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Cosmological Constant and the Final Anthropic Hypothesis

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1. Introduction

The term "anthropic principle" was first introduced in the famous exposition of Carter (1974). The Strong Anthropic Principle (henceforth SAP), as defined by Carter, states that:

> *...the Universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage.*

This principle expresses an observational selection effect: If we have a cosmological theory according to which there are multiple universes or "domains", then when thinking about the observational consequences of that theory we have to take into account only those domains in which observers exist. For example, even if the vast majority of domains are inhospitable to life, the theory would predict that we will be observing one of the exceptional domains where conditions appear to be fine-tuned for life to exist. The only speculative feature of SAP is thus that it is applicable only if there is a multiverse; beyond that it is simply a logical truism, albeit an important one (Leslie 1989). By contrast, the so-called Final Anthropic Principle, introduced in the monograph by Barrow & Tipler (1986), can make no such claim to methodological status. It states that:

> *Intelligent information-processing must come into existence in the universe, and, once it comes into existence, it will never die out.*

We wish to remove the teleological overtones from this statement and focus on the latter part of it, which clearly expresses a scientific hypothesis that is susceptible to refutation on observational grounds. To avoid confusion, one may use the expression "Final Anthropic Hypothesis"

(henceforth FAH) to refer to the following conjecture: *Once intelligent information processing comes into existence, it will never die out.*

It should be noted at this stage that in their explanation and discussion of the Final Anthropic Principle, Barrow and Tipler (1986) do not refer to multiple universes in any form. This should be emphasized all the more strongly for the fact that, in other parts of their book, the possibility that the observed world is but one among many others (the general idea of an ensemble of universes, a "multiverse") *is* explored. In light of recent data, as we shall show in the next section, the existence of a multiverse appears to be the only chance of indefinite survival of intelligent life. It is therefore essential to understand the FAH in such a way as to make room for this possibility. Even with this clarification, however, the FAH as stated above is susceptible to various differing interpretations. In particular, we need to distinguish between the following two meanings:

1. There is at least one intelligent race in the universe that will continue to exist indefinitely. For the sake of brevity, we shall call this interpretation *individualistic*.

2. Any particular intelligent race might eventually die out, but intelligent life as a whole will exist indefinitely. This interpretation may be termed *holistic*.

Statement 1. logically implies statement 2., but not vice versa. In a sense, one could make a comparison with the local character of conservation laws in classical physics. As discussed by Feynman in his popular exposition (Feynman 1965) electric charge could, in principle, be conserved in two ways: locally and non-locally. Charge could be moved within a box, or it could vanish at one point and be created ex nihilo at another point within a box. Physics allows only for the former way of charge conservation, but laws governing life and intelligence in the universe are much less known than laws of classical physics. Obviously, the local way of conservation is analogous to the individualistic interpretation of the FAH conjecture, while non-local appearance and disappearance of charges are similar to rises and falls of intelligent communities at various points in spacetime.

One reason why FAH is an interesting hypothesis is that we might be interested in knowing whether there is any theoretical possibility for the human species or its descendants to survive indefinitely, in the sense of performing an infinite number of computations along its world-line (Tipler 1994). For the settlement of this question, the individualistic reading is obviously more relevant than the holistic reading. From now on, we shall therefore assume the individualistic reading when referring

to the FAH, unless otherwise stated. Our goal is thus to investigate whether recent progress in cosmology can actually support the conjecture that information processing is necessarily finite within our (or any!) domain, and what recourse is left for the proponents of the FAH (see also Tipler 1986). In this respect, it seems that we are in the middle of a major change of cosmological paradigm (not unexpected, however, as even the cursory look at relevant literature could show). Recent results of the surveys of the Type I supernovae at cosmological distances strongly indicate the presence of a large cosmological constant (Perlmutter et al. 1998; Reiss et al. 1998). If the total cosmological density parameter corresponds to the flat ($\Omega = 1$) universe, the contribution due to vacuum energy density is

