

FERMI'S PARADOX – THE LAST CHALLENGE FOR COPERNICANISM?

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SUMMARY: We review Fermi's paradox (or the "Great Silence" problem), not only arguably the oldest and crucial problem for the Search for ExtraTerrestrial Intelligence (SETI), but also a conundrum of profound scientific, philosophical and cultural importance. By a simple analysis of observation selection effects, the correct resolution of Fermi's paradox is certain to tell us something about the future of humanity. Already more than three quarters of century old puzzle – and a quarter of century since the last major review paper in the field by G. David Brin – has generated many ingenious discussions and hypotheses. We analyze the often tacit methodological assumptions built in various answers to this puzzle and attempt a new classification of the numerous solutions proposed in an already huge literature on the subject. Finally, we consider the ramifications of various classes of hypotheses for the practical SETI projects. Somewhat paradoxically, it seems that the class of (neo)catastrophic hypotheses gives, on the balance, the strongest justification to optimism regarding our current and near-future SETI efforts.

Key words. Astrobiology – Extraterrestrial intelligence – Galaxy: evolution – History and philosophy of astronomy

If you do not expect the unexpected, you will not find it; for it is hard to be sought out and difficult.

Heraclitus of Ephesus (cca. 500 BC)

How many kingdoms know us not!

Blaise Pascal, *Thoughts* (cca. 1660)

What's past is prologue...

William Shakespeare,
The Tempest, II, 1 (1610-11)

1. INTRODUCTION: WHERE IS EVERYBODY?

Fermi's paradox (henceforth FP) presents arguably the biggest challenge for any practical SETI activity as well as the least understood of "grand questions" posed in the history of science. As is well-known and established by the research of Jones (1985), the key argument follows a lunchtime remark of the great physicist, Enrico Fermi: "Where is everybody?" First discussed in print by the Russian space science pioneer Konstantin Eduardovich 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 naturalistic origin of life and intelligence. As such, this should worry not only a small group of SETI enthusiasts, but challenges some of the deepest philosophical and cultural foundations of the modern civilization. It is hard to conceive a scientific problem more pregnant and richer in meaning and connection with the other "big questions" of science throughout the ages. In addition, it presents a wonderful opportunity for public outreach, popularization and promotion of astronomy, evolutionary biology, and related sciences.

Tsiolkovsky, Fermi, Viewing, Hart, and their followers argue on the basis of two premises:

(i) the absence of extraterrestrials in the Solar System ("Fact A" of Hart 1975), and

(ii) the fact that they have had, *ceteris paribus*, more than enough time in the history of Galaxy to visit, either in person or through their conventional or 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):

$$t_{\text{FH}} = 10^6 - 10^8 \text{ years}, \quad (1)$$

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 content that this timescale is well-defined, albeit not precisely known due to our ignorance on the possibilities and modes of interstellar travel. For comparison, the accepted age of the Earth as an object of roughly present-day mass is (Allègre et al. 1995)

$$t_{\oplus} = (4.46 \pm 0.02) \times 10^9 \text{ years}. \quad (2)$$

The drastic difference between the timescales in (1) and (2) is one of the ways of formulating Fermi's paradox. In the next section, we shall see that there is still more serious numerical discrepancy in play, when we account for the distribution of ages of terrestrial planets in the Milky Way.

Even more generally, we need not consider the direct physical contact between an extraterrestrial civilization and Earth or the Solar System (insofar as we do not perceive evidence of extraterrestrial visits in the Solar System; however, this is still an act of faith, considering the volume of space comprising our planetary system¹). It is sufficient to consider a weaker requirement: namely that no extraterrestrial civilizations are *detectable* by any means from Earth at present. This includes the detectability of astroengineering or macroengineering projects over

interstellar distances (Dyson 1960, Sagan and Walker 1966, Freitas 1985, Harris 1986, 2002, Zubrin 1995, Timofeev et al. 2000, Arnold 2005). In words of the great writer and philosopher Stanislaw Lem, who authored some of the deepest thoughts on this topic, Fermi's paradox is equivalent to the "absence of cosmic miracles" or the *Silentium Universi* ("cosmic silence"; Lem 1977, 1984). Following the classic review by Brin (1983), we may introduce "contact cross-section" as a measure of the probability of contact – by analogy with introduction of cross-sections in atomic and particle physics – and reformulate FP as the question why this cross-section in the Milky Way at present is so small in comparison to what could be naively expected.

Schematically, Fermi's paradox can be represented as

spatiotemporal scales of the Galaxy + the absence of detected extraterrestrial civilizations (+ additional assumptions) → paradoxical conclusion.

Here, under spatiotemporal scales we include our understanding of the age of the Galaxy, the Solar System and the ages (incompletely known) of other planetary systems in the Milky Way. The additional assumptions can be further explicated as

additional assumptions = "naive realism" + naturalism + Copernicanism + gradualism + non-exclusivity.

