

## SCIENTIFIC ESCHATOLOGY\*

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### Abstract

The future evolution of the universe suggested by the cosmological model proposed earlier at this meeting by the authors is explored. The fundamental role played by the positive “cosmological constant” is emphasized. Dyson’s 1979 paper entitled *Time Without End* is briefly reviewed. His most optimistic scenario requires that the universe be *geometrically* open and that biology is structural in the sense that the current complexity of human society can be reproduced by scaling up its (quantum mechanical) structure to arbitrary size. If the recently measured “cosmological constant” is indeed a fundamental constant of nature, then Dyson’s scenario is, for various reasons, ruled out by the finite (De Sitter) horizon due to exponential expansion of the resulting space. However, the finite temperature of that horizon does open other interesting options. If, as is suggested by the cosmology under consideration, the current exponential expansion of the universe is due to a phase transition which fixes a *physical* boundary condition during the early radiation dominated era, the behavior of the universe after the relevant scale factor crosses the De Sitter radius opens up still other possibilities. The relevance of Martin Rees’ apocalyptic eschatology recently presented in his book *Our Final Hour* is mentioned. It is concluded that even for

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the far future, whether or not cultural and scientific descendants of the current epoch will play a role in it, an understanding (sadly, currently lacking) of community and political evolution and control is essential for a preliminary treatment of what could be even vaguely called *scientific* eschatology.

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## 1 Introduction

On the Silver Jubilee of the founding of the Alternative Natural Philosophy Association it was possible to present a new piece of natural philosophy[1, 2, 3] which the authors believe has profound implications for the new field of particle-astrophysics/cosmology; SLAC has recently made this discipline an important part of its mission. What follows is a discussion of a few of the important questions raised by the future implications of this cosmology if it, and other cosmologies which share with it a positive “cosmological constant”, survive the rigorous scientific scrutiny they are now receiving. The authors believe that the way some of these implications are absorbed by our science and the broader cultures in which our science is embedded will have relevance to the enormous problems the children and grandchildren of those present here will have to face in the coming decades.

During the last fifty years, scientific cosmology has moved from being a speculative field which could be viewed askance by many scientists not intimately associated with it to being one of the “cutting edge” disciplines — both theoretically and observationally — of 21st century science. But most of the technical work in cosmology is confined, necessarily, to the study of the past. The study of the future of the universe rarely gets such careful attention. One goal of this paper is to try to motivate more

working scientists to bring about a similar change of attitude and practice in what we call here *scientific eschatology*.

Coincidentally with the founding of ANPA, Dyson[4] published a paper with the same objective. At that time he could take a geometric view of the problem, defined by whether the universal curvature parameter is positive (closed universes) or negative (open universes). One of his objectives in the paper was, clearly, to make a case for the possibility that rational, scientific, ecological communities of living organisms can look forward to a “time without end”. He easily shows that if the members of such communities depend on the biochemistry with which we are familiar, or, in more colloquial terms, contain “flesh and blood” organisms as an essential constituent, there is no hope that his objective can be reached within either class of cosmologies he considers. He therefore extends the definition of “biology” to include “organisms” (and by implication, ecosystems composed of them) that have the same *structure* as those we have become familiar with on our planet. This was done by postulating a scaling law for quantum mechanical interactions which gave precision to his meaning of *structure*. Even in this context, he was unable to meet his objective of preserving rationality forever within closed (“big crunch”) cosmologies. But for open cosmologies he found a way to show that appropriate “biological” strategies could provide a (subjective) *time without end* for organisms and ecosystems of ever increasing complexity. We will summarize his arguments below.

At the time Dyson wrote, observational evidence for a “cosmological constant” did not exist. Einstein’s motivation for introducing this constant (i.e. to preserve, in the large, a static and infinite universe satisfying his *cosmological principle*) had evaporated with discovery of the red shift for distant galaxies and Hubble’s law. So there was no reason for Dyson to include in his discussion the De Sitter cosmologies produced by a positive cosmological constant. We now know that until about 5 Giga-years ago the rate of expansion of the universe was *decreasing*. We also know that more recently the rate has been *increasing*. From very early times until the present ( $\sim 13.6$  *Gyr*) the observational data can be fitted by a positive cosmological constant  $\Lambda$  together with an evolving matter density which can be checked in other ways. The data are consistent with  $\Lambda$  being strictly constant throughout this period. If  $\Lambda$  is

indeed a “constant of nature”, this fact would render Dyson’s analysis moot.