$$\Omega_\Lambda \approx 0.7. \tag{1}$$

This result indicates not only that the universe will expand indefinitely, but that it will expand in an (asymptotically) exponential manner, manner, similar to the early inflationary phase in its history. It should be mentioned that a non-zero cosmological constant has been considered desirable from a several points of views in recent years, because it would be capable of solving the cosmological age problem and because it would arise naturally from quantum field theory processes (e.g. Klapdor & Grotz 1986; Singh 1995; Martel, Shapiro & Weinberg 1998). A universe with $\Omega \approx 1$ and Ω_Λ similar to the value in (1) would allow the formation of galaxies (e.g. Weinberg 1987; Efstathiou 1995), and it could last long enough for the life, including intelligent observers, to evolve, all in agreement with SAP. However, we shall show that a universe with a cosmological constant of this magnitude is one where intelligent life cannot survive indefinitely, thus apparently contradicting FAH.

2. Future of the Λ-universe

Universes with a cosmological constant Λ, a subclass of the Friedman-Robertson-Walker (FRW) models, are represented by solutions of the Einstein field equations in the generalized form

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}, \tag{2}$$

where Λ is a positive scalar (for other notation see any of the standard General Relativity textbooks, e.g. Weinberg [1972]; for history and phenomenology of the cosmological constant, see the detailed review

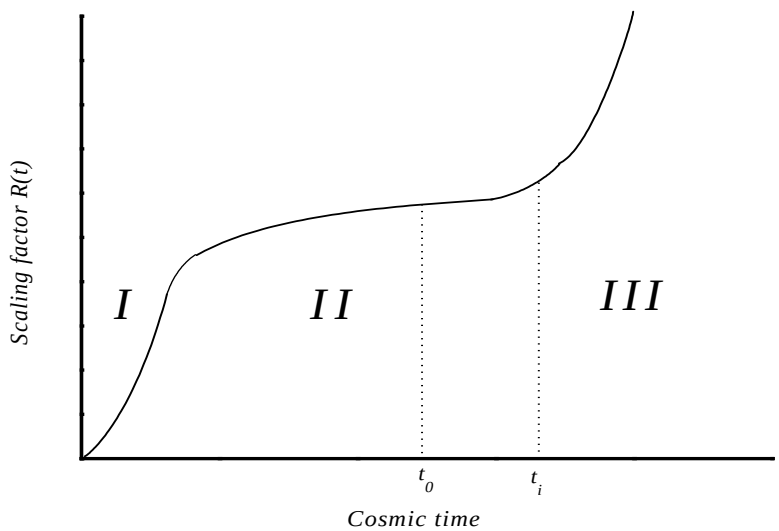

Figure 1. A sketch of evolution of a cosmological domain (conventional "universe"), with present epoch denoted with t_0, and major phases in the universal expansion labeled by Roman numerals (not drawn to scale).

of Carroll, Press & Turner [1992], and references therein). The value of Λ in eq. (2) is related to the vacuum cosmological density fraction as

$$\Omega_\Lambda = \frac{c^2\Lambda}{3H_0^2} = 2.8513 \times 10^{55}\, h^{-2}\Lambda, \tag{3}$$

where Λ is in units of cm^{-2}, and H_0 is the Hubble constant ($H_0 \equiv 100\,h$ km s^{-1} Mpc^{-1}). The Friedmann equation for the matter-dominated case can be written as

$$H(t) = \frac{\dot{a}(t)}{a(t)} = H_0 \left\{ \Omega_m \left[\frac{a(t)}{a(t_0)}\right]^{-3} + \Omega_\Lambda - (\Omega_m + \Omega_\Lambda - 1) \left[\frac{a(t)}{a(t_0)}\right]^{-2} \right\}^{\frac{1}{2}}. \tag{4}$$

In this formula, as well as in all others unless explicitly stated, cosmological matter density fraction Ω_m and vacuum energy density fraction Ω_Λ are evaluated at the present time. The quantity $K_0 = \Omega_m + \Omega_\Lambda - 1$ is sometimes called normalized present-day curvature. For practical purposes, it is convenient to translate the eq. (4) into the "redshift language" as

$$H(z) = H_0[(1+z)^3\Omega_m - (\Omega_m + \Omega_\Lambda - 1)(1+z)^2 + \Omega_\Lambda]^{\frac{1}{2}}. \tag{5}$$