These assumptions are quite heterogeneous. By "naive realism" we denote the working philosophy of most of science (as well as everyday life), implying that there is a material world out there, composed of objects that occupy space and have properties such as size, mass, shape, texture, smell, taste and colour.² These properties are usually perceived correctly and obey the laws of physics. In the specific case of FP, the basic premise following from naive realism is that there are, indeed, no traces of extraterrestrial intelligent presence detected either directly or indirectly ("Fact A" of Hart 1975). We shall discuss below some of the hypotheses for resolving FP which directly violate this realist view; an extreme example – but powerfully present in pop-culture – of such naively anti-realist standpoint is a view that, contrary to scientific consensus, some humans are in contact with extraterrestrial visitors and are conspiring with them (e.g. Barkun 2003). Naive realism and naturalism (Section 4 below) are methodological assumptions, usually used in any scientific research. Copernicanism and gradualism are somewhat more specific tenets, stemming more from our experiences in the history of physical science than from the general epistemology. Copernicanism (often called the Principle of Mediocrity) in narrow sense tells us that there is nothing special about the Earth or the So-

¹In view of this circumstance, it is occasionally suggested that we also need a Search for ExtraTerrestrial Artifacts (SETA) programs as well (Freitas and Valdes 1980, Arhipov 1996, 1997). Although we neglect this possibility in the further considerations in this text it worth noticing that this is a special case of a more generally understood unorthodox SETI programs which we consider in the concluding section.

²Philosophical literature often calls this view *direct realism* or *common sense realism*.

lar System or our Galaxy within large sets of similar objects throughout the universe. In somewhat broader sense, it indicates that there is nothing particularly special about us as observers: our temporal or spatial location, or our location in other abstract spaces of physical, chemical, biological, etc., parameters are typical or close to typical.³ Gradualism, on the other hand, is often expressed as the motto that "the present is key to the past" (with corollary that "the past is key to the future"). This paradigm, emerging from geological science in the 19th century with the work of Charles Lyell – and expanding, through Lyell's most famous pupil, Darwin, into life sciences - - has been subject of the fierce criticism in the last quarter of century or so. We shall return to this issue in Section 7.

Finally, the role of non-exclusivity (or "hardness" in some of the literature) assumption needs to be elucidated. Non-exclusivity (following Brin 1983) is simply a principle of causal parsimony applied to the set of hypotheses for resolving FP: we should prefer those hypotheses which involve a smaller number of local causes. FP is eminently **not** resolved by postulating that a single old civilization self-destructs in a nuclear holocaust. FP **is** resolved by hypothesizing that **all** civilizations self-destruct soon after developing nuclear weapons, but the major weakness of such a solution is obvious: it requires many local causes acting independently in uniform to achieve the desired explanatory end. In other words, such solution is exclusive (or "soft"). As long as we have any choice, we should prefer non-exclusive (or "hard") solutions, i.e., those which rely on small number of independent causes. For instance, the hypothesis, we shall discuss in more detail below, that a γ -ray burst can cause mass extinction over a large portion of the Galaxy and thus arrest evolution toward advanced technological society, is quite non-exclusive.

2. RECENT DEVELOPMENTS

Fermi's Paradox has become significantly more serious, even disturbing, of late. This is due to several independent lines of scientific and technological advances occurring during the last two decades:

- The discovery of nearly 350 extrasolar planets so far, on an almost weekly basis (for regular updates see <http://exoplanet.eu/>). Although most of them are "hot Jupiters" and not suitable for life as we know it (some of their satellites could still be habitable, however; cf. Williams et al. 1997), many other exoworlds are reported to be parts of systems with stable circumstellar habitable zones (Noble et al. 2002, Asghari et al. 2004, Beaugé et al. 2005). It seems that only the selection effects and capacity of present-day instruments stand between us and the discov-

ery of Earth-like extrasolar planets, envisioned by the new generation of orbital observatories. In addition, this relative wealth of planets decisively disproves old cosmogonic hypotheses regarding the formation of the Solar System as a rare and essentially non-repeatable occurrence, which have been occasionally used to support skepticism on issues of extraterrestrial life and intelligence.

- Improved understanding of the details of chemical and dynamical structure of the Milky Way and its Galactic Habitable Zone (GHZ; Gonzalez et al. 2001, Peña-Cabrera and Durand-Manterola 2004, Gonzalez 2005). In particular, the important calculations of Lineweaver (2001; Lineweaver, Fenner and Gibson 2004) show that Earth-like planets began forming more than 9 Gyr ago, and that their median age is $\langle t \rangle = (6.4 \pm 0.7) \times 10^9$ yrs, significantly more than Earth's age. This means that the age difference

$$\langle t \rangle - t_{\oplus} = (1.9 \pm 0.7) \times 10^9 \text{ years}, \quad (3)$$

is large in comparison with the Fermi-Hart timescale in (1). This also means that not only the oldest ones, but a large majority of habitable planets are much older than Earth. The significance of this result cannot be overstated, since it clearly shows that the naive naturalist, gradualist and Copernican view **must be wrong**, since it implies that millions of planets in the Milky Way are inhabited by Gyr-old supercivilizations in clear contrast with observations.

- Confirmation of the **rapid** origination of life on early Earth (e.g. Mojzsis et al. 1996); this rapidity, in turn, offers a strong probabilistic support to the idea of many planets in the Milky Way inhabited by at least the simplest lifeforms (Lineweaver and Davis 2002).
- Discovery of extremophiles and the general resistance of simple lifeforms to much more severe environmental stresses than it had been thought possible earlier (Cavicchioli 2002). These include representatives of all three great domains of terrestrial life (*Bacteria*, *Archaea*, and *Eukarya*), showing that the number and variety of cosmic habitats for life are probably much larger than conventionally imagined.
- Our improved understanding in molecular biology and biochemistry leading to heightened confidence in the theories of naturalistic origin of life or *biogenesis* (Lahav et al. 2001, Ehrenfreund et al. 2002, Bada 2004). The same can be said, to a lesser degree, for our understanding of the origin of intelligence and technological civilization – which we shall henceforth label *noogenesis* – (e.g. Chernavskii 2000).