A review of Dyson’s paper presented here reaches the conclusion that, under his assumptions (which did not include the possibility of a cosmological constant), a “time without end” for the type of “biology” he defines was then a live possibility. Next, the consequences of having a cosmological constant fixed for all time will be examined. At first sight, these consequences are indeed dismal. They could be met by the tragic remarks of Bertrand Russell[5] in *A Free Man’s Worship* or the defiant challenge with which Dyson closes his own article:

As Haldane (1924) [6] the biologist wrote some fifty years ago, “The human intellect is feeble, and there are times when it does not assert the infinity of its claims. But even then:

Though in black jest it bows and nods  
I know it is roaring at the gods  
Waiting the last eclipse,”

Fortunately, we believe there are possible routes to “time without end” which might be reached from where we are in an accelerating expansion scenario. The physics in the class of models presented earlier in this meeting[1] need not *require* the “cosmological constant” to be fixed forever, — only over a well defined and finite period of time. This opens up a new set of possibilities for biological strategies, which might allow our intellectual and cultural heirs to win through to an indefinitely extendable future. The authors of this paper have only scratched the surface of this fascinating subject, but this analysis suggests that heroic action may well be required, not just now, but for many Giga-years into the future. That prompt action in this century is clearly required has been recently argued by the Astronomer Royal[7]. Older members of ANPA will recall, and more recent members should be made aware, that Martin Rees played a highly significant role in supporting the first tottering steps of ANPA toward the robust success we now enjoy. The authors of this article trust he will not mind too much if we take his measured analysis of the current desperate situation as the basis for a plea to the scientific community at large to recognize the tremendous need for a rigorous *political* science; this argument clearly goes beyond

the case Dyson has made for including an extended scientific *biology* in order to establish an adequate basis for *scientific eschatology*. But to make this case we must now complete the steps we have already indicated that lead us to that conclusion.

## 2 Dyson’s “Time without end”

We now take a closer look at Dyson’s pioneering paper. As already noted he rapidly concludes that a “big crunch” universe does not provide enough scope for an optimistic view of the far future. Even in an open (or flat) universe, Dyson’s argument closes the door on the continuation of “flesh and blood” biology of a complexity comparable to that currently experienced on our planet for a *physical* time without end. This focuses his interest on the biology of “...sentient black clouds[8], or sentient computers[9]...”,— structures which we know some (most?) ANPA members dismiss as impossible. To make his argument plausible and quantitative, he proposes a “biological scaling hypothesis” that has as its first consequence the conclusion that the “...appropriate measure of time as experienced subjectively by a living creature is not physical time  $t$  but ...” an integral from zero to  $t$  of the temperature function defined by his scaling law ([4], Eq.56). This is called *subjective* time. “The second consequence of the scaling law is that any creature is characterized by a quantity  $Q$  which measures its rate of entropy production per unit of subjective time.” For a human being living long enough to pronounce “Cogito, Ergo Sum” this works out to be  $\sim 10^{23}$  bits, and for our species  $\sim 10^{33}$  bits. This sets a fixed lower bound for the temperature  $\theta$ , which is ([4], Eq. 73)  $\theta > (Q/N) 10^{-12}deg$ , where  $N$  is the number of electrons available to the society of complexity  $Q$ . For our current biosphere  $N = 10^{42}$ , so our current social complexity cannot be maintained at temperatures lower than  $10^{-23}deg$ .

Here a few comments are in order. Dyson’s biological scaling hypothesis ([4], p. 454) is

*Biological Scaling Hypothesis. If we copy a living creature, quantum*

state by quantum state, so that the Hamiltonian of the copy is

$$H_c = \lambda U H U^{-1},$$

where  $H$  is the Hamiltonian of the creature,  $U$  is a unitary operator, and  $\lambda$  is a positive scaling factor, and if the environment is similarly copied so that the temperatures of the environments of the creature and the copy are respectively  $T$  and  $\lambda T$ , then the copy is alive, subjectively identical to the original creature, with all its vital functions reduced in speed by the same factor  $\lambda$ .

This hypothesis is made in a context which should be spelled out further. Dyson starts his section on biology by posing three deep questions concerning the nature of life and consciousness:

- (i) Is the basis of consciousness matter or structure?
- (ii) Are sentient black clouds, or sentient computers, possible?
- (iii) Can we apply scaling laws in biology?

As is clear in his article, if the answer to (i) is “matter”, Dyson takes this as, in more colloquial language, tying consciousness inexorably to “flesh and blood” and in the cosmological context to certain death. There are traditional ways (eg religious rather than scientific) to escape this dismal conclusion, but the authors of this article follow, instead, Dyson’s optimistic attitude and assume that the basis of consciousness is structural rather than material. The reader should consult his article (and other writings) to see how he justifies his own attitude. He notes that we (i.e. our culture) do not yet know how to answer these three questions “But they are not in principle unanswerable. It is possible that they will be answered fairly soon as a result of progress in experimental biology.”

As just explained, Dyson’s tentative answer to question (i) is “structure”. The fact that “quantum computers” are now claimed to have greatly extended powers compared to “classical computers” lends weight to his tentative conclusion. His tentative “yes” answer to (ii) puts him in the “strong AI” camp. The authors of this

article are not sure this is the right (even tentative) answer today, but HPN feels it likely that *communities* of computers starting in environments with appropriate resources and with inheritance mechanisms and survival pressures sufficiently similar to those encountered in biology would evolve into recognizably conscious beings. The technical point here is that a community that has evolved to the point where its members have independent choices of action available (i.e. have “free will”) is obviously not an *algorithmic computer*.

