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Earths: Rare in Time, Not Space?

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We compare two recent astrobiological approaches to the solution of the problem of the "Great Silence" (or Fermi's paradox): the "rare Earth" hypothesis of Ward and Brownlee, and the phase-transition scenario of Annis. We show that they have important similarities, as far as self-selection of intelligent observers is concerned. In order to better illuminate the differences, we consider the duration of Galactic habitability and the notion of 4-dimensional Galactic Habitable Zone. The notion of "rarity" of complex biospheres can be made more precise in two different ways. We conclude that there are slight reasons to prefer the phase-transition picture, but more important still, the very possibility of such a discrimination between the rival hypotheses testifies that some progress has been made in resolving these difficult issues.

Keywords: Astrobiology, extraterrestrial intelligence, Galaxy, evolution, history and philosophy of astronomy

How many kingdoms know us not!
Blaise Pascal, ***Thoughts***, 207

1. Introduction: Rare Earths and Phase Transitions

In a famous and controversial recent book *Rare Earth: Why Complex Life Is Uncommon in the Universe*, astrobiologists Ward and Brownlee have expounded a view that while simple microbial life is probably ubiquitous throughout the Galaxy, complex biospheres, like the terrestrial one, are very rare due to the exceptional combination of many distinct requirements [1]. These requirements are well-known to even a casual student of astrobiology: being in the very narrow interval of distances from the parent star, having a large moon to stabilize the planetary axis, having a giant planet ("Jupiter") at the right distance to deflect much of the impacting cometary and asteroidal material, etc. Each of these requirements is *prima facie* unlikely, so that their combination is bound to be incredibly rare and probably unique in the Milky Way. In addition, Ward and Brownlee break new grounds with pointing out the importance of hitherto downplayed factors, like the importance of plate tectonics or "Snowball Earth" episodes for the development of complex life. We cannot enter into a detailed presentation of this "rare Earth" (henceforth RE) hypothesis; the book of Ward and Brownlee makes a rich and highly rewarding reading, with many independent strands masterfully weaved into the grand mosaic. It is sufficient to say here that RE offers a solution to the (in)famous Fermi's "paradox" (or the "Great Silence" problem): there are no alien societies in the Galaxy since the Earth (i.e., a complex metazoan habitat) is inherently very rare[1]. Even if some of them exist by a fluke, they are likely to be of non-technological character (like the large cetaceans here on Earth) due to one or more of sensitive parameters, like the existence of plate tectonics. On this theory, Earths are fantastically rare at all epochs and in all spatial locations in the Galaxy, as well as in other galaxies. Consequently, intelligent life (and especially the one in possession of technology) is also fantastically rare.

The seminal paper of Annis [2] opened a new vista by introducing (though not quite explicitly) the notion of global regulation mechanism, that is, a dynamical process preventing or impeding uniform emergence and development of life all over the Galaxy[2]. In Annis' model, which he dubbed the phase-transition model for reasons to be explained shortly, the role of such global Galactic regulation is played by gamma-ray bursts (henceforth GRBs), collosal explosions caused either by terminal collapse of supermassive objects ("hypernovae") or mergers of

1. For the best review of Fermi's "paradox" and its many solutions, see Brin [3]; useful pointers are to be found in [21] and [24] as well. The most recent, refreshing and very systematic, though not quite unbiased, review is the book of Webb [4].
2. A similar suggestion has been made earlier by Clarke [8], although his model was entirely qualitative and used wrong physical mechanism (Galactic core outbursts) for global regulation; see also [9,10].