³Note that this does not mean that our locations in these spaces are *random*. The latter statement is obviously wrong, since a random location in configuration space is practically certain to be in the intergalactic space, which fills 99.99...% of the volume of the universe. This is a sort of a long-standing confusion and the reason why Copernicanism is most fruitfully used in conjunction with some expression of the observational selection effects, usually misleadingly known as the anthropic principle; for detailed treatment see Bostrom 2002.

- Exponential growth of the technological civilization on Earth, especially manifested through Moore's Law and other advances in information technologies (see, for instance, Schaller 1997, Bostrom 2000). This is closely related to the issue of astroengineering: the energy limitations will soon cease to constrain human activities, just as memory limitations constrain our computations less than they once did. We have no reason to expect the development of technological civilization elsewhere to avoid this basic trend.
- Improved understanding of the feasibility of interstellar travel in both the classical sense (e.g. Andrews 2003), and in the more efficient form of sending inscribed matter packages over interstellar distances (Rose and Wright 2004). The latter result is particularly important since it shows that, contrary to the conventional skeptical wisdom, it makes good sense to send (presumably extremely miniaturized) interstellar probes even if only for the sake of communication.
- Theoretical grounding for various astroengineering/macroengineering projects (Badescu 1995, Badescu and Cathcart 2000, 2006, Korycansky et al. 2001, McInnes 2002) potentially detectable over interstellar distances. Especially important in this respect is the possible combination of astroengineering and computation projects of advanced civilizations, like those envisaged by Sandberg (1999).
- Our improved understanding of extragalactic universe has brought a wealth of information about other galaxies, many of them similar to the Milky Way, while not a single civilization of Kardashev's (1964) Type III has been found, in spite of the huge volume of space surveyed (Annis 1999b).

Although admittedly uneven and partially conjectural, this list of advances and developments (entirely unknown at the time of Tsiolkovsky's and Fermi's original remarks and even Viewing's, Hart's and Tipler's later re-issues) testifies that Fermi's paradox is not only still with us more than 75 years after Tsiolkovsky and more half a century after Fermi, but that it is more puzzling and disturbing than ever.⁴ In addition, we have witnessed substantial research leading to a decrease in confidence in the so-called Carter's (1983) "anthropic" argument, the other mainstay of SETI scepticism (Wilson 1994, Livio 1999, Čirković et al. 2009). All this is accompanied by an increased public interest in astrobiology and related issues (Des Marais and Walter 1999, Ward and Brownlee 2000, 2002, Webb 2002, Grinspoon 2003, Cohen and Stewart 2002, Dick 2003, Chyba and Hand 2005, Michaud 2007). The list

above shows, parenthetically, that quite widespread (especially in popular press) notion that there is nothing new or interesting happening in SETI studies is deeply wrong.

In the rest of this review, we survey the already voluminous literature dealing with Fermi's Paradox, with an eye on the classification scheme which could help in understanding many hypotheses posed in this regard. FP is fundamentally intertwined with so many different disciplines and areas of human knowledge, that it is difficult to give more than a very brief sketch in the present format. It should be noted straight at the beginning that it is not entirely surprising that several scientific hypotheses resolving FP have been formulated, in a qualitative manner, in the recreational context of a piece of SF art; astrobiology is perhaps uniquely positioned to exert such influence upon human minds of various bents. After all, much of the scientific interest in questions of life beyond Earth in the 20. century was generated by works such as Herbert G. Wells' *War of the Worlds*, Sir Arthur Clarke's *2001: Space Odyssey*, or Sir Fred Hoyle's *The Black Cloud*.

In Fig. 1, we schematically present a version of FP based upon the scenario of Tipler (1980), using self-replicating, von Neumann probes which, once launched, use local resources in visited planetary systems to create copies of themselves. It is clear that the exponential expansion characteristic for this mode of colonization leads to the lowest values for the Fermi-Hart timescales (1). It is important to understand, however, that FP is **aggravated** with von Neumann probes, but it is not really dependent on them. FP would still present a formidable challenge if at some stage it could be shown that interstellar von Neumann probes are unfeasible, impractical or unacceptable for other reasons (possibly due to the danger they will pose to their creators, as speculated by some authors; see the "deadly probes" hypothesis in Section 7).

Two further general comments are in order. **(I)** Although it is clear that philosophical issues are unavoidable in discussing the question of life and intelligence elsewhere in the universe, there is a well-delineated part of philosophical baggage which we shall leave at the entrance. Part of it is the misleading insistence on the definitional issues. The precise definition of both life and intelligence in general is impossible at present, as accepted by almost all biologists and cognitive scientists. This, however, hardly prevents any of them in their daily research activities. There is no discernible reason why we should take a different approach in astrobiology and SETI studies and insist on the higher level of formal precision in those fields. Intuitive concepts of life and intelligence are developed enough to enable fruitful research in these fields, in the same manner as the intuitive concept of life enables research in the ter-

⁴One is tempted to add another item of a completely different sort to the list: The empirical fact that we have survived more than sixty years since the invention of the first true weapon of mass destruction gives us at least a vague Bayesian argument countering the ideas—prevailing at the time of Fermi's original lunch—that technological civilizations tend to destroy themselves as soon as they discover nuclear power. This is not to contest that the bigger part of the road toward safety for humankind is still in front of us; see, e.g. Bostrom and Čirković (2008).

