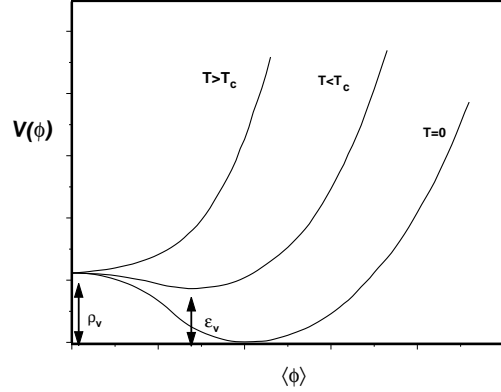


Fig. 1. The temperature dependent Higgs potential. For $T > T_c$, $\langle\phi\rangle = 0$ and the vacuum energy density ρ_v is constant but insignificant. For $T < T_c$ $\langle\phi\rangle \neq 0$ and the vacuum energy density ϵ_v depends on T , being zero for $T \rightarrow 0$.

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}(\rho_r + \epsilon_v) \quad (7)$$

requires also the knowledge of variation of ρ , ϵ_v with time or with a . The relation between a and T is given by the first law of thermodynamics [16]

$$a^3 \frac{d\rho}{da} = -3(P + \rho)a^2 \quad \text{or} \quad a^3 \frac{d}{da}(\rho_r + \epsilon_v) = -4\rho_r a^2 \quad (8)$$

after taking into consideration the corresponding equations of state. This last equation then leads to the following relations between a and T or ϵ and T :

$$a \propto \frac{1}{T^2} \quad \text{or} \quad T \propto \frac{1}{a^{1/2}} \quad \text{and} \quad \epsilon_v, \rho_r \propto \frac{1}{a^2} \quad (9)$$

The presence of a vacuum component makes therefore a great deal of difference in the cooling of the universe: As long as $\epsilon_v \propto T^4$, the universe has to expand by twice as many decades to cool by the same factor as under adiabatic conditions. During this period the vacuum energy is never dominant but it is comparable to that of radiation and keeps feeding into it as ϵ_v slowly decreases. It was argued in [16] that this behavior should terminate at some point, else it would over-dilute the baryon/photon ratio.

With the relation between a and T (Eq. 9) it is easy to compute the evolution of a (Eq. 2) to obtain $a \propto t$, indicating that the horizon diverges logarithmically for $t \rightarrow 0$. However, this divergence is very mild and it is unlikely that it can resolve the Horizon Problem. Motivated by the work of [13, 14] and prompted by the referee of the paper I had submitted I considered also the case $\epsilon_v \propto T^2$ for $T < T_c$. The slower decrease in the vacuum energy density then gave a very different relation between a and T , namely [16]

$$\frac{a}{a_c} = \frac{T_c}{T} \exp \left[\frac{1}{4} \left(\frac{T_c^2}{T^2} - 1 \right) \right] \quad \text{for } T < T_c \quad (10)$$

where a_c is the value of a when the temperature drops to the critical one T_c . This expression leads to a much slower decrease of T with a , which, when substituted into Eq. (2) yields an exponential expansion $a \propto \exp[t^{1/3}]$, which can expand the Horizon size to values much larger than R_H , thereby resolving the Horizon Problem in a robust way. One can also see that an exponential expansion quickly renders the RHS of Eq. (5) $\ll 1$, resolving also the Flatness Problem.