Support for Dyson’s tentative “yes” answer to (iii) is provided by recent work by Fred Young[10], a former president of ANPA. Young makes a strong case that the basic structures of biology can be represented by scaling laws using small-protein concentration ratios for physiological modelling at the cellular level, tissue and system organizational modelling at the organism level, biological species organization at the ecological level, etc. The authors of this article find Young’s results to date quite compelling and extremely promising for the future of his approach to biology.

We now return to Dyson’s paper at the point where he has established the finite temperature bound  $\theta > (Q/N) 10^{-12}deg$  below which any society of complexity  $Q$  bits controlling  $N$  electrons must not fall. This bound is arrived at by asserting that the rate of energy dissipation (i.e. use of energy by the society) must not exceed the power that can be radiated away into space. At that point it can still dissipate the energy which it must expend to keep on operating. Below that point it must decrease its complexity or increase its controlled number of electrons. Since the supply of energy available to the society is assumed finite, it must reach this point at a finite time, and Dyson remarks ([4], p. 456):

We have reached the sad conclusion that the slowing down of metabolism described by my biological scaling hypothesis is insufficient to allow a society to continue indefinitely.

Here Dyson examines a possible way to insure “time without end” for entities who “live” in this cold and forbidding future. This is, quite simply, the biological strategy of *hibernation*. Life can metabolize at a higher temperature and then hibernate at

a much lower temperature to stretch out its *subjective* time. To quote Dyson again ([4], p 4550))

Suppose then that a society spends a fraction  $g(t)$  of its time in its active phase and a fraction  $[1 - g(t)]$  hibernating. The cycles of activity and hibernation should be short enough so that  $g(t)$  and  $\theta(t)$  [Here  $\theta(t)$  is a function Dyson has already assumed technologically available subject to explicit thermodynamic constraints] do not vary appreciably during any one cycle. Then (56) and (59) [previous constraints] no longer hold. Instead subjective time  $[u(t)]$  is given by

$$u(t) = f \int_0^t g(t')\theta(t')dt',$$

[rather than  $u(t) = f \int_0^t \theta(t')dt'$ ]

and is no longer bounded. The parameter  $f$  was chosen by Dyson to have a value of  $(300 \text{ deg sec})^{-1}$  as a scale comparable to that of human society to make the subjective time rate  $u(t)$  dimensionless. Hence the constraints which led to his dismal conclusion no longer applied. In this way he was able to achieve a system with an infinite subjective time in an expanding universe, while expending only a finite amount of energy.

One matter where the finite energy limitation is serious is in the storage of memory. As Dyson remarks ([4], p. 456)

I would like our descendants to be endowed not only with an infinitely long subjective lifetime but also with a memory of endlessly growing capacity. To be immortal with a finite memory is highly unsatisfactory; it seems hardly worth while to be immortal if one must erase all trace of one's origins in order to make room for new experience.

Digital memory with the finite energy resources available to a periodically hibernating society is obviously not an option which meets this requirement when *digital* memory storage in condensed matter is employed. Dyson turns to analog memory and



claims that the angles between a finite number of structures (e.g. stars) in an expanding universe can be used for an *analog* memory storage of ever increasing capacity. So far as we can see here, the point to focus on is that for indefinitely expanding storage capacity for *information* to be available, the system must have no finite upper bound on the *entropy*. In Dyson's expanding universe scenario, even though the energy available to the society is finite, the unbounded expansion of the volume over which this energy is distributed means that there is, indeed, no *a priori* upper limit on the entropy. Consequently analog storage might meet the requirement he imposes. As with much of this discussion, meeting *technological* challenges this requirement poses starting from any particular configuration could prove to be daunting.

### 3 Asymptotically De Sitter Universes

Recent observational results have tentatively convinced most of the experts that the energy density of our universe is currently partitioned into approximately 73% dark energy, 23% dark matter and 4% ordinary matter and radiation, in a space that is flat rather than either "closed" or "open". The simplest way to fit the data is to assume that the various interlocking pieces of evidence which lead to this picture constitute an actual *discovery* of Einstein's cosmological constant  $\Lambda$  as a new universal constant *and* a measurement of that constant to a couple of percent. In the approach taken in the paper presented earlier in this meeting[1], these authors prefer to think of it as a *phenomenological* constant specified as constant only over a finite interval in universal time. That point of view is explored eschatologically in the next section. In this section we adopt the more naive approach.

The specific consequences of interest here which follow from this assumption are that:

a) The matter energy density that drives the cosmological expansion in the dynamical Friedman-Lemaitre (FL) equation, which we call  $\rho_{FL}$ , will eventually become insignificant compared to the cosmological constant density  $\rho_{\Lambda} = \frac{\Lambda c^4}{8\pi G_N}$  (here  $G_N$  is Newton's gravitational constant).