binary neutron stars. GRBs observed since 1960s have been known for almost a decade already to be of cosmological origin, arising in galaxies often billions of parsecs away, and it has been calculated that these are the most energetic events in the universe since the Big Bang itself. Astrobiological and ecological consequences of GRBs and related phenomena have been investigated recently in several studies [5-7]. To give just a flavor of the results, let us mention that Dar [6] has calculated that the terminal collapse of the famous supermassive object Eta Carinae could deposit in the upper atmosphere of Earth the energy equivalent to the simultaneous explosions of 1 kiloton nuclear bomb per km^2 all over the hemisphere facing the hypernova! Annis suggested that GRBs could cause mass extinctions of life all over the Galaxy (or at least the Galactic habitable zone, henceforth GHZ; see [11]), preventing or arresting the emergence of complex life forms. Thus, there is only a very small probability that a particular planetary biosphere could evolve intelligent beings in our past. However, since the regulation mechanism exhibits secular evolution, with the rate of catastrophic events decreasing with time, at some point the astrobiological evolution of the Galaxy will experience a change of regime. When the rate of catastrophic events is high, there is a sort of quasi-equilibrium state between the natural tendency of life to spread, diversify, and complexify, and the rate of destruction and extinctions. When the rate becomes lower than some threshold value, intelligent and space-faring species can arise in the interval between the two extinctions and make themselves immune (presumably through technological means) to further extinctions, and spread among the stars. Thus the Galaxy experiences a phase transition: from an essentially dead place, with pockets of low-complexity life restricted to planetary surfaces, it will, on a very short (Fermi-Hart-Tipler) timescale, become filled with high-complexity life. We are living within that interval of exciting time, in the state of disequilibrium [12], on the verge of the Galactic phase transition; this is the phase-transition (henceforth PT) scenario.

It is obvious that the PT scenario explains the "Great Silence": there simply has not passed enough time for civilizations significantly older than ours to arise. On the other hand, entrance into the disequilibrium regime is easy to obtain within the framework of Annis' GRB-dominated PT picture: cosmology assures us that the average rate of GRBs increases with redshift, i.e. decreases with cosmic time on the average as $\propto \exp(-t/\tau)$, with the time-constant τ of the order of 10^9 yrs [2]. The quantitative model of PT-type will be presented in a subsequent study [13].

It is important to understand that the GRB-mechanism is just one of possible physical processes underlying the PT paradigm. Any catastrophic mechanism operating on sufficiently large scales (in comparison to the GHZ scale) and exhibiting secular evolution can play a similar role. There is no dearth of such mechanisms; some of the ideas proposed in the literature which have not been clearly shown to be non-viable are cometary impact-causing "Galactic tides" [14,15], neutrino irradiation [16], clumpy cold dark matter [17], or climate changes induced by spiral-arm crossings [18]. Moreover, all these effects are cumulative: total risk function of the global regulation is the sum of all risk functions of individual catastrophic mechanisms. The secular evolution of all these determine collectively whether and when conditions for the astrobiological phase transition of the Galaxy will be satisfied. (Of course, if GRBs are the most important physical mechanism of extinction, as Annis suggested, then their distribution function will dominate the global risk function and force the phase transition.)

These two hypotheses, RE and PT, are not dissimilar at all. On the contrary, they share some of their best features, notably the employment of observation-selection effects (cf. [19]) in astrobiology. According to RE, the existence of a complex biosphere on Earth (and, by extension, us as intelligent observers) selects a much narrower range of parameters in the astrobiological parameter space than previously thought. On the other hand, the PT scenario suggests that the same fact (the existence of a complex biosphere) selects a particular epoch, in addition to selection of the same (or similar) habitable range of astrobiological parameters. Both RE and PT reject the so-called Principle of Mediocrity (or Copernican Principle): that there is nothing special about local conditions in both the spatial and temporal sense. Both RE and PT lean heavily on recent astrophysical and astrochemical evidence; for instance, recent calculations of metallicity requirements for terrestrial planet formation are crucial for the RE hypothesis, and the observations of cosmological GRBs and their evolution rate are an important underpinning of the PT hypothesis. In this manner, they are different from a host of other explanations of the "Great Silence", like the Zoo-hypothesis of Ball [20], or the stock "nuclear holocaust" scenarios of von Hoerner, Sagan, and others (e.g., [21,22]). The latter type of explanation explicitly rely on assumptions of sociological nature, which is certainly a methodological disadvantage.