This relation governs the universal expansion and can be integrated into the past or future. Doing the latter shows that our domain cannot remain matter-dominated at all times. Since the simplest dimensional analysis (as well as physical experience) shows that the vacuum energy density becomes progressively more important as the distances between fundamental observers increase, we expect the universe to become dominated by cosmological constant at some moment of its history. This epoch at which universe becomes vacuum-dominated is obtained from the equation (e.g. Adams & Laughlin 1997)

$$t_i = t_0 + \tau_m \frac{\sinh^{-1}(1) - \sinh^{-1}(\sqrt{x})}{\sqrt{x}}, \tag{6}$$

(here $\sinh^{-1}$ denotes the inverse hyperbolic sine, not the reciprocal) where

$$x \equiv \frac{\Omega_\Lambda}{\Omega_m} = \frac{\Omega_\Lambda}{\Omega - \Omega_\Lambda} = \frac{\Omega_\Lambda}{1 - \Omega_\Lambda}, \tag{7}$$

the last equality, applying, of course, to the globally flat universe ($\Omega = 1$). The current age of the universe is denoted by t_0 and the time constant τ_m is defined as

$$\tau_m \equiv (6\pi G \rho_m)^{-\frac{1}{2}} = \left(\frac{9}{4} H_0^2 \Omega_m\right)^{-\frac{1}{2}} = \frac{6.5327 \times 10^9\ h^{-1}}{\sqrt{\Omega_m}}\ \text{yr}. \tag{8}$$

Here, ρ_m is the matter density of the universe (i.e. matter plus - quite negligible for the purposes of the present discussion - radiation energy density). One should keep in mind that the current age of the universe for Ω_Λ given by the eq. (1) is (Perlmutter et al. 1998)

$$t_0 = 14.9^{+1.4}_{-1.1} \times \frac{0.63}{h}\ \text{Gyr}. \tag{9}$$

The history of our domain is schematically presented in the Figure 2 (see also the complementary Fig. 1 in Kardashev 1997). Three major epochs are denoted by large Roman numerals. The epoch of primordial inflation (I) has been discussed in many - already classic - references (e.g. Guth 1981; Linde 1983; Barrow 1988), and we shall not discuss its details here. The entire history of the universe, as we know it from observations (characterized mainly by the structure formation and evolution processes) is contained in the epoch of power-law expansion (II), described in classical cosmology textbooks (Weinberg 1972; Peebles 1993). We are currently inhabiting this expansion phase, our epoch being denoted by t_0; as can be seen from the eqs. (1) and (6) above, it is likely that t_0 is already located within the phase III, or at least close to the end of the phase II (see Fig. 2).