(b) Consequently, the FL (Hubble) equation is replaced asymptotically by  $[\frac{\dot{R}}{R}]^2 \simeq$

$\frac{8\pi G_N}{3c^2}\rho_\Lambda = \Lambda c^2/3$ , which implies that  $R(t) = R_E e^{\sqrt{\frac{\Lambda}{3}}ct} \equiv R_E e^{\frac{ct}{R_\Lambda}}$ . Here  $R_\Lambda$  is sometimes called the De Sitter radius or horizon, and  $R_E$  is set at a time when  $\rho_{FL}$  is negligible compared to  $\rho_\Lambda$ . Although objects of the scale of the gravitationally bound super-cluster have dynamics which are determined by local matter densities, the late time exponential expansion defines a cosmological De Sitter horizon  $R_\Lambda = \sqrt{\frac{3}{\Lambda}} \simeq 16.6 \text{ Glyr}$  which serves as a causal boundary, i.e. anything which crosses this boundary can never re-establish luminal contact with our region of the universe. Our galaxy appears to be close to the edge of, and probably bound to a super-cluster with a radius of about 50 mega-parsecs  $\approx 0.16 \text{ Gly}$ . If we therefore take the current FL scale parameter ( $R_0 = R(t_0)$  at time  $t_0$ ) in our (gravitationally bound) locality to be about 100 mega-parsecs, we find that this scale parameter will cross the De Sitter horizon (i.e.  $R(t) = R_\Lambda$ ) when  $t \simeq t_0 + 65 \text{ Gyr}$ . Here the current time  $t_0$  is usually taken to be about 13.6 *Gyr*. This means that all other galaxies not in our local super-cluster will vanish within about 65 *Gyr*. This consequence already precludes useful discussion of Dyson's analog memory storage and far-ranging communications strategies if  $\Lambda$  is indeed a universal constant on a par with  $\hbar, c, G_N$  and  $k_B$ . Both of these strategies rely on scaling laws that assume causal (i.e. luminal) contact can always exist if the society waits long enough. For further discussion see (c), (i) and Section 4 below.

(c) Since the De Sitter horizon has a finite area, the causal region of the De Sitter space will have[11] a finite entropy  $S_\Lambda = k_B \frac{\pi R_\Lambda^2}{L_P^2}$ , where  $L_P = (\hbar G_N)^{\frac{1}{2}} c^{-\frac{3}{2}}$  is the Planck length and  $k_B$  is Boltzmann's constant.

(i) Because finite entropy implies finite information storage capacity, this fact precludes, simply using counting arguments, any way of realizing Dyson's analog storage method for constructing an indefinitely extendable memory. As a counting argument, this holds for quantum-coherent systems (eg quantum computers) as well as for digital computers.

(ii) Systems with finite entropy undergo Poincaré recurrences[12]. Such recurrences are due to the finite number of configurations (microstates) available to a system with finite entropy. Because there are only a finite

number of configurations that the system fluctuates among, the system will eventually return to any given initial configuration. Since these recurrences have only to do with counting of states, this fact applies to both classical and quantum statistical systems. Such recurrences are maximally destructive of information.

(iii) One strategy of despair that has sometimes been suggested is to find a way to pass clues about our experience in this universe through its fiery destruction to provide information that could prove useful to new societies evolving in the cycle that might emerge after we are consumed. Clearly, the destruction of information precludes placing any hope in this possibility.

(iv) This list of unpleasant facts about a De Sitter universe could easily be extended. This might explain why Dyson has not, to our knowledge, extended his analysis to such universes.

There may still be a finite strategy arising from the fact that in such universes the De Sitter horizon maintains a finite temperature. The existence of a horizon creates an information deficit within the space bounded by that horizon. The subtle quantum correlations in states near the horizon must be described statistically in terms of the degrees of freedom and parameters accessible in the causal region. Whenever there are such statistical degeneracies in ways to describe a particular physical state, the concept of temperature becomes a meaningful tool to describe macroscopic states. There are many states across any horizon which can describe any given measured state within the causal region, thus associating an entropy and temperature with that horizon. Consequently, this could serve as an inexhaustible source of energy to run a *steady state* (constant rate of energy throughput) forever. For instance a sufficiently clever technological society could focus the thermal energy coming from some finite area of the horizon on a “boiler” which could be maintained at a higher temperature than the horizon. That society could then employ a thermodynamically viable engine to extract useful work (e.g. turn heat into low temperature matter or energy density) by a cycle between the “boiler” and a “condenser” at some temperature intermediate

between the boiler temperature and the horizon temperature. To be viable, the time scale of the work cycle must be much less than the equilibration time of the heat engine[13]. This engine will, of course, be a non-equilibrium element of a much larger thermodynamic system which includes the De Sitter horizon. The condenser would require an efficient radiator (essentially already assumed possible by Dyson) to get rid of the thermodynamically required waste heat for the cycle. So far as we can see, such a device is not in conflict with the second law of thermodynamics. This society would have the inescapable informational problems arising from finite memory, and political problems arising from having to decide how the finite resources are budgeted between current and future needs. However, we will have to find solutions to the political problems if we are to get through the next century, as we discuss later.

