Astrobiological Phase Transition: Towards Resolution of Fermi's Paradox

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Abstract Can astrophysics explain Fermi's paradox or the "Great Silence" problem? If available, such explanation would be advantageous over most of those suggested in literature which rely on unverifiable cultural and/or sociological assumptions. We suggest, instead, a general astrobiological paradigm which might offer a physical and empirically testable paradox resolution. Based on the idea of James Annis, we develop a model of an astrobiological phase transition of the Milky Way, based on the concept of the global regulation mechanism(s). The dominant regulation mechanisms, arguably, are γ-ray bursts, whose properties and cosmological evolution are becoming well-understood. Secular evolution of regulation mechanisms leads to the brief epoch of phase transition: from an essentially dead place, with pockets of low-complexity life restricted to planetary surfaces, it will, on a short (Fermi–Hart) timescale, become filled with high-complexity life. An observation selection effect explains why we are not, in spite of the very small prior probability, to be surprised at being located in that brief phase of disequilibrium. In addition, we show that, although the phase-transition model may explain the "Great Silence", it is not supportive of the "contact pessimist" position. To the contrary, the phase-transition model offers a rational motivation for continuation and extension of our present-day Search for ExtraTerrestrial Intelligence (SETI) endeavours. Some of the unequivocal and testable predictions of our model include the decrease of extinction risk in the history of terrestrial life, the absence of any traces of Galactic societies significantly older than human society, complete lack of any extragalactic intelligent signals or phenomena, and the presence of ubiquitous low-complexity life in the Milky Way.

Keywords Biogenesis · Extraterrestrial intelligence · Mass extinctions · Evolutionary contingency · Catastrophism · Galaxy evolution

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Introduction: Fermi's paradox

Fermi's paradox offers, arguably, the biggest challenge for any practical SETI philosophy. As well-known and established by the research of Jones (1985), the key argument follows the famous lunchtime remark of the great physicist, Enrico Fermi: *Where is everybody?* First discussed in print by the Russian space science pioneer Konstantin Tsiolkovsky, and in the last decades elaborated in detail by Viewing, Hart, Tipler and others (for detailed reviews, see Brin 1983; Webb 2002), the argument presents a formidable challenge for any theoretical framework assuming the naturalistic origin of life and intelligence. As such, this should worry not only a group of SETI enthusiasts, but challenges some of the deepest philosophical and cultural foundations of Earth's modern civilization.

Tsiolkovsky, Fermi, Viewing, Hart, and their supporters argue on the basis of two premises: the absence of extraterrestrials in the Solar System, and the fact that they have had, ceteris paribus, more than enough time in the history of the Milky Way Galaxy to visit our Solar System, either in person or through their self-replicating probes. Characteristic time for colonization of the Galaxy, according to these investigators, is what we shall call the Fermi–Hart timescale (Hart 1975; Tipler 1980):

$$t_{\mathrm{FH}} \sim 10^6 - 10^8 \text{ years}, \tag{1}$$

making the fact that the Solar System is (obviously) not colonized hard to explain, if not for the total absence of extraterrestrial cultures. It is enough for our purposes to consider that *this timescale is well-defined*, albeit not precisely known due to our ignorance on the possibilities and modes of interstellar travel.

As discussed in more detail elsewhere (Ćirković and Bradbury 2006), there are reasons for finding Fermi's Paradox even more disturbing following recent results in astronomy, astrobiology, information theory and computer science. Particularly relevant is the result of Lineweaver (2001; see also Lineweaver et al. 2004) that the difference between the median age of Earth-like planets in the Milky Way and the age of Earth is:

$$\bar{t} - t_{\oplus} = 1.8 \pm 0.9 \text{ Gyr.} \tag{2}$$

Such a huge difference (and this is only the *median* age difference; in fact, to assess the validity of Fermi's paradox we ought to consider the *oldest* habitable planets where, presumably, the oldest technological civilizations emerged first) makes Fermi's question significantly more puzzling. Before Lineweaver's study it was still possible to argue that the age distribution strongly peaks near $t_{\oplus}$ or even at some smaller value. Coupled with the assumption of a narrow distribution of biological evolutionary timescales, it would have made the ages of hypothetical technological civilizations small enough in comparison with t_{FH}. This "Copernican" way of addressing the paradox without introducing new elements in the overall picture is now closed. Thus, finding novel plausible explanations for the "Great Silence" is still very much a worthwhile endeavour.