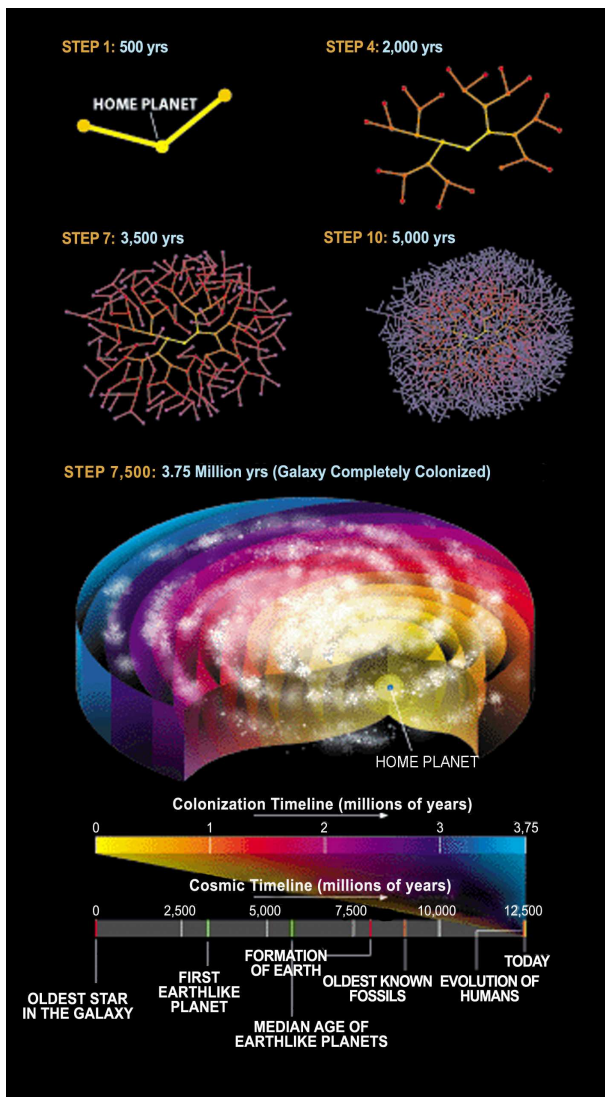


Fig. 1. *Fermi's paradox in a model with slow von Neumann probes, giving a typically low Fermi-Hart timescale for the colonization of the Milky Way. The relevant timescales are also shown.*

restrial biology and other life sciences; or, even more prominently and dramatically, the intuitive concept of number has enabled immensely fruitful research in mathematics for millennia before the advent of set theory as the axiomatic foundation for modern mathematics finally enabled completely general and formal definition of number (by personalities such as Frege, Russell, Gödel, Turing, Church, Kleene, and Post; e.g. Hatcher 1982, Penrose 1989). History of science also teaches us that formalization of paradigms (including precise definitions) occurs only at later stages of mature disciplines (Butterfield 1962, Kragh 1996) and there is no reason to doubt that astrobiology will conform to the same general picture.

It is clear, for instance, that the Darwinian evolution on Earth brought about at best a few intelligent species⁵ and only one with technological capacities for engaging in SETI and similar large-scale cosmic activities. In these cases, the precise definition of intelligent species (much less a conscious one; see the disturbing comments of Jaynes 1990 and Raup 1992, showing that consciousness is in any case much less than what is colloquially presumed) is unnecessary; while the awareness that this might be radically different in the SETI context is desirable, we need to proceed along the same, broadly operationalist lines. For this reason, we shall use the terms "extraterrestrial intelligence", "intelligent beings", etc. in their non-technical or vernacular meaning, roughly as placeholders for beings we are interested in meaningfully communicating with.

(II) A useful way of thinking about FP is by analogy with Olbers' paradox in classical cosmology, which has been first elucidated by Almár (1992). Both intentional signals and unintentional manifestations of advanced technological civilizations in FP are analogous to the light of distant stars which we would expect, on the basis of wide spatiotemporal assumptions, to flood us, terrestrial observers. That this is not happening points to some flaw in either the reasoning or the assumptions. We know now (e.g. Wesson et al. 1987) that Olbers' paradox is resolved mainly by the fact that the stellar population of the universe is of finite age: the light simply has not had enough time to establish thermodynamical equilibrium with the cold and empty interstellar (intergalactic) space. Contrary to a popular opinion – occasionally found even in astronomy textbooks – Hubble expansion actually is almost negligible, minor effect in resolving Olbers' paradox. FP can, in principle, also be resolved by the finite age of the stellar population (and hypothetical extraterrestrial civilizations), which would correspond to the "rare Earth" class of hypotheses (see Section 6 below). However, FP is significantly less constrained and thus allows for additional classes of explanation, as will be elucidated below. But this analogy strengthens the general analogy which exists between the current immature and vigorous stage of astrobiology and the state in which physical cosmology has been in 1920s and 1930s (Kragh 1996, 2007, Dick 1996, 2003).

3. WHAT'S PAST IS PROLOGUE

It has been noticed as early as the Byurakan conference (Sagan 1973) that the search for extraterrestrial intelligence and the issue of the future of intelligence here, on Earth, are closely linked. If we accept Copernicanism, than within reasonable temporal and physical constraints, we expect the status of evolution on Earth to reflect the Galactic average for given age of our habitat. This is exactly the rationale for the assumption (widely used in the orthodox SETI; e.g. Shklovskii and Sagan 1966, Tarter 2001,

⁵The status of intelligence of marine mammals is still unclear (e.g. Browne 2004), while we still do not know whether undoubtedly intelligent neanderthals were truly separate species, distinct from *Homo sapiens* (e.g. Hawks and Wolpoff 2001).