A more ambitious, and more speculative possibility is that the “steady state” societies we have considered so far are not energy limited. Consequently, they might even sequester more energy than they need to keep going, and become energy *accumulating* societies containing expanding resources of condensed matter, part of which could be devoted to expanding local resources. Perhaps it might be possible to use accumulated resources to modify the cosmology itself.

To explore this possibility, examine Einstein’s equation, which describes the connection of the local geometry to the local energy densities:

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}. \quad (3.1)$$

We assume that the local, gravitationally bound, energy densities which remain have clustered in a spherically symmetric manner. The space-time metric for a system with spherical symmetry has the form  $ds^2 = g_{tt}c^2dt^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2 + g_{\phi\phi}d\phi^2$ . Upon inserting this form into Einstein’s equation, the radial component of the metric can be shown to be given by

$$(g_{rr})^{-1} = 1 - \frac{8\pi G_N}{c^4 r} \int_0^r (\rho(\tilde{r}) + \rho_\Lambda) \tilde{r}^2 d\tilde{r}. \quad (3.2)$$

The time-time component  $g_{tt}$  of the metric and the inverse of the space component  $g_{rr}^{-1}$  will have the same zero, which determines the location of the horizon, and fixes the center as the same as the center of the mass distribution.

For example, if there is a mass  $M$  associated with the galactic super cluster more or less localized near the center of the region, the horizon scale  $r_H$  associated with the local cosmology satisfies

$$0 = 1 - \frac{2G_N M}{c^2 r_H} - \frac{r_H^2}{R_\Lambda^2} = 1 - \frac{R_M}{r_H} - \frac{r_H^2}{R_\Lambda^2}, \quad (3.3)$$

where  $R_M$  is the Schwarzschild radius  $R_M \equiv \frac{2G_N M}{c^2}$ . Note that if  $M = 0$ , the horizon is located at  $R_\Lambda$  as expected. It is of interest to note that if  $R_M > \frac{2R_\Lambda}{3\sqrt{3}}$ , there is no horizon in the causal region. One might hope to be able to eliminate the De Sitter horizon by increasing the mass  $M$ , however the society would be trapped between two horizons which are drawn together as the mass  $M$  is increased. This would indeed be a hostile environment for finite beings.

Alternatively, if the mass density  $\rho_M$  is uniformly distributed throughout the region, the horizon scale satisfies

$$r_H = \sqrt{\left(\frac{3c^4}{8\pi G_N}\right) \frac{1}{\rho_m + \rho_\Lambda}}. \quad (3.4)$$

The entropy associated with this horizon is given by  $S = k_B \frac{\pi r_H^2}{L_P^2}$ , whereas the temperature is given by  $T = \frac{\hbar c}{2\pi k_B r_H}$ . Any societal activity which is capable of increasing the energy density within the causal region would be expected to utilize processes that preserve entropy, converting entropy from the larger horizon (at a cooler temperature) into the lower horizon entropy (of smaller area and higher temperature) added to the local entropy densities associated with the increased local energy densities. Such adiabatic processes will unfortunately not change the overall finite entropy, and therefore not prevent recurrences or solve information limits. However, if such processes can occur, the society has access to increasing energy supplies, increasing temperatures, and the associated increasing rates of subjective time as defined by Dyson.

### 3.1 A possible societal strategy

We see that if a society is able to modify the overall energy contained within the causal region, then the regional cosmology can be changed. It remains to demonstrate whether such activities can be fruitful even in principle. Suppose the society disperses

heat engines uniformly throughout the region, and uses the cold materials produced by those engines to construct other engines. The associated energy densities would then satisfy

$$\frac{d\rho_M}{dt} = \alpha\rho_M \Rightarrow \rho_M = \rho_{Mo}e^{\alpha t}, \quad (3.5)$$

where  $\alpha$  is determined by the efficiency of the engines in converting horizon heat into cold materials. The initial available density of engines  $\rho_{Mo}$  is expected to be a fraction of the galactic super cluster density relative to the De Sitter horizon. Therefore, the society would make significant modifications to the De Sitter cosmology in the region in a time of the order

$$t_{modify\ DeSitter} = \frac{1}{\alpha} \log \left( \frac{\rho_\Lambda}{\rho_{Mo}} \right), \quad (3.6)$$

as long as this time is significantly less than the Poincaré recurrence time.