Our goal in the rest of this paper is, therefore, to illuminate the distinctions between the two, and to demonstrate that, while the empirical discrimination is still unfeasible, there are several epistemological and methodological issues on which the PT picture is more satisfactory. To understand this, we have to consider first some philosophical notions relevant for our purpose.

2. Anthropic "Window of Opportunity"

We expect intelligent observers to arise only within a well-defined temporal "window of opportunity". Since its appearance against the background cosmological time is an observation selection effect, we shall dubb it the anthropic window. Boundaries of this window are still not very well-known, since we do not know enough about the physical, chemical, and biological pre-conditions of observership. However, some of the relevant processes are currently intensely investigated, and we may at least broadly outline the intervals for its lower and upper boundaries. First, we have to inquire about the physical processes limiting the conditions friendly to the origination of complex life. The lower limit on the anthropic window has been the subject of much discussion which, actually, helped flesh out the anthropic principle(s) itself ([23]; for a review, see [24], esp. Chapter 4). Historically, it has been concluded that intelligent observers require such important astrophysical processes, like the galaxy formation, sufficient amount of stellar nucleosynthesis, and the Main Sequence stellar stability. Recently, Lineweaver has calculated that the average age of terrestrial planets in the Milky Way is 6.4 ± 0.9 Gyr, and they have started forming about 9.3 Gyr ago [25]. This epoch can be taken as the lower boundary of the anthropic window.

The upper boundary is much less investigated territory, belonging to the nascent discipline of physical eschatology[3]. Since luminous stars are producing entropy at a finite rate, and since the overall baryonic matter density is finite (and rather small in comparison to the total cosmological energy-density, $\Omega_B/\Omega \approx 0.05$), it is obvious that the star-formation in spiral disks will cease at some point, and that the present stelliferous era (Adams and Laughlin 1997) will come to an end. When will that happen is much less certain, due to astrophysical uncertainties about the rate of infall of matter into the spiral disks, but will occur most probably in about 100 – 1000 Gyr [26]. Since the latter value is roughly comparable to the lifetime of the dimmest Main Sequence stars [27], we can take it as the boundary of the era in which there are shining stars. If stars are formed after this epoch, it must be through very rare exotic means, such as the brown dwarf collisions [28], which are quite unlikely to produce and retain habitable planets. Thus, the end of the stelliferous epoch is the definite *terminus ante quem* for the emergence of life on habitable planets.

However, other earlier *terminii* are possible. Will chemical evolution make planets hostile to complex life before the end of the stelliferous era? In recent astrobiological discussions, it was suggested that at least two different processes can bring the *terminus* earlier: i.) the lack of radioactive elements generating plate tectonics, and ii.) the lack of water for planet formation and subsequent biological activities. As far as the role of plate tectonics in the emergence of complex metazoan life goes, it is still a highly speculative issue. Ward and Brownlee make much of it in their monograph, but conclusions are not unequivocal. Even they admit that, for instance, complex and intelligent metazoans can develop on oceanic planets or on planets with only small, volcanic islands. On the other hand, the astrophysical side of the story in this case is clear: with the decline of supernova rates in future, radioactive elements (mainly U, Th, and radioactive isotope ^{40}K) will decline in abundance until completely disappearing at the timescales of dozens or hundreds of Gyr. However, we should study the role of geophysical processes in general, and plate tectonics in particular, in emergence of intelligence and technological civilization, before we accept this earlier *terminus*.

As far as the mechanism ii.) is concerned, the situation here is somewhat inverse: the biological side of the story is obvious – without water no habitable planet can form whatsoever. The astrophysics is not very clear, especially if we take into account the notion of **limiting metallicity** [28], i.e. we expect that due to opacity effects, the amount of elements heavier than helium will have an asymptotic value of about 20%[4].

We should keep in mind two additional points:

- Anthropic window appears on the background of an ever-expanding universe dominated by the cosmological constant (e.g., [29,30]). In the infinite cosmic time, the probability of a randomly chosen epoch being located within the finite interval is zero. Yet, we find ourselves living exactly in such an epoch. This is another instance of failure of the naively understood "Copernican

3. Physical eschatology is a rather young branch of astrophysics, dealing with the future fate of astrophysical objects, as well as the universe itself; for an overview and bibliography see [31].