Duric and Field 2003) that most of the members of the hypothetical "Galactic Club" of communicating civilizations are significantly older from ours.⁶ This applies to the future as well – the status of extraterrestrial biospheres older than the Earth reflects, on the average, the **future** status of the terrestrial biosphere. This reflects a deeper tension at the very heart of FP: belief in unlimited progress coupled with the Copernican assumption, lead to either contradiction or bleak prospects for our future.

This is especially pertinent and disturbing in view of Fermi's paradox. The fact that we observe no supercivilizations (of Kardashev's Type III, for example) in the Milky Way in spite of plentiful time for their emergence is *prima facie* easiest to explain by postulating the vanishing probability or impossibility of their existence in general. An obvious consequence is that for humanity or its descendants the transformation into a supercivilization is either overwhelmingly unlikely or flatly impossible. But the cut goes deeper both ways – if, as some disenchanting SETI pioneers (in particular Iosif Shklovskii and Sebastian von Hoerner; see, e.g. von Hoerner 1978 and comments in Lem 1977) argued, the reason beyond absence of extraterrestrial signals is the prevalent self-destruction of each individual extraterrestrial civilization, for instance, through nuclear annihilation soon after the discovery of nuclear energy, that would mean that humanity is also overwhelmingly likely to self-destruct in a nuclear holocaust. If natural hazards (in form of, for example, impacts by comets and asteroids or supervolcanic eruptions; cf. Rampino 2002) are the main culprits beyond the absence of extraterrestrials – automatically implying that they are, on the average, more frequent than inferred from the terrestrial history thus far, which might be a consequence of the anthropic bias (cf. Bostrom 2002, Čirković 2007) – then we, humans, have statistically bleak prospects when faced with similar natural catastrophes. And the same applies to whatever causative agent causes the contact cross-section to be extremely small; for instance, if intelligent communities remain bound to their home planets in a form of cultural and technological stasis due to imposition of global totalitarianism which, provided technological means already clearly envisioned (Caplan 2008), could permanently arrest progress, this would mean that our own prospects of avoiding such hellish fate are negligible. In that sense, the astrobiological history of the Milky Way is a Shakespearean prologue to study of the future of humanity.

Exactly this form of "mirroring" of whatever provides the solution to Fermi's paradox is the reason why some of the researchers interested in the future of humanity are expressing their hopes that the Earth is unique in the Galaxy, at least in terms of evolving intelligent beings (e.g., Hanson 1998a, Bostrom 2008). This would correspond to those solutions of FP rejecting Copernicanism (see Section 6 below), which these authors consider a lesser evil. However, such a form of pessimism is not mandatory – we can have both optimism toward SETI and optimism about humanity's future. This forms one of the motivations for developing some of the neocatastrophic solutions to FP (Section 7) which avoid this tension.

4. NATURALISM AND CONTINUITY

The successes of science since the so-called "Scientific Revolution" of the 17. century (celebrated, among other things, in the International Year of Astronomy 2009, as 400 years since Galileo's invention of the telescope and consequent revolutionary discoveries) have led to a worldview which could be called naturalistic, since it assumes the absence of supernatural forces and influences on the phenomena science is dealing with (Kuhn 1957, Butterfield 1962). Here, as in the case of intelligence, we are using rough, non-technical definition which is entirely sufficient for meaningful discussion.⁷

One of the central issues of astrobiology is to what extent we can talk about biogenesis (and, by extension, noogenesis) in naturalistic terms. This issue has been investigated in depth by Fry (1995, 2000), who showed that a necessary ingredient in any scientific account of biogenesis is so-called **continuity thesis**: "the assumption that there is no unbridgeable gap between inorganic matter and living systems, and that under suitable physical conditions the emergence of life is highly probable." Adherence to the continuity thesis, as Fry demonstrates, is a precondition for scientific study of the origin of life; contrariwise, the views that biogenesis is a "happy accident" or "almost miracle" are essentially creationist, i.e., unscientific. The classification suggested below relies on this analysis of the continuity thesis and in part on its extension to noogenesis.⁸

The continuity thesis has been supported by many distinguished scientist throughout history, but none did more to promote it than the great British

⁶The magnitude of the age difference has been, however, constantly underestimated even before the results of Lineweaver cited above became available. The orthodox SETI literature does not discuss the age differences of the order of Gyr, which is indicative of the optimistic bias on part of the authors.

⁷It might be interesting to note that Alfred Russell Wallace, co-discoverer of natural selection with Darwin, has in several regards been a precursor to the contemporary astrobiology and in particular to study of FP. Beside speculating on the life on Mars in a separate treatise, in his fascinating book *Man's Place in the Universe* (Wallace 1903), preceding even Tsiolkovsky's formulation of FP for about three decades, he argued that naturalism cannot account for the fine-tuned structure of the universe. That was perhaps the last attempt of large-scale denial of naturalism.

⁸Whether such an extension is legitimate, remains an open question, too difficult to be tackled here. We mention in passing that at least one of the proposed solutions discussed below – the adaptationist hypothesis of Raup (1992) and Schroeder (2002) – explicitly denies this generalization.