5 “Nothing Succeeds like Success”

Considerations and calculations similar in spirit to those discussed above were worked out at approximately the same time by Sato [17] and Guth [18]; the early stage exponential expansion of the Universe driven by the energy density of the vacuum was given the name [18] ‘Inflation’, a term resonant with the state of the US economy at the time, which has been since adopted universally, despite the subsequent change in the state of the US economy. The evolution of the Universe as described in [17, 18] proceeds through the formation of bubbles with $\rho_v = 0$ surrounded by exponentially expanding space of $\rho_v \neq 0$; the hope was that eventually the $\rho_v = 0$ regions would occupy the entire volume of the universe, which in the mean time had inflated enough to resolve the Horizon and Flatness problems. The problem was that, due to a secondary minimum of $V(\phi)$ at $\phi = 0$, the transition rate to $\rho_v = 0$ was too slow to complete the transition. This shortcoming was overcome in the ‘New Inflation’ [19] where the Universe was considered to ‘slowly roll’ down on a potential similar to that corresponding to $T = 0$ in Fig. 1, with the expansion dominated by a roughly constant ϵ_v and with the present horizon constituting a small patch of the expanding universe with $\Omega = 1$ with extremely high accuracy.

However, the most important feature of the ‘New Inflation’ is that it affords a process that can produce the fluctuations necessary for the formation of cosmological structure: During the ‘slow-roll’ period of the evolution of the Universe the geometry of space is that of de Sitter space with a cosmological horizon at a constant coordinate distance. Quantum fluctuations of the field ϕ created with constant amplitude $\delta\phi$ decrease until they cross the de Sitter horizon; then, as they are stretched by the expansion of the Universe to super-horizon scales, their amplitude freezes to the value they had at horizon crossing; this is due to an interplay between the scalar field and metric perturbations; in fact because the field perturbation is proportional to $\delta\phi \propto V_{,\phi}/V$ it increases toward the end of inflationary phase. After the end of the phase transition, the Universe resumes its conventional expansion; as the horizon size increases the fluctuations come within the horizon at roughly the constant amplitude they had when exiting the de Sitter horizon to produce the Harrison–Zeldovich spectrum of cosmological perturbations. These

have subsequently left their imprint as fluctuations on the CMB temperature which were recently measured by both the COBE and WMAP [20] missions confirming the general predictions of the inflationary scenario.

A most interesting feature of the above process is that the amplitude of perturbations depends on the shape of the potential $V(\phi)$ and the energy scale of inflation. Furthermore, small deviations of the fluctuation spectrum from the precise Harrison–Zeldovich form, can also give an estimate of the number of e-foldings of inflation which was found (for the simplest models) to be of order of 60-70 (while it could, in principle, be much larger) [20], suggesting an expansion by a factor of roughly 10^{30} , the minimum required to reconcile the disparity between the size of the universe and the Planck length at $t = t_P$ discussed in §2.

While the issue of the horizon size or the flatness of the universe are resolved in an appealing way by the inflationary scenario, these issues provide little additional quantitative evidence in support of its fundamental premises. However, the production, amplitude and spectrum of the resulting matter fluctuations and their imprint on the CMB, the result of the quantum fluctuations of the field ϕ , provides a unique to date method for the production of the fluctuations necessary to produce the observed structure in the Universe and a much more rigorous instrument of scrutiny of the above ideas. The interested reader can find of all these in the modern literature (e.g. the monograph by Mukhanov[21]). While there has been at least one (sound in my opinion) objection against the entire ‘Inflationary’ edifice[22], in the absence of a successful accompanying account of the CMB fluctuations, this has gained little traction. Despite these objections and those raised in the next section concerning the nature of the ingredients of the Inflationary Paradigm, the success of this scheme in addressing the CMB fluctuations make it an indispensable tool in modern cosmology; it is then not unreasonable to conclude that in science as in business “nothing succeeds like success”.

6 Discussion and Speculations

It is fair to say that the ideas of Cosmological Inflation provided the impetus and the physical notions for tracing (with great success) the evolution of the Universe to an era impossible to imagine 30 years ago. In my personal view, a great deal of the appeal of this scenario lies in its simplicity: The mathematics of the original inflationary proposal are almost trivial, while the complexity of even the theory of fluctuations is moderate.