4. In the same time, rough calculations of Adams and Laughlin show that the asymptotic abundance of hydrogen is also about 20%, the rest of matter being converted to chemically inert helium.

principle". A spatial analogue of this is clear: if we were to be located in a truly typical or random position in space, we would have expected to be located in the intergalactic space, which by far dominates the spatial volume of the universe[5]. The fallacy of this reasoning is rather obvious.

- On the other hand, the anthropic window applies only to the emergence of life and intelligence. Once they arise, intelligent observers can, in principle, exist at an epoch outside the window. Of course, the observers would need sophisticated technological methods to do this, but those would presumably exist prior to the end of the "anthropic window"; a well-known example is Dyson's "hibernating" civilization in an ever-expanding universe ([32]; but see [33]).

3. 4-Dimensional Galactic Habitable Zone

Thus, we have outlined the boundaries (at least in principle) of the Galactic habitable zone in both space and time (see Fig. 1). In spatial terms, GHZ is an annular ring, slowly expanding outward as the Galactic chemical evolution builds up sufficient metallicity to build new habitable terrestrial planets[6]. Its inner radius, which separates the region of instability of planetary orbits due to frequent stellar encounters (and possibly also nuclear activity, high cosmic-ray flux, and other effects) stays constant in the first approximation. In temporal terms, it is the interval (-9.3 Gyr, +1000 Gyr) in which habitable terrestrial planets can arise around Main Sequence stars.

A wider, 4-D spatiotemporal perspective has proven repeatedly useful in the history of physical science, since Einstein and Minkowski. Hereby we propose that such a perspective can be useful in astrobiology, too; in particular, it offers a convenient framework for discriminating between the two observation-selection approaches to explanation of the "Great Silence." In addition, we are able to be more precise in defining what "rare" really means in the astrobiological context.

Within the RE paradigm, there are just a few points, possibly only a single point, representing formations of planets friendly to complex metazoan life in the entire 4-volume of the generalized GHZ. There is no correlation to be expected between those few points, and if it really is only a single point (our Earth!), its position in 4-D GHZ is purely random. If we follow the history of those small number of points, there will be no discernible pattern either, nothing which could tell us something about the future of life in the Galaxy.

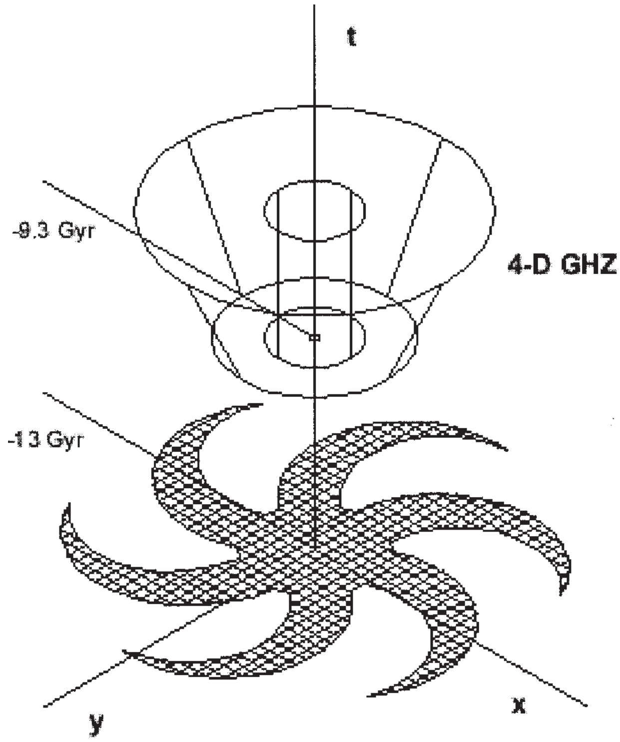

Fig. 1 A schematic presentation of 4-D GHZ with one spatial dimension ("thickness" of the disk) suppressed. A snapshot at each epoch of the Galactic history shows an annular ring with an ever-increasing outer boundary.