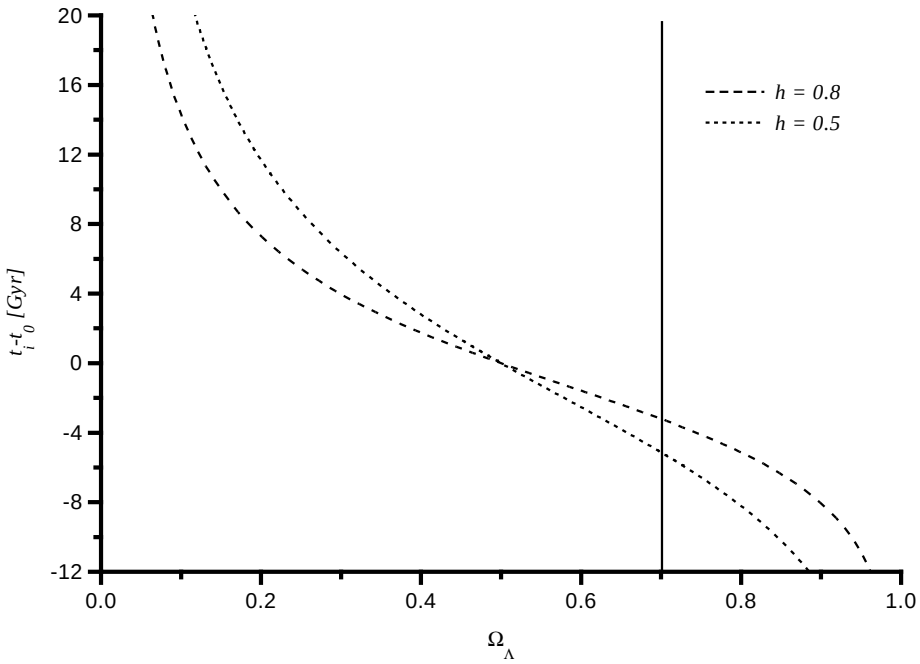

Figure 2. Duration of remaining time prior to the onset of future (quasi) exponentially expanding phase in Gyr as a function of cosmological constant contribution to the universal energy density in globally flat FRW universe. Vertical line represents the currently believed value of vacuum energy density. Note that that for $\Omega_\Lambda > 0.5$, the value of $t_i = t_0$ is negative, i.e. de Sitter expansion *has already begun.*

Finally, the epoch denoted by "III" is the epoch of future exponential expansion, or "future inflation", dominated by residual cosmological constant Λ. In this epoch, the scale factor behaves according to the de Sitter law, i.e.

$$R(t) = R_0 \exp(Ht), \tag{10}$$

where the effective Hubble constant is given as $H = c\sqrt{\Lambda/3}$. The present epoch, denoted by t_0 is likely located in proximity to the epoch t_i, given by the eq. (6), characterizing the onset of future inflation (Kardashev 1997), but $t_0 > t_i$. In the Fig. 2, the remaining time $t_i = t_0$ until the future inflation sets in is shown as a function of cosmological constant energy density. As the entire discussion, this applies to the case of global flatness of our domain. Since Hubble constant is still poorly known, limiting values $h = 0.8$ and $h = 0.5$ are drawn (the latter case has somewhat greater weight according to most modern measurements). We notice that, for the recent measurements of $\Omega_\Lambda \sim 0.7$, the change from the power-law expansion toward the de Sitter state given by (10) has occured $2 - 4$ Gyr ago (dependent on the exact value of H_0). This is already small in comparison with the current age

of the universe, as given by the eq. (9), the ages of spiral galaxies,[1] and of Pop I stars. Therefore, it is conceivable that the terrestrial life began, interestingly enough, in the power-law, matter-dominated phase of universal expansion, different from the one we are living in now. This is not completely unexpected, if we keep in mind the Weak Anthropic Principle, as pointed out, by Barrow & Tipler (1986), Weinberg (1987) and Efstathiou (1995).

Prospects for survival of intelligent observers (and life in general) are bleak in any form of open universe (Davies 1973; Dyson 1979; Barrow & Tipler 1986; Tipler 1986). The entropy of each region increase, and all available sources of energy for information processing (actually negentropy) are inevitably depleted on time-scales varying according to the particular open model considered. Of course, the exponential expansion is fastest at creating such inhospitable environment, since after it sets in the size of the horizon of each observer is shrinking rapidly (for the exact treatment of horizons, see Ellis & Rothman 1993). The size of the de Sitter horizon is given in such universe as

$$R_h = \frac{c}{H_0}\Omega_\Lambda^{-0.5} \approx 3.6 \times 10^9 \left(\frac{\Omega_\Lambda}{0.7}\right)^{-0.5} h^{-1} \text{ pc.} \tag{11}$$