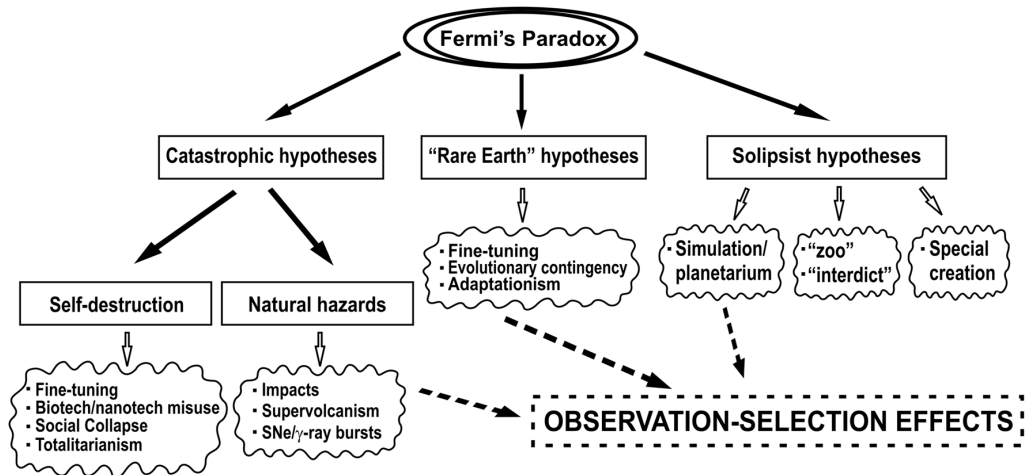


Fig. 2. The proposed high-level classification of the solutions to FP. In an extremely simplified form, the respective replies to Fermi's question *Where is everybody?* by proponents of solipsist, "Rare Earth" and (neo)catastrophic hypotheses are "They are here", "They do not exist", and "They have been prevented from coming yet". Only a small subset of proposed hypotheses is shown as examples in each category.

polymath John B. S. Haldane (1892-1964). In both his research writings in biology, mathematics, astronomy, etc., and in philosophical essays (especially Haldane 1972 [1927]), he insisted on the continuity between physical (in particular cosmological), chemical, biological and even cultural evolutions. Haldane was a co-author of the famous Oparin-Haldane theory of biogenesis, which emphasized law-like aspects of the process. This was in complete accordance with his philosophical and methodological principles, and enabled him to be put down foundations of what is today often called future studies as well (Clark 1968; Adams 2000).

An important novelty in comparison to the previous SETI reviews is the necessity of taking into account hitherto unrecognized possibilities, especially the Haldanian notion of **postbiological** evolution, prompted by Moore's Law and great strides made in the cognitive sciences. For instance, the great historian of science Steven J. Dick (2003) cogently writes:

But if there is a flaw in the logic of the Fermi paradox and extraterrestrials are a natural outcome of cosmic evolution, then cultural evolution may have resulted in a postbiological universe in which machines are the predominant intelligence. This is more than mere conjecture; it is a recognition of the fact that cultural evolution - the final frontier of the Drake Equation - needs to be taken into account no less than the astronomical and biological components of cosmic evolution. [emphasis in the original]

It is easy to understand the necessity of re-defining SETI studies in general and our view of Fermi's Paradox in particular in this context. For example, postbiological evolution makes those behavioral and social traits like territoriality or expansion drive (to fill the available ecological niche)

which are—more or less successfully—”derived from nature” lose their relevance. Other important guidelines must be derived which will encompass the vast realm of possibilities stemming from the concept of postbiological evolution.

5. SOLIPSIST SOLUTIONS

The label refers to a classic 1983 paper of Sagan and Newman criticizing Tipler's (1980, 1981) skepticism toward SETI studies based on Fermi's Paradox (FP) and strengthened by the idea of colonization via von Neumann probes. Here, however, we would like to investigate solipsist solutions to FP in a different - and closer to the usual - meaning.

Solipsist solutions reject the premise of FP, namely that there are no extraterrestrial civilizations either on Earth or detectable through our observations in the Solar System and the Milky Way thus far. On the contrary, they usually suggest that extraterrestrials are or have been present in our vicinity, but that the reasons for their apparent absence lie more with our observations and their limitations than with the real state-of-affairs.

Of course, this has been for so long the province of lunatic fringe of science (either in older forms of occultism or more modern guise of "ufology") but to neglect some of these ideas for that reason is giving the quacks too much power. Instead, we need to consider all the alternatives, and these clearly form well-defined, albeit often provably wrong or undeveloped ideas. Hypotheses in this class serve another important role: they remind us of the magnitude of the challenge posed by FP to our naive worldview – and they should be evaluated in this light. Some of the solipsist hypotheses discussed at least half-seriously in the literature are the following (listed in rough order from less to more viable ones):