Among many hypotheses offered thus far (popular review of Webb 2002 is characteristically subtitled *Fifty Solutions to the Fermi's Paradox*), there are several broad classes. We shall neglect the solipsist category arguing that our observed astrophysical reality is an illusion or supercomputer-like simulation (e.g. Baxter 2000) as well as the related class of hypotheses based on the assumption that extra-Solar System advanced technological civilizations are unobserved because they are intentionally hiding from humans (e.g., the "Zoo hypothesis"; Ball 1973). While these ideas can be true, they are next to useless in any practical scientific sense, being more related to the theological mode of

thinking. In contrast, one cannot neglect other sociological explanations of the "Great Silence", among which the classical nuclear self-destruction hypothesis of von Hoerner and Shklovsky deserves a special place (von Hoerner 1975; Lem 1977). According to this scenario, each technological civilization destroys itself through nuclear warfare—and today one may add biotechnological/nanotechnological or any other advanced style of global warfare—before it establishes significant presence beyond its home planet. In addition to explaining Fermi's paradox, this solution offers a rather bleak picture of humanity's future. However, one could argue that this would require a very high degree of correlation between not only physical and biological, but also cultural and social conditions on many habitable planets throughout the Galaxy. Brin (1983) persuasively argues that the true solution has to be *non-exclusive*, meaning that it should apply to all (or almost all) space in the Milky Way and all (almost all) times in its history thus far. Occasionally, non-exclusive solutions are dubbed "robust" or "hard", while the exclusive solutions, such as extinction through nuclear war, are "soft". Even the most objective, mathematical studies, such as that by Newman and Sagan, were compelled to, somewhat resignedly in tone, conclude that "[i]t is curious that the solution to the problem 'Where are they?' depends powerfully on the politics and ethics of advanced societies" (Newman and Sagan 1981, p. 320). There is something deeply unsatisfactory about their answer. It is especially disappointing to encounter it after a lot of displayed mathematical analysis by the authors, and keeping in mind by now about half a century of sustained and often carefully planned and executed SETI efforts (e.g., Duric and Field 2003). In view of this council of despair, it is not surprising to notice both the disenchantment of some SETI pioneers (Shklovsky, von Hoerner) and the obvious eagerness with which they endorsed the pessimistic, mandatory self-destruction hypothesis.

Thus, for multiple reasons, an astrophysical (necessarily "hard") explanation of Fermi's paradox would be vastly preferable over a sociological or any other kind. Herein, we show that such an explanation is indeed forthcoming—recent advances in astrophysics and astrobiology presented us with a uniquely convenient starting point for advancing such an explanation. The core of the present astrobiological phase transition (APT) model can be encapsulated in the statement that *we are not living in the epoch of astrobiological equilibrium*. Much of the tension caused by Fermi's paradox stems from the tacit assumption of equilibrium state; once that assumption is abandoned, we are faced with a wider spectrum of possibilities which depend on the unknown "astrobiological dynamics": rates of biogenesis (origination of life) and noogenesis (origination of intelligence) on distant habitable planets as functions of their total physical, chemical, and ecological parameters. Fermi's paradox acts as a boundary condition on all possible astrobiological models, and for each imaginable astrobiological history we can ask the simple question: "How probable under this history is it that the newly-emerged observers at a typical point will face Fermi's question?"