On the other hand, on the PT paradigm, the situation is entirely different. There is a characteristic timescale, which we can call t_{PT}, which denotes the epoch (or beginning of the short interval) of phase transition, which is explicable in astrophysical terms (as the moment, say, in which the average interval between GRBs becomes shorter than the complex metazoan evolution timescale). Prior to t_{PT}, there are no points denoting planets inhabited by complex metazoan lifeforms; even if they appear, at random points, their histories are very short. As we approach t_{PT}, we begin to notice more and more such points, and as one or more of them passes this critical stage in Galactic evolution, they begin to bifurcate and diffuse filling the 4-D GHZ at rather short timescales (Fermi-Hart-Tipler colonization timescales). The Galaxy passes into an entirely different regime of its history, since it becomes filled with life. Even more, it is reasonable to assume that the emergent Kardashev's Type III civilization(s) of the post-phase-transition epoch will spread their influence beyond

5. In fact, the temporal version is stronger, since in the infinite – but spatially homogeneous, in accordance with the Cosmological Principle – universe, the subset of "inhabitable" locations (like the surfaces of terrestrial planets in habitable zones of G-type stars in disks of spiral galaxies, etc.) is also infinite. Thus, the ratio of habitable to non-habitable region will tend to a small, but still finite value. In contradistinction, the ratio of habitable (finite) to non-habitable (infinite) temporal intervals is zero!

6. The increase is approximately linear with time if we accept the assumptions of [11], namely that the radial metallicity profile stays exponential at all times and that the mass scale of a terrestrial planet is exponential with [Fe/H].

the confines of GHZ, since they will have technological capabilities to make otherwise inhospitable planetary systems habitable by terraforming or even creation of entirely artificial planets or advanced habitats, like the Dyson spheres [34,35].

Thus, if we claim that Earths are rare (which seems to be necessary for explanation of the "Great Silence" in any case), it is important to understand that they can be rare in time as well as in space. If we restrict the interesting – from the astrobiological point of view – 4-volume to the history of our Galaxy so far, we obtain two quite different pictures, both of which can explain the "Great Silence". These are:

1. RARITY IN SPACE ⇔ RE hypothesis;
2. RARITY IN TIME ⇔ PT hypothesis.

Both have causal explanation through regulation mechanisms; the only distinction is that in one case the mechanism is predominantly global and evolving, while in the second case the mechanism is some stochastic combination of global and local factors, with the latter being dominant (rarity of Moon, "right" kind of Jupiters, etc.).

On the RE paradigm, Earths are intrinsically rare. On PT, they are rare only in comparison to the ensemble of past planets. While the "biological part" of the story is similar (and poorly understood!) in both pictures, the "physical part" is easier to quantify in PT. Namely, global regulation mechanisms are astrophysical, and thus subject to rather simple, well-known laws. Correlations do not exist in the RE picture, neither in space nor time, while correlations in the PT picture are present only in the temporal domain[7].

Parenthetically, the issue of habitability of future planets has different status in RE and PT theories. On RE, future planets are bound to be inhospitable for the lack of nuclides, among other things. On the other hand, PT virtually guarantees the colonization of the Milky Way by intelligent species, since there are many starting points of such colonization, and other obstacles to colonization (for instance, those of sociological nature) are not supposed to be universal. Of course, it is enough that colonization starts once prior to the remote end of the stelliferous era, for the Galaxy to end in the life-filled state.

4. Observer-Selection Hypotheses and SETI

One of the important points of divergence between the two observer-selection hypotheses in astrobiology is, obviously, their treatment of time. While on RE the temporal evolution either does not matter or even worsen chances of encountering an Earth in the Galaxy (due to the decline in plate tectonics generators), the very core of PT approach encompasses a temporal evolution quality. The latter hypothesis suggests that our presence on Earth now selects a particular (and rather special) epoch of the history of the Milky Way: namely the epoch in which global regulation enables the emergence of complex, intelligent lifeforms. Thus, this is another instance of the so-called Weak Anthropic Principle (WAP), or, more generally, an observation-selection effect (for the best modern treatment, see [19])[8]. Conclusions in astrobiology, similarly to those in cosmology, have to be drawn after Bayesian taking into account those features of our (astro)physical environment which influence the number or probability distribution of intelligent observers[9].