We will estimate the scale of this time by assuming that the thermal distribution of particles associated with the De Sitter horizon is the same as that associated with a black body cavity at that temperature. The efficiency of a Carnot engine running between the optimal temperatures is given by  $e = \frac{W_{out}}{Q_{in}} = 1 - \frac{T_H}{T_{boiler}} < 1$ . The thermal distribution of low mass particles in the cavity satisfies

$$n(\epsilon)d\epsilon = \frac{g}{2\pi^2(\hbar c)^3} \frac{\epsilon^2 d\epsilon}{e^{\epsilon/k_B T} - 1}, \quad (3.7)$$

where  $n(\epsilon)$  is the number of quanta per unit energy per unit volume, and  $g$  is the degeneracy of the thermal quanta. We will design the collectors on the heat engines so that they are efficient at collecting radiations of wavelengths ( $\lambda_{collected} \leq \lambda$ ) comparable and smaller than the dimension of the collector of area  $\lambda \times \lambda$ . We will assume that the collector scale is considerably smaller than the horizon scale, which means that the exponential in the Planck formula is much larger than 1. Only a fraction  $f_Q$  of those quanta in a region of space will have directions toward the collector, and the rate at which usable quanta strike the collector can be estimated to be

$$\frac{\Delta N_{collected}^-}{\Delta t} \approx f_Q \left( \int_{\hbar c/\lambda}^{\infty} n(\epsilon) d\epsilon \right) \times c \times Area_{collector}. \quad (3.8)$$

Since the area of the collector defines the wavelength  $\lambda^2$ , the rate of the collection of quanta is estimated to be

$$\frac{\Delta N_{collected}^-}{\Delta t} \approx f_Q \frac{g}{\pi} \left( \frac{c}{R_\Lambda} \right) e^{-(2\pi)^2 \frac{R_\Lambda}{\lambda}}. \quad (3.9)$$

This rate is clearly exponentially small in the horizon scale compared to the scale size of the heat collector. We expect that the rate of heat conversion  $\alpha$  should be related to the rate of quantum collection multiplied by the average energy per quantum collected relative to the rest energy  $mc^2$  of each heat engine, in order to satisfy Eq. 3.5. Thus, an estimate of the rate of exponential growth in energy density in the society due to the heat engines is given by

$$\begin{aligned}\alpha &\sim f_Q \frac{g}{\pi} \left( \frac{c}{R_\Lambda} \right) \frac{hc/\lambda}{mc^2} e^{-(2\pi)^2 \frac{R_\Lambda}{\lambda}} \\ &\approx f_Q 2g \left( \frac{c}{R_\Lambda} \right) \frac{\lambda_m}{\lambda} e^{-(2\pi)^2 \frac{R_\Lambda}{\lambda}},\end{aligned}\tag{3.10}$$

where  $\lambda_m$  is the Compton wavelength of the mass of each heat engine.

We now can compare the time scale required for such heat engines to have (local) cosmological significance with the Poincaré recurrence time scale of that cosmology. Recurrences are expected to occur stochastically on time scales given by[12]

$$t_{recurrence} \cong t_{reshuffle} e^{\frac{S_\Lambda}{k_B}},\tag{3.11}$$

where  $t_{reshuffle}$  is the typical time scale associated with the microscopic reshuffling of those configurations that give rise to the finite entropy  $S_\Lambda$ . The configurations are counted by the thermodynamic weight  $\Omega$  in the Boltzmann identification  $S = k_B \log \Omega$ . This reshuffling time can be estimated to be a fraction  $f_R$  of the causal transit time  $\frac{R_\Lambda}{c}$  across the De Sitter patch (causal region), giving recurrence times of the order

$$t_{recurrence} \cong f_R \left( \frac{R_\Lambda}{c} \right) e^{\pi \left( \frac{R_\Lambda}{L_P} \right)^2}.\tag{3.12}$$

Comparison of the recurrence time with the energy accumulation rate of the heat engines given by

$$t_{modify\ DeSitter} \approx \frac{\pi}{f_Q g \log \left( \frac{\rho_\Lambda}{\rho_{Mo}} \right)} \left( \frac{R_\Lambda}{c} \right) \frac{\lambda}{\lambda_m} e^{(2\pi)^2 \frac{R_\Lambda}{\lambda}}\tag{3.13}$$

gives design constraints on the size of the heat engines:

$$\frac{\lambda}{\lambda_m} e^{(2\pi)^2 \frac{R_\Lambda}{\lambda}} < \frac{f_R f_Q g \log \left( \frac{\rho_\Lambda}{\rho_{Mo}} \right)}{\pi} e^{\pi \left( \frac{R_\Lambda}{L_P} \right)^2}.\tag{3.14}$$

Although on the left hand side of the equation, the macroscopic size of the collector  $\lambda$  is expected to be decades of orders of magnitude larger than the Compton wavelength

associated with the mass of the heat engine, the exponentiation of the square of the horizon scale relative to the Planck length on the right hand side of the equation should give considerable flexibility in the design of a workable engine.

Since there seem to be no inconsistencies in building engines which can utilize the heat of the horizon to store energy density, we can speculate on the consequences of such actions. As the horizon scale shrinks, the temperature associated with the horizon increases. Using Dyson’s association of the subjective time rate with the temperature of the organism/society, any evolving “biological” organisms will have increasing rates of subjective time. However, if the process of energy density storage is indeed adiabatic, the overall entropy of the local cosmology will remain fixed, leaving the Poincaré recurrence time unchanged. Such a strategy could indeed increase *relative* subjective time without bound. In such an environment, Dyson’s strategy of hibernation would not be useful, since it would only serve to slow down relative subjective time. No mention is here made of the formidable engineering tasks involved in constructing heat engines which function efficiently in increasingly hot spaces. We have been unable to come up with any *a priori* reasons against such societal intervention on a cosmological scale. Note that in contrast to Dyson’s scenario which accommodates biology to a changing cosmological environment, this society alters both the cosmology and itself to manipulate its subjective time.