So far, the most significant contribution, in this respect, has been the phase transition idea of James Annis (1999), which is a prototype disequilibrium hypothesis: there is no Fermi's paradox, since the relevant timescale is the time elapsed since the last "reset" of astrobiological clocks and this can be substantially smaller than the age of the Milky Way. Annis suggests that gamma-ray bursts (henceforth GRBs), whose cosmological and extremely energetic nature is now increasingly understood (e.g., Mészáros 2002; Woosley and Bloom 2006) serve as such catastrophic reset events when they occur in our home stellar system. The seminal importance of Annis' idea for the SETI endeavor and astrobiological studies, in general, has not been sufficiently appreciated yet. Here, we attempt to (a) generalize Annis' model to a general neocatastrophic astrobiological

regulation, and (b) to present results of a simple numerical model of GHZ in this manner, and to show that they have the capacity to resolve Fermi's paradox.

Several highly relevant developments have occurred from the time of publication of Annis' paper, the most notable event being a great increase in our understanding of the nature and subtypes of GRBs. In particular, biotic effects of GRBs occurring in our Galaxy have been subject to much investigation since the realization of their cosmological—and hence highly energetic—nature (Thorsett 1995; Scalo and Wheeler 2002; Thomas et al. 2005; Galante and Horvath 2007). The number of discovered extra-Solar System planetary systems and their diversity continues to increase (e.g., Jones et al. 2006; von Bloh et al. 2007). Also, the nascent science of astrobiology progressed in great strides, with the emphasis on the robustness, adaptability and mobility of life in the cosmic context. Although the paleobiological evidence on Martian life remains controversial, most researchers now believe that it is realistic to expect exchange of biological and protobiological material between planets and moons during the history of the Solar system (e.g. Gladman et al. 2005; Cockell 2008). This idea has received an important place within the "rare Earth" theory, developed by Ward and Brownlee (2000) or Conway Morris (2003), which has received much attention in both corporate and academic research and popular science circles. The idea of biological exchanges leads naturally to the modern, rehashed versions of the classical panspermia hypothesis (e.g., Napier 2004), which undermines the assumption of independent biogenesis and evolution in different planetary systems. Finally, the development of the theory of the Galactic habitable zone (henceforth GHZ) by Gonzalez et al. (2001), as well as Lineweaver (2001; Lineweaver et al. 2004), enabled a quantitative treatment of the fundamental astrobiological issues (comprehensive review in Gonzalez 2005). This is particularly important since it offers a paradigm which can bridge the gap between astrobiology in its narrow sense and SETI studies. Very interesting analyses of large-scale trends in the set of habitable planets can be found in work of Franck, von Bloh and Bounama (2007; see also Bounama et al. 2007); the present approach is, in several ways, complementary to their efforts. All these developments are pieces in a big jigsaw puzzle which hides the quantitative solution to the problem of the "Great Silence".

Catastrophes and Phase Transition

Intuitively, it seems clear that any form of catastrophic event affecting planetary biospheres in the Milky Way Galaxy will reduce the hypothetical civilizations' ages and, thus, reduce the tension inherent in Fermi's paradox. Moreover, *global* catastrophic events affecting large parts of GHZ will tend to reset many local astrobiological clocks nearly simultaneously, thus significantly decreasing the probability of existence of extremely old civilizations, conforming to Annis' scenario. In order to test this intuition numerically, we have performed a series of simple Monte Carlo experiments on a simulated GHZ comprising 10^9 stars ranging from early F to late K spectral classes in the Milky Way Galaxy's thin disk. The distribution of ages of Earth-like planets is taken from Lineweaver (2001) data on the chemical evolution constraints and, for the sake of demonstrative simplicity, we have taken the age of the thin disk to be exactly 10 Gyr. More technical details on the model and its implementation can be found in Vukotić (2008) and the discussion of other plausible regulation mechanisms is given by Vukotić and Ćirković (2007, 2008).

We note, in passing, that this APT model is a natural consequences of applying resurgent (neo)catastrophist ideas in astrobiology. Following the seminal work of Alvarez et al.

