Physical eschatology and life in the distant* universe

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I. INTRODUCTION

The universe is *really* big—possibly infinite in size. In the universe we can see, best estimates gives hundreds of billions of galaxies each with on average hundreds of billions of stars. The Drake equation gives a simple way to calculate the likelihood of other intelligent life being out there by simply combining best estimates of how likely each of the necessary conditions for life like others appearing come into existence. You can actually go through the arithmetic, but there's so much uncertainty in most of the parameters involved that it's impossible to get a good estimate.

Regardless, it seems pretty damn arrogant to assume we're the only ones out there, and goes against the successful principle in astronomy that humans and Earth really aren't that special after all. And most scientists agree that it appears almost certain that there is other intelligent life out there, somewhere. Since human society has existed for such a short time, it is easy to surmise that any intelligent life we would find off Earth would likely be extremely advanced technologically. But what would that life look like? And why have we not found it yet (the Fermi paradox)?

Likewise, it seems intrinsically worth knowing the range of possible futures for human civilization. Assuming we don't kill ourselves off, what or where could humanity be millions of years in the future? And finally, could some form of intelligent life exist forever?

Physical eschatology is this application of physics to eschatology, the study of the end of time [4]. It is, of course, intrinsically bound up with the fate of life.

II. LIFE AS INFORMATION THEORY

> "Let us avoid defining 'life' to be a special process based on the carbon atom, and instead let quantum field theory define 'life' in its most general sense." [15]

Physicists are pretty lame biologists, so let's assume that intelligent life is ultimately just glorified information processing. Then all we need to do is count information content encoded in bits, which is bounded by the (information theoretical) entropy of a system,

$$S = -\sum_i p_i \log_2 p_i, \tag{1}$$

which gives the minimum number of bits required encode a message with probabilities given by p_i.

The Brillouin inequality [14] gives an upper bound on the amount of information I (in bits) of the information that can be processed with energy E at temperature T,

$$I \le \frac{E}{k_{\mathrm{B}} T \ln 2}, \tag{2}$$

where k_{B} is the Boltzmann constant. (You can get this bound by converting the minimal thermodynamic entropy created by process (that is, if it were reversible) to information entropy.)

Alternatively, the Bekenstein bound (treating a black holes as the most efficient form of information storage) limits the information stored (in bits) within a sphere of radius R of total energy E by

$$I \le \frac{2\pi E R}{\hbar c \ln 2} = 2.58 M R \times 10^{38}\ \text{bits/g/cm}, \tag{3}$$

where M is the mass of the sphere, and limits the rate of information processing to

$$\frac{dI}{dt} \le \frac{\pi E}{\hbar \ln 2} = 3.86 M \times 10^{48}\ \text{bits/s/g}. \tag{4}$$

In practice, the Brillouin inequality is almost certainly the most relevant limiting quantity.

III. IMMEDIATE STRATEGIES FOR INTELLIGENT LIFE

Accordingly thermodynamic principles embodied in Eq. (2), suggest that it is advantageous for life to get as much energy as possible in as cold an environment as possible. The strategy of search projects for intelligent life like SETI has in general been to look for intelligent life similar to that that we know, but this is a pretty strong motivation for why intelligent life might actually be quite different.

Fortunately, many of these alternative prospects would be straightforward to identify through observational astronomy. Prospects include looking for Dyson spheres (stars surrounded by spheres to capture all of their energy) [7], Matrioshka Brains (huge computational structures) [2] or even more exotic alternatives. There are

*By distant, of course, we refer to both space and time.

also other identifiable signals of interstellar life, like matter anti-matter reactions, transits of stars by artificial objects or heat collectors for life in cold parts of the solar system [9].

Intelligent life may also find it very advantageous to leave our part of the galaxy because it is too hot due to impacts from interstellar dust [6]. The outer reaches of the galaxy may also be more habitable because interstellar hazards like supernovae, cosmic ray heating and other even rarer events. All of these events become much less likely and hazardous the further one goes from the center of the galaxy, the primary constraint being the lack of available mass and energy.

Finally, the SETI project relies on the assumption that alien civilizations would broadcast their presence outward at high power via radio communications. There are lots of philosophical reasons why alien life would choose not to do so, but more practically, most efficient form of long range communications may be even be by matter, not light [6].