Structures not gravitationally bound to the Local supercluster are already streaming across this boundary, which will coincide with the radius of the visible universe in several Gyr (again, exact value depends on H_0). Some time after that, at the epoch which we can denote by t_h, the Local supercluster will remain effectively the only structure existent for local observers. However, the exact sequence of events depends on the values of several still poorly known parameters, since the depletion of galactic sources of energy, like normal stars or accreting black holes, depends on the total quantity of gas available within gravitationally bound systems and details of star-formation physics (Tipler 1986; Adams & Laughlin 1997; Ćirković 1999). Therefore, this depletion may well be postponed until some point in the inflationary epoch. In other words, we still cannot perceive with certainty what will be the position of the "see-saw" between local (galactic) and global (cosmological) processes at the moment information processing ceases in our domain. The point of essential inhospitability of eternally expanding universes has been noted by several authors; for instance, Tipler (1986, 1994) insists that only a special subclass of closed universes satisfies FAH within a domain. The three basic conditions formulated by Tipler (1986) to be satisfied for indefinite information processing seem to preclude FAH

[1] which are more likely to harbour intelligent observers than the early Hubble types, due to more advanced chemical evolution processes.

in any sort of open universe, and *a fortiori* any with non-vanishing vacuum energy density.

3. Many universes and the strategy of survival

In the sense discussed above, the quantity t_h represents the *terminus ante quem* for the development and evolution of intelligent observers in our universe. It is irrelevant for our present discussion whether t_h has a sharp value or varies slightly due to the growth of cosmological inhomogeneities so that limited regions can remain causally connected at some time $t_h + \Delta t$ (where Δt is small in comparison to t_h and to t_0). However, in order to establish most stringent constraints, one may require that chain of occurences which leads to emergence of intelligent observers (i.e. formation of Earth-like planets, formation of primitive lifeforms, etc.) begins before t_i, the transitional epoch to the vacuum-dominated expansion. This requirement is most probably satisfied for the case of human observers (as seen from Fig. 1, and data on age of life, Earth, etc.).

What could the strategy of survival in such circumstances look like? Since the entropy increase in each domain must necessarily preclude further information processing in such a future inflationary universe, even if all other requirements for sustaining intelligent observers are satisfied, the only way of continued existence of such observers would be to leave the cosmological domain where they originated. At first, it sounds like a paradox, but in many contemporary versions of inflationary cosmology, such "escape from the universe" is theoretically possible. Most significant quantum cosmological hypothesis, from this point of view, is so-called "chaotic inflation", devised by Linde (1983), and subsequently developed by Linde (1988, 1990) and other researchers (e.g. Vilenkin 1995; Garcia-Bellido, Garriga & Montes 1998); it is also discussed in this context by Barrow & Tipler (1986).

As Linde (1983) writes in the original paper on chaotic inflation:

> *In any case, in the infinite (open) universe at $t \sim t_p$ there should exist infinitely many domains of the type desired, which give rise to an infinite number of mini-universes in which life may exist.*

Many different (but generally similar) concepts of many-universe cosmologies appeared in the last few years, some based on the results of quantum cosmology, others purely speculative. The details, however, are not important in our present context. One constraint that the FAH does impose on this type of scenario is that the time t_i that is available in the universe before the onset of its exponential expansion phase must be sufficient to allow evolution of intelligent life and

the technological advance necessary for development and application of "inter-universe" transportation, through traversable wormholes or otherwise (e.g. Morris, Thorne & Yurtsever 1988). We thus have the following inequality:

$$t_i(\Omega, \Lambda, H_0) \geq \tau. \tag{12}$$

The left-hand side of this inequality is cosmological "marble", dependent only on the three listed cosmological "parameters" (hopefully to be determined very soon and thus cease to be theoretical parameters) while the right-hand side is "wooden" evolutionary biology, sociology, technology and other "soft" disciplines (to paraphrase Einstein on his field equations in the General Relativity). If we somehow knew it were an exact equality, we should have wonder about the strangeness of such a coincidence. As it is, this inequality represents a necessary condition for FAH to be correct.

4. Discussion

It seems clear that within a single cosmological domain, the presence of a non-zero vacuum energy density makes indefinite survival of intelligence impossible. However, there are now several theories according to which individual domains are but infinitesimally small regions of the *multiverse*, over which quantum fields vary in a chaotic manner. Some of these theories appear to permit travel from one domain to another. Since such theories appear quite viable, at least at todays level of understanding, it is still not possible to rule out indefinite survival of intelligent beings in this wider context. Thus, while the Final Anthropic Principle in its classical formulation pertaining to a single universe can be considered refuted by empirical discovery of $\Omega_\Lambda > 0$, it can be *reformulated* to encompass the entire multiverse.