(1980), we have become aware that discrete and multiple global catastrophes played very a significant role in the overall evolution of our terrestrial biosphere (e.g., Raup 1991; Courtillot 1999; Erwin 2006). Moreover, some of the actual catastrophes whose remarkable traces are seen in the geological record are of astrophysical origin, emphasizing the new paradigm according to which the Solar System is an unclosed system, strongly and openly interacting with its immediate galactic environment (e.g., Clube and Napier 1990; Leitch and Vasisht 1998; Shaviv 2002; Melott et al. 2004; Pavlov et al. 2005; Gies and Helsel 2005; Gillman and Erenler 2008). This neocatastrophist tendency is present both in the "rare Earth" camp, in the ongoing research on biogenesis (e.g., Raup and Valentine 1983; Maher and Stevenson 1988), and even in the debates on evolution of humanity (Rampino and Self 1992; Ambrose 1998; Bostrom and Ćirković 2008), but all its ramifications have not yet been elucidated in any detail. In particular, we point out here an important effect: punctuation of the astrobiological evolution of the Milky Way with large-scale catastrophes affecting significant fraction of GHZ will, somewhat counter-intuitively, have the net effect of strengthening the rationale for our present-day SETI efforts. Abandoning the old-fashioned gradualist leads, as we shall show here why, to undermining of Fermi's paradox.

Global regulation has been assumed to occur in form of GRBs, modeled as random events occurring with exponentially decreasing frequency (Annis 1999):

$$\nu(t) = \nu_0 \exp\left(-\frac{t}{t_\gamma}\right), \tag{3}$$

with the fixed characteristic timescale $t_\gamma = 5$ Gyr in accordance with the cosmological observations (e.g., Bromm and Loeb 2002). Biological timescales for noogenesis are randomly sampled from a log-uniform distribution between 10^8 years (the minimum suggested by McKay 1996; Davis and McKay 1996) and 10^{11} years (the longest lifetime of a sun-like star; Adams and Laughlin 1997). For simplicity it has been assumed that the age of our Galaxy is exactly 10 Gyr and that all extant planets are sampled from the age distribution of Lineweaver (2001). It is taken that the chain of events leading to life and intelligence can be reduced by a catastrophic event at any planet in our toy-model Galaxy with probability Q, and its astrobiological clock is then reset. The toy-model counts only planets achieving noogenesis *at least once* and it does not take into account any *subsequent* destructive processes, either natural or intelligence-caused (like nuclear or biotech self-destruction). Probability Q can, in the first approximation, be regarded as a geometrical probability of an average habitable planet being in the "lethal zone" of a GRB (Scalo and Wheeler 2002), and more complex effects dealing with the physics and ecology of the extinction mechanism can be subsumed in it. One of the major tasks facing future modelers is to disentangle these various probabilities.

One should mention that the degree to which Galactic GRBs disrupt ecologies on habitable planets is controversial. Studies of Thorsett (1995), Scalo and Wheeler (2002), Dar and De Rújula (2002), and Galante and Horvath (2007) tend to assign large "lethal zones" to such events, while a recent study of Thomas et al. (2008) obtain significantly smaller volumes (and thus astrobiologically less interesting). Without going into details of this debate, two points are worth mentioning here. The first is that GRBs here are placeholders for any kind of large-scale regulation mechanisms, perhaps the easiest to model, but certainly far from unique (for a review of alternative mechanisms, see Vukotić and Ćirković 2008). Secondly, if the hypothesis that a GRB caused at least one of the known Phanerozoic mass extinctions (Melott et al. 2004) obtains additional empirical support, the astrobiological importance of such events would be reinforced. Contingent

nature of biological evolution virtually guarantees that any derailing from the pathways leading to intelligence would result in a huge delay of noogenesis. Stephen Jay Gould's "paradox of the first tier" points in that direction: "…mass extinctions are sufficiently frequent, intense, and different in impact to undo and reset any pattern that might accumulate during normal times" (Gould 1985).

As we perceive in Fig. 1, the system exhibits a systematic shift of behavior as we move from small values of Q (gradualism) to large values of Q (catastrophism). At large Q, we have a step-like succession of astrobiological regimes, governed by external timescale forcing (Vukotić and Ćirković 2007). In each regime, it is obvious that the ages of inhabited planets are not independent and uncorrelated, just the contrary, as we expected from the considerations above.