## 4 Is the “Cosmological Constant” Really Constant?

The scenario presented at this meeting only infers that  $\Lambda$  be constant during the finite time period for which the rate of expansion of the relevant FL scale factor is sub-luminal. This interval is illustrated for a specific choice of scale factor[1] in Fig.1, but our remarks here apply to the whole class of models which give a reasonable fit to current data and meet this requirement. In the model discussed in[1], the earlier time corresponds to a phase transition characterized by quantum de-coherence such as occurs when the ground state of a Bose-Einstein condensate starts to “evaporate” due to the confining density falling below the critical density at that temperature. Note that in such a model, density is falling more rapidly than temperature, so



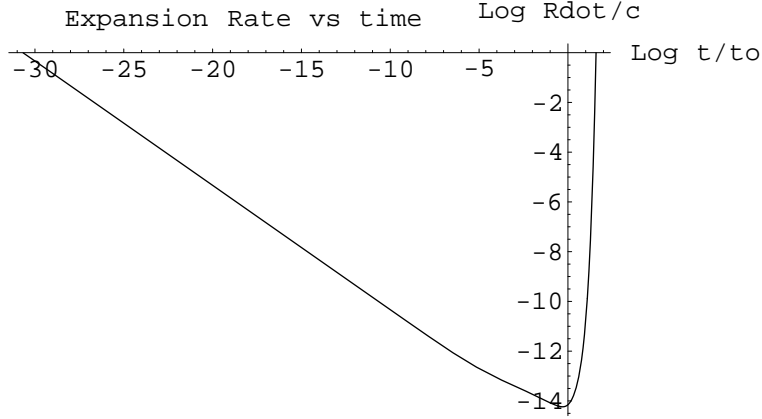


Figure 1: Finite time period of sub-luminal expansion rate

that it is consistent to assume that all of the energy is locked up in the (quantum-correlated) ground state of the condensate (lowest spacial frequency mode, using spacially periodic boundary conditions) *prior* to de-coherence. What happens at the future time  $t_E$  when this scale radius crosses the putative De Sitter horizon, or even whether there *is* a De Sitter horizon at that time, is the focus of the discussion in this section.

To focus our thinking, we will initially assume that the “dark energy” which is driving the exponential expansion at late times (but prior to the second time that  $\dot{R} = c$ ) is “vacuum energy” due to zero point motions of sources[14]. The vacuum energy in the Casimir effect depends only on  $\hbar c$  and the boundary conditions, independent of the *coupling constant* to the electromagnetic field. Nevertheless, it is possible to calculate the measured force effect using the charges and currents in the conducting bounding surfaces due to the fluctuations arising from the uncertainty principle. This gives the same result because, physically, the boundary conditions necessarily require that the boundaries themselves be made of *material* objects which act as electromagnetic conductors or dielectrics. Thus, from a *physical* point of view, we might expect “dark energy” effects to disappear once the scale radius of the gravitationally bound portion of the universe we are considering has crossed the (now putative) De Sitter horizon and

is, *ipso facto*, out of luminal contact. For instance, Casimir plates separated by a De Sitter horizon are *not* expected to exhibit the Casimir effect. Using the interpretation of dark energy espoused here, we question whether it will continue to manifest as a cosmological constant at late times. The De Sitter cosmology requires that the cosmological constant be in fact a constant. If this is not the case, then expectations and predictions of a horizon, with its associated properties, are premature.

At even sooner times, we expect the scale associated with the cosmological inhomogeneities responsible for galactic clustering and the fluctuations in the cosmic microwave background radiation to become comparable to or cross the De Sitter scale radius. As stated in the previous section, if the expansion is primarily due to dark energy during the intervening period, this is expected to occur in about 65 Gyr. Generally, we expect local geometry to be determined by local energy densities as described using Einstein's equation  $G_{\mu\nu}(x) = 8\pi G_N T_{\mu\nu}(x) + \Lambda g_{\mu\nu}(x)$ . For dynamically significant periods of time prior to this crossing, it is clear that the homogeneity and isotropy assumptions inherent in a Friedman- Lemaitre cosmology do not hold on the scale of galactic clustering. This means that the local geometry generated,  $G_{\mu\nu}(x)$ , is neither pure (cosmological) FRW-Lemaitre nor the Schwarzschild-like region of an isolated galactic cluster in Minkowski space (which would have no space-time expansion from dark energy). For instance, our local gravity is primarily the Schwarzschild space-time generated by Earth, with negligible influence from the overall cosmological acceleration due to the dark energy (or else we would be leaving the surface of the Earth!). This means that our local space-time is not undergoing the exponential expansion associated with a cosmological constant, despite our presence in an accelerating cosmology. We expect the evolution of our local scales to be determined by our local energy (and dark energy) densities, appropriately matching asymptotic boundary conditions. Likewise, on scales for which the cosmological matter inhomogeneities are important, the local densities are expected to have significant influence on the behavior of the geometry relative to cosmological dynamics. As the scale of relevance to galactic clustering crosses the De Sitter scale radius, one must take care in describing the De Sitter scale as a horizon. It is not unreasonable to suggest that the association of a given scale distance with supra-luminal rates of expansion could

be only a temporary phase in the evolution of a cosmology that contains radiation, matter, and dark energy.