IV. COSMOLOGY IN BRIEF

A. The history of the universe

The universe started 13.7 billion years ago (bya) with the big bang. It expanded really quickly to form a "primordial soup" and a few billion years later structures start to form, so we get fun stuff like the Milky Way (8 bya), the solar system and Earth (4.6 bya), and life (3.7 bya). Civilization arrived on Earth in the form of humanity on the order of 10,000 years ago.

B. The future of the universe

Cosmology is still a young science, and the long term fate of the universe remains poorly understood (as shown, for example, by so-called dark energy and dark matter). We don't really understand what's going to happen, but there are 3 likely prospects [1, 3]. Our uncertainty is especially large because cosmological observations in the vicinity of the Milky Way may not even be indicative of that of the entire universe [5].

a. Big crunch The universe eventually stops expanding, slows down, and collapses back in on itself, the big bang in reverse. Intelligent life is pretty much screwed in this case: fortunately, the evidence seems to be pretty strongly against this case at the moment.

b. Heath death The universe expands forever, as stars eventually grow old and decay to black holes. Eventually after $\sim 10^{100}$ years even super-massive black holes evaporate, and the universe becomes an increasingly cold and dilute gas of particles. Entropy wins. There remains only a finite amount of energy that can be captured and utilized by any advanced civilization.

c. Big rip The universe expands forever, and the rate of acceleration increases over time (positive jerk?). Eventually after some finite time the entire universe gets ripped apart in a singularity where all bonds between particles are destroyed. This would also be, predictably, pretty bad news for civilization.

V. CAN LIFE LIVE FOREVER?

The universe is almost assuredly not going to last forever in any sort of conventionally useful state. But even so, are there strategies that intelligent life can adopt to live essentially forever? The answer depends on our choice of cosmology, and interesting, there remain prospects for each.

A. Omega point theory

Tipler suggests that even in a universe that will eventually crunch back in on itself, it may be possible for civilization to experience an infinite subjective lifetime in finite proper time using the infinite sheer energy created by the universe's collapse [15]. This is not quite as bizarre as it seems, and is the flavor of attempts to make life live forever. All that matters is that the subjective lifetime of a civilization diverges faster to infinity than the rate of collapse. However, this scenario has been widely criticized, it would only be possible in the case of what is currently believed to be an unlikely cosmological future, so I'm not going to worry about it further.

B. Beating heat death with scaling

Freeman Dyson [8] in a famous 1979 paper made one of the first serious examinations of the potential for life to live nearly forever, introducing the biological scaling hypothesis. If life obeys the laws of quantum mechanics, then the evolution of its state $|\psi\rangle$ according to the Schroedinger equation is specified completely by the Hamiltonian (energy) operator H:

$$H|\psi\rangle = i\hbar\frac{d}{dt}|\psi\rangle . \tag{5}$$

Thus if we copy a living creature's quantum state such that the new state is identical except with a Hamiltonian

$$H_c = \lambda U H U^{-1}, \tag{6}$$

where λ is some scale factor and U is a unitary operator, and if the environment of the creature is similarly reduced in temperature from T to λT, then the creature will operator identically to its original merely with its vital functions reduced in speed by the factor λ.

Accordingly, Dyson introduces subjective time u, given by

$$u(t) = f \int_{t_0}^{t} T(t')dt', \tag{7}$$

where f is a constant $300\,\mathrm{s}^{-1}\mathrm{T}^{-1}$ to make subjective time unit-less and scale it to proper time and room temperature.

Dyson realized that in a universe undergoing heath death, there is no way that a civilization could capture an infinite amount of energy. But with finite energy, perhaps there is some way that the subjective lifetime of a civilization could be made infinitely long?

A measure of intelligence is given by the rate of entropy production per unit of subjective time u,

$$Q = \frac{dS}{du}. \tag{8}$$

With subjective time calibrated to proper time t for humans, a best estimate of for an entire human body is about $Q = 10^{23}$ bits [8]. For an entire civilization, a reasonable estimate is $\log_2 Q > 50 - 100$ [12]. Then the metabolic rate of a civilization is given by

$$m = \frac{dE}{dt} = k_{\mathrm{B}} T \frac{dS}{dt} = kfQT^2. \tag{9}$$

In contrast, subjective time from Eq. (7) proceeds at a rate proportional to T. This difference in the dependence on temperature would allow for life to live forever if temperature decreases continually as $T(t) \propto t^{-\alpha}$ with $1/2 < \alpha \leq 1$, as in this case the integral of energy consumption would converge to a finite value, but the subjective time experienced would not [10].