What do we expect to see in the neocatastrophic model? Roughly, something akin to the simplified sketch (not drawn to scale) in Fig. 2: an appropriately defined astrobiological complexity will tend to increase with time, but the increase will not become monotonous until a particular epoch is reached. At least a part of the mechanisms determining this epoch—the epoch of phase transition—will be *global* in nature, and thus amenable to a simplified, spatially-averaged treatment. At very early epochs (I), the Galaxy was completely dead; at some point in time the emergence of simple life became possible (and even probable; cf. Lineweaver and Davis 2002). For most of the Galaxy history thus far, its astrobiological structure was in a state we denote with "II"—containing enclaves and pockets of simple life, but the emergence of complex life-forms and a fortiori the emergence of intelligent and tool-making species was strongly suppressed by both local and global regulation mechanisms.
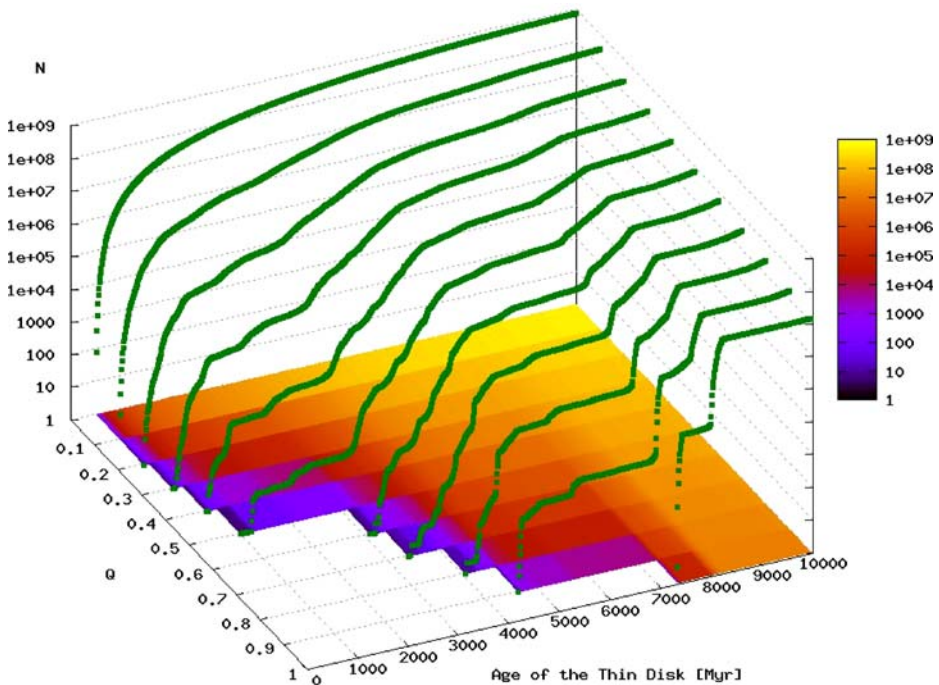

Fig. 1 Galactic Habitable Zone in 1-D simple quantitative model. Presented is the number of planets that have achieved noogenesis at least once (cumulative plot), as a function of the age of the Milky Way thin disk stellar population and the mean extinction probability Q per global catastrophe