- Those who believe **UFOs** are of extraterrestrial intelligent origin quite clearly do not have any problem with FP (e.g. Hynek 1972; for a succinct historical review see Chapter 6 of Dick 1996). The weight of evidence obviously tells otherwise.
- As far as it can be formulated as a hypothesis, traditional views of **special creation** of Earth and humanity belong to this class. The most valiant attempt in this direction has been made, as already mentioned, by Alfred Russel Wallace (1903), who argued for the key role of "cosmic mind" in the grand scheme of things and on the basis of teleological (mis)interpretation of the then fashionable model of the universe similar to the classical Kapteyn universe. As discussed in detail by Crow (1999), such views were occasionally dressed in garb of the traditional theology (especially of Christian provenance), but the association is neither logically nor historically necessary (see also Dick 2000, 2003). Today, this way of looking at the problem of life and intelligence beyond Earth is abandoned in most mainstream theologies (William Lane Craig, personal communication).⁹
- The **Zoo hypothesis** of Ball (1973) and the related **Interdict hypothesis** of Fogg (1987) suggest that there is a uniform cultural policy of advanced extraterrestrial civilization to avoid any form of contact (including having a visible manifestations) with the newcomers to the "Galactic Club". The reasons behind such a behavior may be those of ethics, prudence or practicality (Deardorff 1987). In each case, these do not really offer testable predictions (if the extraterrestrial civilizations are sufficiently powerful, as suggested by the age difference in 3), for which they have been criticized by Sagan, Webb and others. As a consequence, a "leaky" **interdict** scenario is occasionally invoked to connect with the alleged extraterrestrial origin of UFOs (Deardorff 1986), which is clearly problematic.
- **Directed panspermia** of Crick and Orgel (1973) suggests that Earth has indeed been visited in a distant past with very obvious consequence – namely the existence of life on Earth! Those two famous biochemists proposed – partly tongue-in-cheek, but partly to point out the real problems with the then theories of biogenesis – that our planet has been intentionally seeded with microorganism originating elsewhere. In other words, we are aliens ourselves! This motive has been extensively used in fiction (e.g. Lovecraft 2005 [1931]). It is very hard to see how we could ever hope to test the hypothesis of directed panspermia, in particular its *intentional* element.
- The **Planetarium hypothesis** of Baxter (2000) suggests that our astronomical observations do not represent reality, but a form of illusion, created by an advanced technological civilization capable of manipulating matter and energy on interstellar or Galactic scales. For a fictional description of this scenario, see Reynolds (2004).
- The **Simulation hypothesis** of Bostrom (2003), although motivated by entirely different reasons and formulated in a way which seemingly has nothing to do with FP, offers a framework in which FP can be naturally explained. Bostrom offers a Bayesian argument why we might rationally think we live in a computer simulation of an advanced technological civilization inhabiting the "real" universe. This kind of argument has a long philosophical tradition, going back at least to Descartes' celebrated second *Meditation* discussing the level of confidence we should have about our empirical knowledge (for an interesting recent review, see Smart 2004). Novel points in Bostrom's presentation are invoking Moore's Law for suggesting that we might be technologically closer to the required level of computing sophistication than we usually think, as well as adding a Bayesian conditioning on the number (or sufficiently generalized "cost" in resources) of such "ancestor-simulations" as he dubs them. It is trivial to see how FP is answered under this hypothesis: extraterrestrial civilizations are likely to be simply beyond the scope of the simulation in the same manner as, for example, present-day simulation of the internal structure of Sun neglect the existence of other stars in the universe.

It is difficult to objectively assess the value of solipsist hypotheses as solutions to FP. Most of them are either untestable in principle like the eponymous metaphysical doctrine, or testable only in limit of very long temporal and spatial scales, so that they do not belong to the realm of science, conventionally understood. In other words, they violate a sort of "naive" realism which underlies practically entire scientific endeavor. Their proponents are likely to retort that the issue is sufficiently distinct from other scientific problems to justify greater divergence of epistemological attitudes – but this is rather hard to justify when one could still pay a smaller price. For instance, one could choose to abandon Copernicanism, like the Rare Earth theorists (Section 6), or one might abandon gradualism (which has been discredited in geo- and planetary sciences anyway) and end up with a sort of neocatastrophic hypothesis (Section 7).

Some of them, but not all, violate the non-exclusivity requirement as well; this is, for instance, obvious in Zoo, Interdict or Planetarium scenarios, since they presume a large-scale cultural uniformity. This is not the case, however, with the Simulation hypothesis, since the simulated reality is likely to be

⁹Special creation, however, possesses some methodological similarities with the "rare Earth" hypotheses as well; see Section 6 below.

clearly designed and spatially and temporally limited. Directed panspermia has some additional problems – notably the absence of any further manifestations of our "parent civilization", in spite of its immense age. If they became extinct in the meantime, what did happen with other seeded planets? The Copernican reasoning suggests that we should expect evolution to occur faster at some places than on Earth (and, of course, slower at other sites as well) – where are our interstellar siblings, then?

Observation selection effects are important ingredient in at least some of these hypotheses. The directed panspermia could, for instance, be linked with a curious puzzle posed recently by Olum (2004), which also helps illustrate intriguing interplay between modern cosmology and astrobiology. Starting from the assumption of an infinite universe (following from the inflationary paradigm), Olum conjectures that there are civilizations much larger than ours (which currently consists of about 10^{10} observers). Spatial extent and amount of resources at disposal of such large civilizations would lead, in principle, to much larger number of observers (for example, 10^{19} observers in a Kardashev Type III civilization). Now, even if 99% of all existing civilizations are small ones similar to our own, anthropic reasoning suggests that the overwhelming probabilistic prediction is that we live in a large civilization. Since this prediction is spectacularly unsuccessful on empirical grounds; with a probability of such failure being about 10^{-8} , something is clearly wrong here. Olum offers a dozen or so hypothetical solutions to this alleged conflict of the anthropic reasoning with cosmology, one of them being the possibility that we are indeed part of a large civilization without being aware of that fact. Directed panspermia hypothesis can be regarded as operationalization of that option. There are several systematic deficiencies in Olum's conclusions (Ho and Monton 2005, Ćirković 2006), but in any case the very fact that some form of the principle of indifference and the counting of observers is used in this discussion shows how closely the theory of observation selection effects (cf. Bostrom 2002) is tied with the issues at the very heart of FP.