On the other hand, this reformulation may introduce additional problems, of the sort which has been known for the long time, and which faces all cosmologies containing past temporal infinities. Namely, as succinctly pointed by Paul Davies in his critiques of Ellis' cosmological model (see Davies 1978),

> *There is also the curious problem of why, if the Universe is infinitely old and life is concentrated in our particular corner of the cosmos, it is not inhabited by technological communities of unlimited age.*

This problem has been plaguing all variants of the classical steady- state theory of Bondi & Gold (1948) and Hoyle (1948).[2] Essentially the same

[2] There are galaxies of arbitrary age in this theory, since new ones are perpetually created as the old ones recede away, and the characteristic time scale $\tau_s = (3H_0)^{-1}$

problem appears if we reformulate Davies' statement in terms of the multiverse: Why has our universe (our inflated bubble in Lindes picture) not been colonized or visited by some supercivilization originating in a bubble much older than our own?

In the multiverse reformulation, there is now the problem of why our causally connected domain (or even more general, our inflated bubble in Linde's picture) has not already been inhabited (or visited) by supercivilizations originating in any bubble much older than ours. The simplest solution is to assume that interbubble migration is impossible (which might be supported by independent physical evidence in due course). As we have seen above, however, this involves sacrificing the FAH. While, undoubtedly, there are more subtle ways to retain interbubble travel while not producing recognizable effects of technological origin ("The Great Silence"; see e.g. Brin 1983 and Hanson 1998), this puzzle further reduces the probability that the FAH is a correct physical proposition.

One conceivable way out for the proponent of FAP would be if it turns out that new bubbles are forming at a sufficiently high rate. Associated with travelling from one bubble to another there is presumably some minimum cost, such as the matter and energy that have to be used in the construction of a wormhole. Also, we can assume that it takes some finite time for the construction to be completed. A supercivilization contemplating colonizing other bubbles would have to choose some strategy of how to expend the resources they command. For example, there might be a tradeoff between the amount of energy expended in the construction of a wormhole and how quickly the project can be completed. On the other hand, it might be worth spending a lot of resources to complete a few wormholes quickly in order to then use the resources in the domains thus colonized to build yet more wormholes, and so on. Call a strategy optimal if it maximizes the expansion rate $dN_C(t)/dt$ of the civilization in the long run (where $N_C(t)$ denotes the number of domains the civilization has colonized by time t). Suppose that the average growth rate of the number of domains in existence is

is only an average age of galaxies. At the time of formulation of the steady-state theory, τ_s was considered small ($\sim 6 \times 10^8$ yrs, due to the gross overestimate of the value of Hubble constant at the time), and the Milky Way has already been an extraordinary old galaxy, which certainly implied that surrounding galaxies are far less probable to achieve the same degree of chemical and biological evolution (if our case is an average one). However, if we take τ_s to be an order of magnitude higher, in accordance of today's best knowledge, the anthropic argument of Davies quoted above gains force. Since the fraction of galaxies that are older than age t is given by $\exp(-t/\tau_s)$, it follows that there are almost 2% of all galaxies in any large enough comoving volume which are *twice* the age of the Milky Way.

$dN_D(t)/dt$. We can then formulate the following inequality:

$$\frac{dN_C(t)}{dt} < \frac{dN_D(t)}{dt}. \tag{13}$$

If this inequality is satisfied, the fraction of all domains that are inhabited by a supercivilization originating from some other domain will tend to be negligible, consistent with the observation that our universe does not seem to have been colonized by any such a civilization. (If, on the other hand, the inequality were violated, the multiverse would become satiated with supercivilizations, in apparent contradiction to observation.)

Eq. (13) imposes an upper bound on $dN_D(t)/dt$. The FAH, as we saw in earlier sections, implies that $dN_D(t)/dt > 0$, but only future research will tell whether FAH is in fact correct.

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