Fig. 2 Schematically illustrated, evolution of astrobiological complexity in the history of the Milky Way according to the phase-transition hypothesis
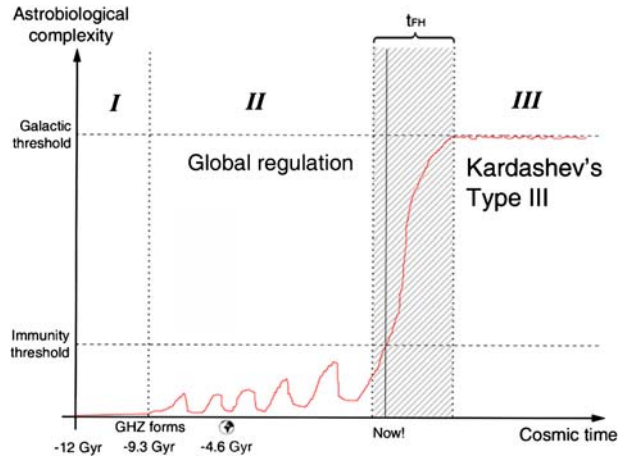
Obviously, we are not facing Fermi's paradox in this epoch, since there was not enough time for intelligent observers capable of creating large interstellar civilizations to emerge (even if the physical and biological environment was conductive to emergence at any given epoch). However, the frequency of resetting events decreased due to the astrophysical evolution of the Galaxy (the key point of Annis' model), and at some time which may lie in our past (as drawn in the sketch) or it may conceivably still be in our future, the balance will shift toward high probability of complex intelligent observers emerging and creating large interstellar civilizations. That is the epoch of phase transition (shaded in Fig. 2); of course, its duration is completely speculative, though one could expect it to be similar to the Fermi–Hart timescale in Eq. 1. Afterwards, the Galaxy will be dominated by one, or several, spatially large civilizations similar to what Nikolai Kardashev (1964) envisaged as "Type III" societies—those whose energy resources are comparable to the luminosity of an entire galaxy. In that epoch, an observer will not perceive Fermi's paradox, since the Milky Way will be filled with life.[1] This epoch III clearly belongs to our future. All in all, Fig. 2 is a rough epistemic guideline necessary in order to make the APT model exact.

To confirm the intuition related to the resolution of Fermi's paradox contained in the astrobiological landscape of Fig. 1, above, we plot the timescales for noogenesis on habitable planets in our APT model in Fig. 3. Since the habitable planets in GHZ are of equal a priori weighting with respect to the probability of biogenesis and noogenesis, the number of planets with the given interval of timescales for noogenesis is representing the likelihood of having intelligent beings on a planet after the relevant interval of time elapses since the planet's formation. The absence of large t-values for larger values of Q, testifies on the efficiency of the global regulation mechanism in suppressing the tension within Fermi's paradox.

A particularly interesting feature of the results shown in Fig. 3 is that they give justification to the "Copernican" view of Earth, its enveloping biosphere and humankind: the age of Earth log $t_\oplus = 3.66$ Myr) does not enter our APT model, but it is still tantalizingly close to the maximum-likelihood age of planets where noogenesis has been completed—at least once. It is important to perceive that with increase in the resetting probability Q we obtain fewer and fewer habitable planets with ages $t > t_\oplus$, while there are

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[1] We speak here of "life" in the most completely generalized context, without excluding the possibility (which we, indeed, consider likely) that most of the observers in advanced technological civilizations will be of postbiological nature (Dick 2003).
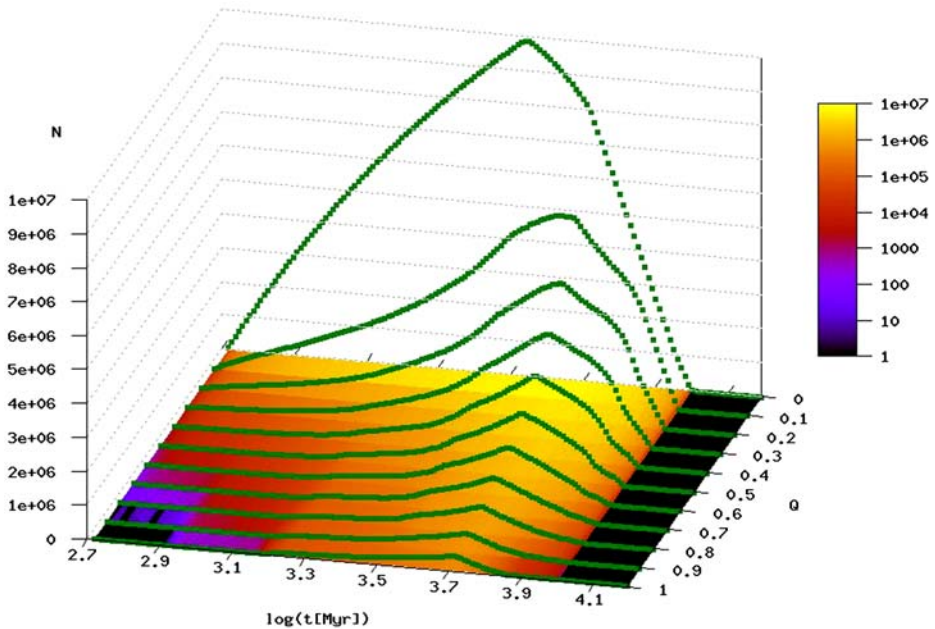
Fig. 3 Age distribution of timescales for noogenesis in the toy-model of the Galactic Habitable Zone