Unfortunately, there are fundamental limits to how cold something can get, even in the absolute dead of inter-galactic space. Dyson's creative solution is to put civilization in hibernation mode so that it will never reach that temperature, turning it off for just long enough to evaporate heat. Whether such a strategy would work as one could imagine is quite controversial. Finding a reliable clock for hibernation could be quite tricky or impossible [12]. In particular, it is questionable whether the infinite and smooth range of energy states for necessary for such computation and a clock could be found, as known quantum systems do not have an infinite range of ground state energies. The resolution to such issues depends critically on details of the cosmological future and the limits of quantum mechanics. Another potential problem is that with a finite amount of energy only a finite number of states may be encoded, so civilization would be finite state machine and thus have no choice but to eventually repeat itself. Fortunately in any case, there is plenty of time to figure such issues.

C. Seeding other universes

If you allow for really exotic cosmology, our universe may only be an inflationary bubble in the real universe, which is overwhelmingly even bigger. In this case, we may be able to create other inflationary bubble (other universes) and possibly even seed them with messages or even intelligent life itself through creating some sort of worm hole or shooting things through black holes [11, 13]. So even if the case of the Big Rip its conceivable (okay, maybe a bit of a stretch) to have life live forever.

VI. MORAL IMPERATIVES?

Cirkovic rather speculatively shows [5] that under the assumption that humanity will not be able to live forever, there are huge irreversible losses of potential lives for every delay we take in colonizing the accessible universe, which he limits at the local supercluster of galaxies. According to his estimations of the potential of life in some sort of final state, on the order of

$$\Delta n \sim 5 \times 10^{46} \tag{10}$$

human lives worth of thought are lost forever for each 100 years of delay. Perhaps we should feel a sense of urgency as the universe wastes entropy at a tremendous rate?

[1] FC Adams and G Laughlin. A dying universe: the long-term fate and evolution of astrophysical objects. *Reviews of Modern Physics*, 69:337–372, 1997.

[2] RJ Bradbury. Matrioshka brains. Available online at `http://www.aeiveos.com:8080/~bradbury/MatrioshkaBrains/MatrioshkaBrainsPaper.html`, 2001.

[3] S Caroll. The future of the universe. Available online at `http://cosmicvariance.com/2006/01/26/the-future-of-the-universe/`, 2006.

[4] MM Cirkovic. Resource letter: PEs-1: Physical eschatology. *American Journal of Physics*, 71(2):122–133, 2003.

[5] MM Cirkovic. Forecast for the next eon: Applied cosmology and the long-term fate of intelligent beings. *Foundations of Physics*, 34(2):239–261, 2004.

[6] MM Cirkovic and RJ Bradbury. Galactic gradients, post-biological evolution and the apparent failure of seti. *New Astronomy*, 11(8):628–639, 2006.

[7] FJ Dyson. Search for artifical stellar sources of infrared radiation. *Science*, 131(3414):1667–1668, 1960.

[8] FJ Dyson. Time without end - physics and biology in an open universe. *Reviews of Modern Physics*, 51(3):447–460, 1979.

[9] FJ Dyson. Looking for life in unlikely places: reasons why

planets may not be the best places to look for life. *International Journal of Astrobiology*, 2(2):103–110, 2003.

[10] K Freese and WH Kinney. The ultimate fate of life in an accelerating universe. *Physics Letters B*, 558(1-2):1–8, 2003.

[11] J Garriga, VF Mukhanov, KD Olum, and A Vilenkin. Eternal inflation, black holes, and the future of civilizations. *International Journal of Theoretical Physics*, 39(7):1887–1900, 2000.

[12] LM Krauss and GD Starkman. Life, the universe, and nothing: Life and death in an ever-expanding universe. *Astrophysical Journal*, 531(1, Part 1):22–30, 2000.

[13] AD Linde. Life after inflation. *Physics Letters B*, 211(1-2):29–31, 1988.

[14] A Sanberg. The physics of informatio nprocessing superobjects: Daily life among the jupiter brains. *Journal of Evolutiona and Technology*, 5:1–34, 1999.

[15] FJ Tipler. The ultimate fate of life in universes wihich undergo inflation. *Physics Letters B*, 286(1-2):36–43, 1992.