Once all cosmologically “co-moving” matter associated with the current exponential expansion has lost (luminal) causal contact with the finite, gravitationally bound system we believe will be left behind, we expect the regional situation to change. One conjecture is that from then on there is no reason to believe that the De Sitter scale radius, having no physical system to support it, should remain a “horizon” (meaning that regions beyond this “horizon” which were receding supra-luminally would again move sub-luminally). More precisely, the horizon (which is a global concept) never really existed, but there would only be a temporary loss of luminal contact as objects cross into a region which will recess at supra-luminal rates. After that time, objects which achieve (necessarily sub-luminal) escape velocity from the finite system (which now will hardly be describable as having “uniform density” on scales comparable to the De Sitter radius) would presumably continue to spread out into the *flat space* which is then the appropriate boundary condition for describing escape velocity. They could well be out of reach in terms of intact recovery as objects. However they would still remain in (eventual) luminal contact. This conjecture raises eschatologically important opportunities and issues which we now explore.

Fortunately, there would be no information horizon limiting the potential complexity of memory. This means that the entropy of the system need no longer be finite, and hence there would be no “big crunch” due to a Poincaré recurrence.

Unfortunately there would be no cosmological heat source to draw upon for energy, so that the finite energy crisis would be exacerbated. This implies that in the earliest stages of this scenario all efforts should be made to collect energy resources to be utilized during the cold far future. Hibernation would be a very bad idea until AFTER causal contact begins to be re-established with the remaining accessible parts of the universe.

Our position on the fringes of the bound galactic super cluster is advantageous for the transitional stage of the eschatology. Regions in the bound cluster nearest the outer orbits are well positioned with regards to communications, access to external information, and energy required for transportation. It looks as though we are

destined to be on the dynamic frontier.

## 5 Apocalyptic Eschatology

Up to now the assumption has been implicitly made that the eschatological problem of primary concern has been whether “biology” in Dyson’s sense can continue indefinitely (at least in subjective time) at the level of complexity our civilization has already achieved and with an ever growing memory. As has been seen, the technological challenges are formidable, but nothing in the laws of physics as now known precludes this possibility with anything like certainty. Implicit also in this analysis is the assumption that strict causality, or in theological terms predestination, does not hold. In other words, such societies are assumed to have, in some effective sense, *free will*, that is to make choices which have meaningful consequences relevant to the survival of themselves and/or their heirs. For better or worse, we so far only have knowledge of *one* such society that has passed the technological threshold needed to even envisage the far stretches of time involved. Hence we have no *scientific* way to estimate the probability of success. But we do have available reasonably well understood examples of societies at somewhat lower levels of technological development which have not had the foresight to avoid collapse, or even extinction[15, 16].

For a thoughtful analysis of the current situation we turn to the Astronomer Royal, Martin Rees[7], who will be remembered by older ANPA members for his invaluable assistance in getting ANPA going. He comes to the shocking conclusion that our global society has only a 50-50 chance of surviving the challenges we will meet in the current century. What strikes the authors of this paper as most depressing in the picture he paints is not just the individual problems — which are threatening enough — but the fact that he, in common with Dyson’s earlier treatment of the far future, fails to discuss the fact that even if a technological means of meeting the problems is conceivable, there is no *global* decision making process in prospect, let alone available, that can bring together the planetary resources needed and direct them into the search for and implementation of the action needed on the time scale available. A promising start on the analysis of the problem of environmental collapse

has been made by Jared Diamond, using a broad enough sample of examples to be meaningful. He finds, somewhat to his surprise, that there are no cases of collapse due solely to environmental change ([16], p. 11). Four of the five different sets of factors needed to make the analysis (environmental damage, climate change, hostile neighbors, friendly trading partners) can be more or less important or even absent, but understanding the society's responses to its environmental problems *invariably* is needed to understand the result. In other words, the basic problem falls squarely in the political arena, as our own analysis of the situation had concluded prior to encountering this recent development in his work. In short, the *political science* needed for the task has yet to be created. This is not the place to suggest how that might be achieved, other than the stale remark that without such a guide to global mobilization, the future is bleak.

To end on a more cheerful note, once our species succeeds in meeting the political problem, and avoiding the threatening apocalypse, the future for our intellectual and cultural heirs could well continue as long as the political will to do so persists.

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