That being said, again in my personal view, the characterization of Inflation as a ‘scenario’ rather than a ‘theory’ is also not unfair. To begin with, while in its original versions the scalar field employed to resolve the cosmological puzzles was considered to be the Higgs field, for reasons unknown to me, this association was dropped in favor of an altogether independent scalar field ϕ (the inflaton), unencumbered by such an association (perhaps because

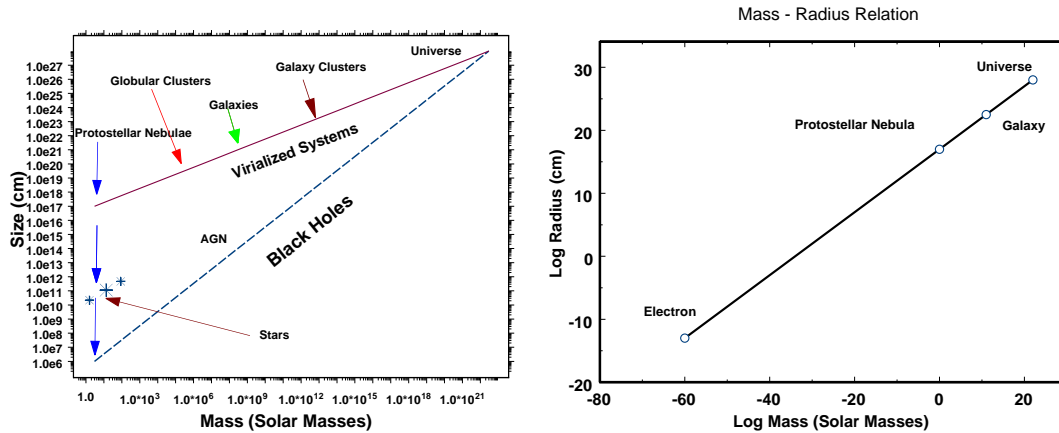


Fig. 2. Left: The Mass-Radius relation $r^2 = 2MR_H$ (solid) along with black hole line $r = 2M$; arrows point to the regions occupied by classes of the objects noted. Right: The same relation extrapolated to the mass of the electron.

of the constraints it imposed on the models). Furthermore, the all important self-interaction potential $V(\phi)$ of this field remains (again in my personal, poorly informed view) in the realm of phenomenology. Despite these objections, the concordance of its predictions with the CMB data has set the bar for future alternative, competing schemes.

On the other hand, the success of the ‘slow-roll’ Inflation in confronting the CMB fluctuations has lent the confidence to venture into notions removed from the constraints of observations such as eternal inflation, i.e. the creation, through unlikely but sufficiently large fluctuations, of domains (‘baby’ universes) that inflate much faster than the parent domains which in their turn also self-reproduce and so on (see e.g. [23] and references therein). Each such region becomes, then, a universe of its own, with (possibly) different values of the inflaton field ϕ and possibly different values of the physical constants. With the apparent proliferation of ‘universes’, the question is whether our accessible to observation domain is special. To the best of my understanding, a seriously considered (and perhaps prevailing) view is that we live in the domain with the proper parameters to foster life, thereby enunciating a truly cosmic version of the Copernican view. So, while the inflationary scenario draws support from its consistency with the CMB observations, some of its other (more far reaching) consequences lie outside the domain of the observable. The question that arises, then, is whether one should accept all these implications as true or should consider the inflationary scenario as an *ansatz* that simply provides a framework within which one can work out and fit the CMB fluctuation data, much in the same way that the Bohr quantum theory did provide a resolution to the issue of the atomic spectra. The answers to these questions lie possibly in future more accurate observations or alternative theoretical developments.

To provide an example of a theory that addresses coincidences with fine tuning akin in precision to that of the standard cosmology, I will refer to the locally scale invariant theory of gravity considered in [25, 26]. This theory is defined by the unique action ($C^{\alpha\beta\gamma\delta}$ is the Weyl tensor)

$$I_W = -\alpha \int d^4x (-g)^{1/2} C^{\alpha\beta\gamma\delta} C_{\alpha\beta\gamma\delta} \quad (11)$$