practically none with $t \gg t_\oplus$, thus effectively removing Fermi's paradox. However, in contrast to the "rare Earth" hypothesis, our scenario *retains the typicality of Earth* within the habitable planets set.

A separate vital issue, centering mainly on which additional timescales should be added to the selected noogenesis timescale to make the site "immune" from further resetting, must be considered. This would correspond to the timescale necessary for building of durable technological civilization capable of undertaking constructive protective measures against the effects of regulation mechanisms. Obviously, it is a complicated and delicate question dealing with biological and cultural dynamics rather than with the physical environment, so we refrain from judgment in this case. It seems intuitively clear, on the basis of recorded human history thus far, that this timescale is likely to be of short duration in comparison to the astrophysical and evolutionary timescales considered here. On the other hand, this is clearly related to the issue of expansion of a technological civilization into space, since, for instance, an Earth-confined humanity has practically no chance of surviving on the timescales comparable to t_{FH} (Bostrom and Ćirković 2008).

Predictions

A theory without predictions is not scientific. If the APT model is to survive, it has to offer an array of (at least in principle) verifiable predictions. Some of the specific predictions of the present models are:

- We shall not find any traces or remnants of intelligent societies much older than ours anywhere in the Galaxy; no "interstellar archaeology" (cf. Freeman and Lampton 1975) will ever become a meaningful discipline.

- We shall not receive and perceive any *extragalactic* ETI signals, nor shall we detect activities of advanced extragalactic societies, at least not before humans are on the way of becoming (or joining) the Kardashev Type III super-society. This is the consequence of roughly parallel secular evolution of the global regulation mechanisms in the Milky Way and other nearby similar spiral galaxies.
- The phase transition model predicts that SETI endeavors will be crowned by success on timescales *shorter than* the t_{FH}. While this is still uncomfortably long from the human point of view, innovative strategies can significantly decrease the timescale to achieve success.
- The ages of discovered societies will be comparable to our own, i.e. incompatible with any broad distribution (uniform, broad Gaussian, etc.).
- Improved paleontological evidence will confirm and quantify the conclusions of Kitchell and Pena (1984) that the average extinction risk has been decreasing with time during both Precambrian and Phanerozoic. Quantitative measure of the risk decrease depends on the intricacy of the total risk function, which comprises both global and local risks, including any number of unknown parameters intrinsic to the macro-evolutionary processes (e.g., Jablonski 1986).
- We shall find ubiquitous traces of low-complexity life, from other habitats in our Solar System (Mars, Europa) to the other planetary systems, unbound planets and even possibly ISM and proto-stellar clouds. This is in agreement with Ward and Brownlee's the "Rare Earth" hypothesis. However, this is necessary to qualify with the realistic possibility of biological exchange between Earth and our Solar System's other planets; stronger prediction would be finding life biochemically unrelated to the existing terrestrial example.
- Improved geological and paleontological techniques will find coincidences between most of the extinction events, with *catastrophes of global, Galactic origin*; that is, investigations of less eroded environments in our Solar System will give ample evidence of high-energy γ- and cosmic-ray bombardment episodes approximately coincident with some of the major known Earth-biosphere extinction events. The lunar surface would be a convenient place for such investigations (along the lines of Ruderman and Truran 1980, applied to the GRB case).

Of course, further development of the APT model, in particular assembling a realistic total risk function for Earth-like planets, will enable further specific predictions.