We now perceive an important epistemological advantage of PT over RE: it manages to retain the Principle of Mediocrity over the surfaces of simultaneity. Indeed, there is nothing special about the position of Earth right now (except for the necessary fact that it is within the GHZ). However, our temporal location is rather special, since we are evolved complex metazoans on the verge—in terms of astrophysical timescales—of having capacities to leave our home biosphere and embark on the venture of Galactic colonization.

The situation is somewhat similar to the one in the history of 20th Century cosmology. It is well-known that the historically all-important steady-state cosmological model of Bondi and Gold [36][10] was based upon the "Perfect Cosmological Principle." This principle can be simply expressed as the homogeneity of the universe in 4-dimensional spacetime (instead of just in 3-dimensional space, the latter statement being, since Eddington and Milne called the Cosmological Principle). It was repeatedly pointed out by the steady-state defenders that their theory can be easily falsified, while the rival Big Bang

7. If we discard the possibility of interstellar panspermia for the moment.

8. Thus, we strongly reject the unsupported assertion of Webb that a possible discovery of extraterrestrial intelligence would refute WAP [4]; in our view, WAP is an analytic consequence of the naturalistic existence of intelligent observers, and cannot be refuted.

9. There is another important assumption needed here in order for this mode of reasoning to be applicable to the PT paradigm: that new complex-lifeform habitats cannot be expected to arise in a colonized Galaxy; this is antithetical to proposals such as the "Zoo Hypothesis" of Ball [20].

10. The version of the late Sir Fred Hoyle, the greatest champion of the steady-state concept, was somewhat different, being based upon the modification of the gravitational field equations, and not on universal methodological principles [37]. For detailed history, see [38].

paradigm included events (close to the initial singularity) which are unobservable even in principle. In spite of often acknowledged epistemological superiority (e.g., [39]), the development of observational cosmology in the 1960s has decidedly refuted the steady-state paradigm. This has reaffirmed the importance of evolutionary change in cosmology and astrophysics in general; we are not to consider only processes we witness today. Dicke's explanation of the so-called "large-number coincidences" goes far toward explanation why our temporal position must be atypical [23]. On the other hand, the (restricted) Cosmological Principle continues to hold, and it is routinely empirically confirmed these days by, for example, microwave background observations. Thus, if we restrict ourselves to the surfaces of simultaneity, there is really nothing atypical or special about our location. If we reason by analogy in astrobiology, we conclude that the PT paradigm has epistemological advantage over RE [11].

TABLE 1: *A Comparison Between the two Rival Astrobiological Paradigms.*

	RE paradigm	PT paradigm
Observer Selects	astrobiological parameters	astrobiological parameters + *time*
Dominant Regulation	local	global
Ubiquity of Simple Life?	yes	yes
Solar System Typical Today?	no	yes
Correlations Between Earths?	none	temporal correlations
Galactic Colonization Probability	low	high
SETI Makes Sense?	no	yes

The most important consequence of this is that SETI projects make sense in PT paradigm, in contrast to RE. We expect to encounter many extraterrestrial civilizations throughout the Galaxy at approximately the same level of complexity and technological development as our own in the PT paradigm. Their detection and communication with them would be, obviously, of great interest to humanity.

5. Conclusions

Our conclusions can be summarized in Table 1.

Although much work remains to be done in giving precise quantitative form to both observation-selection astrobiological paradigms, their very appearance testifies that there is some real progress in this young and immature field, which is now, after a lull, receiving renewed attention. It is to be hoped that further numerical work, on both the astrophysical and biological sides of the story, will help further discriminate between these two options.

11. For a similar analogy of the situation in cosmology and astrobiology, see [12].

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