whose static spherically symmetric geometry with a charge Q reads

$$g_{00} = 1/g_{rr} = 1 - 3\beta\gamma - \beta(2 - 3\beta\gamma)/r - Q^2/(8\alpha\gamma r) + \gamma r - kr^2 \quad (12)$$

where β , γ , k are integration constants. One should note first that in this theory charge modifies geometry the same way as mass, possibly evading the problems that the Q^2/r^2 term of the Einstein gravity solution entails! For $\gamma = 0$, $Q = 0$ this metric is that of Schwarzschild - de Sitter. However the linear term (analogous to the quark potential) is totally novel and being asymptotically non-flat, it is reasonable to associate γ with the inverse Hubble length R_H . The presence of this term provides a *first principles* characteristic acceleration $2M/r^2 \simeq 1/R_H$ and suggests deviations of order 1 from the Newtonian potential at distances such that $r^2 \simeq 2MR_H$ i.e. at a radius that is the geometric mean of the Schwarzschild and the Hubble radius. It is interesting to note that several classes of virialized objects (including the Universe for which $2M \simeq R_H$) lie on this line (Fig 2a). This is relevant to inflation because the mass-radius relation associated with galaxies and their clusters presumably originates in the inflationary perturbations. One could suggest that these systematics (known as the Tully-Fisher and Larson relations in galaxies and star forming regions respectively) are due to the non-linear dynamics of clustering. However, extrapolation of this relation by 60(!) orders of magnitude to the mass of the electron (Fig. 2b), yields for the radius the classical electron radius!!! So, it is not only the size of the Universe at the Planck time that presents us with a fine tuning problem. There exist numerical relations equally astounding but very little understood even outside the standard gravity and cosmology, apparently related to the metric of Eq. (12).

As suggested in §2 the origin of the Horizon and Flatness problems can be traced in part to the presence of a scale in the gravitational Lagrangian. Actually, in some Inflation variants the universe at creation had a size equal to the Planck length and mass equal to the Planck mass, gaining mass as it inflated. As described above, inflation as of today does not provide estimates of the real size of the universe, since we cannot predict how long this period lasts and, even worse (depending on one's view), it allows for the possibility of a huge number of disjoint domains (Multiverse). At this section of speculations I would like to venture to a totally different point of view which at present provides only hints on directions that may be followed in the future. It involves the notion of information, which, as it has been suggested, may lie at the root of all physics [24]. To be sure, it is easy to see that the Special

Theory of Relativity rests on and can be formulated on the condition of a finite, maximum information propagation speed, namely c . Pursuing a similar line of thought, I would suggest Quantum Mechanics as the framework for imposing a finite, maximum information density, namely h . Within this same framework, then, gravity appears to be the source of free energy necessary to process the available information; as such, it also provides a sense for the direction of time, in fact gives rise to time itself. What about the total amount of information? A (pre-Inflation) universe of size equal to l_P and mass M_P contains only one bit of information. In my view such a universe is rather uninteresting and likely to remain virtual. This immediately raises the issue of whether any amount of information can be converted from virtual to real or whether a minimum amount is necessary (while these considerations border the metaphysical, so are those pondering the existence of other universes totally inaccessible to us). Perhaps this is possible only for sufficiently large number of bits [10^{90} ? (i.e. the number of bits the observable universe contained at the Planck time assuming one bit per horizon); could this be *the* reason gravity is so weak?] and perhaps a very specific geometrical arrangement is needed (as discussed in [22]) for their conversion from virtual to real, presumably by the influence gravity [22]. Such a proposal would resolve in a different way the issues of Horizon and Flatness (but it would also need to provide the dynamics necessary to produce the CMB fluctuations, as discussed above). Under the same proposal, it would be natural to also consider a finite amount of the total available information and therefore a closed universe. Considering that such theory, like that of Eq. (11), may involve a Lagrangian with a dimensionless coupling constant (and therefore lacking the Planck density $\Lambda_P \propto 1/l_P^4$ as its characteristic density), the present need for a non-zero cosmological constant, some 120 orders of magnitude smaller than Λ_P , should be considered with some caution.

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