Discussion

We have outlined a quantitative model of astrobiological evolution of the Milky Way which can avoid Fermi's paradox, based on the qualitative phase-transition hypothesis of Annis (1999). Its main points can be summarized as follows:

I. In astrobiological terms, we are currently living in a disequilibrium period of the phase transition. $\sim 10^8$ years ago our Galaxy was dead as far as high-complexity life was concerned; in $\sim 10^8$ years the Galaxy will be entirely filled with high-complexity life.

II. The phase transition is governed by an intricate interplay between (a) the natural tendency of life to grow, spread, complexify, and fill all available ecological niches, and (b) global regulations mechanism(s).

III. GRBs are the best candidates for such a *global* regulation mechanism; there are some additional vaguely plausible candidates. Many types of local regulation supplement global mechanisms.

IV. The epoch of phase transition is not just the only one meaningful for SETI projects on a wider background of the Galactic history; the specific nature of phase transition enables us to direct SETI more precisely, and to give it concrete theoretical groundings.

V. The phase transition model strongly suggests that technological development and interplanetary/interstellar space colonization should be the foremost priorities in humanity's global policy-making.

In the forthcoming study, we shall generalize the present APT model with more phenomenological details, notably (1) the realistic GRB luminosity function, (2) finite disk scale-height and other inhomogeneities of GHZ, (3) better accounting for the distribution of the absorbing ISM, (4) local limitations on the habitability of planets, like the probability of creating "ocean-worlds" (Léger et al. 2004) or destruction of habitable worlds by migrating giant planets (Peplinski et al. 2008), (5) geophysical and biotic feedback effects on the duration of geological inhabitability (Lovelock and Whitfield 1982; Caldeira and Kasting 1992; Gerstell and Yung 2003; Bounama et al. 2007), and (6) non-zero probability of interstellar panspermia (Napier 2004; Wallis and Wickramasinghe 2004). In addition, the biological ("local") side of the tale needs to be elaborated in more detail. But all these refinements are unlikely to change the general conclusion that the phase-transition scenarios can defeat Fermi's paradox without recourse to non-physical factors.

Finally, an important philosophical point of relevance is contained in the distinction between two closely related issues: (1) our existence in the apparently silent Galaxy (Fermi's question) and (2) the "anthropic" puzzle why humans find their species living in this particular epoch in a civilization with small—in the Galactic context—number of observers (Olum 2004). The latter is similar to some of the other anthropic puzzles, like the "Doomsday argument" of Leslie, Gott, and Carter (see Gott 1993; Leslie 1996; Bostrom 2002). The phase-transition model proposed here has the potential to address (1), but it is unclear to what extent it help solving more general problem (2); that said, an attempt in this direction has been made by one of the present authors (Ćirković 2006).

We have shown that 1-D models, like the toy model of GHZ presented here, can in principle offer support to Annis' phase transition hypothesis for explanation of Fermi's paradox. However, it is also clear that any such model is inherently limited when particulars of the spatial distribution of habitable and (potentially) colonized sites are taken into account. As argued in more detail in Vukotić and Ćirković (2008), there is a deeper logic in the successive application of these classes of models for resolving the long-standing arguments of SETI skeptics. While Carter's (1983) anthropic argument was, essentially, a 1-D problem (only the number of inhabited planets at given epoch mattered), Fermi's paradox is essentially a 3-D problem (spatial extent of civilizations at given epoch). Thus, the toy 1-D model can serve to undermine Carter's argument (as shown in Ćirković et al. 2008), but a stronger class of models is necessary to eliminate Fermi's paradox. We shall investigate whether 3-D cellular automata models are up to the task in a subsequent work. In particular, phase transitions are common phenomena in nonlinear systems studied thus far with help of probabilistic cellular automata (e.g., Kaneko and Akutsu 1986). Finally, in order to face the hardest of all skeptical arguments, the argument from biological contingency originating with Simpson and Mayr, additional complexity stemming from the size of the relevant parts of evolutionary morphospace is required. It is unclear at the present time just how one could quantify such a situation, but it is to be hoped that the rapid development of evolutionary and astrobiological modeling will be employable. In this situation, it certainly is premature to conclude that we have strong reasons for belief in our uniqueness in the Galaxy.

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