We mention the solipsist hypotheses mostly for the sake of logical completeness, since they are in any case the council of despair. If and when all other avenues of research are exhausted, we could always turn toward these hypotheses. Still, this neither means that they are all of equal value nor it should mislead us into thinking that they are necessarily improbable for the reason of desperation alone. Bostrom's simulation hypothesis might, indeed, be quite probable, given some additional assumptions related to the increase in our computing power and decrease of information-processing cost. Directed panspermia could, in principle, get a strong boost if, for instance, the efforts of NASA and other human agencies aimed at preventing planetary contamination (e.g. Rummel 2001, Grinspoon 2003), turn out to be unsuccessful, thus unintentionally setting off

biological evolution on other Solar System bodies. Finally, solipsist hypotheses need not worry about evolutionary contingency or generic probabilities of biogenesis or noogenesis, unlike the other contenders.

Jumping ahead, a clearly non-exclusive solution to FP obeying all methodological desiderata has not, in general, been found thus far. Even the most objective, mathematical studies, such as the one of Newman and Sagan, were compelled to, somewhat resignedly, 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 this sort of answer. It is especially disappointing to encounter it after a lot of mathematical analysis by the same authors, and keeping in mind by now more than half a century of sustained and often carefully planned and executed SETI efforts.¹⁰ This circumstance, as well as occasional (sub)cultural and even political appeal, explains why solipsist hypotheses are likely to reappear from time to time in the future.

6. "RARE EARTH" SOLUTIONS

This class of hypotheses is based upon the celebrated book *Rare Earth* by Peter Ward and Donald Brownlee, whose appearance in 2000 heralded birth of the new astrobiological paradigm. They 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. These ingredients of the **Rare Earth hypothesis** (henceforth REH) are well-known to even a casual student of astrobiology:

- Circumstellar habitable zone: a habitable planet needs to be in the very narrow interval of distances from the parent star.
- "Rare Moon": having a large moon to stabilize the planetary axis is crucial for the long-term climate stability.
- "Rare Jupiter": having a giant planet ("Jupiter") at right distance to deflect much of the incoming cometary and asteroidal material enables sufficiently low level of impact catastrophes.
- "Rare elements": Radioactive r -elements (especially U and Th) need to be present in the planetary interior in sufficient amount to enable plate tectonics and functioning of the carbon-silicate cycle.
- "Rare Cambrian-explosion analogs": the evolution of complex metazoans requires exceptional physical, chemical and geological conditions for episodes of sudden diversification and expansion of life.

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.

¹⁰Therefore, it is not surprising to notice the Conway Morris (2003), as a leading proponent of "intelligent design" in science is at least honest in admitting that in such picture it could be that naturalism will have to be abandoned after all.

In addition, Ward and Brownlee break new grounds with pointing the importance of hitherto downplayed factors, like the importance of plate tectonics, inertial interchange events, or "Snowball Earth" episodes of global glaciation for the development of complex life. In many ways, REH has become somewhat of a default position in many astrobiological circles, and – since it predicts the absence of rationale for SETI – a mainstay of SETI scepticism. Thus, its challenge to Copernicanism has been largely accepted (although, as argued below, there are lower prices to be paid on the market of ideas) as sound in the mainstream astrobiology. Particular Rare Earth hypotheses (insofar as we may treat them as separate) are difficult to assess lacking first-hand knowledge of other Earth-like planets, but some of the difficulties have been exposed in the literature thus far.

For instance, the famous argument about Jupiter being the optimal "shield" of Earth from cometary bombardment has been brought into question by recent work of Horner and Jones (2008, 2009) who use numerical simulation to show that the off-handed conclusion that Jupiter acts as a shield against bombardment of inner Solar System planets is unsupported. Moreover, they conclude "that such planets often actually increase the impact flux greatly over that which would be expected were a giant planet not present." If results of Horner and Jones withstand the test of time and further research, it is hard to imagine a more detrimental result for the entire Rare Earth paradigm.

This example highlights the major problem with REH. In supposing how the state-of-affairs could be different, Rare Earth theorists assume simple, linear change, not taking into account self-organizing nature of the relevant physical systems. The example of Jupiter is again instructive, since asking about the fate of Earth in the absence of Jupiter is self-contradictory: Earth is a part of the complex system which includes Jupiter as a major component, so there are no guarantees that Earth would have existed at all if Jupiter were not present. Even if it existed, we would have to account for many other differences between that particular counterfactual situation and the actual one, so the question to what degree is justified to call such a body "Earth" would be very pertinent.

Another important methodological problem for the "rare Earth" hypotheses is that at least in some respects they are equivalent to the doctrines openly violating naturalism, e.g., creationism. This similarity in style rather than in substance has been most forcefully elaborated by Fry (1995), as mentioned above. If one concludes that the probability of biogenesis – even under favorable physical and chemical preconditions – astronomically small, say 10^{-100} , but one still professes that it was completely natural event,¹¹ than a curious situation arises in which

an opponent can argue that supernatural origin of life is clearly more plausible hypothesis! Namely, even a fervent atheist and naturalist could not rationally claim that her probability of being wrong on this metaphysical issue is indeed smaller than 10^{-100} , knowing what we know on the fallibility of human cognition. According to the dominant rules of inference, we would have been forced to accept the creationist position, if no other hypothesis were present (Hoyle and Wickramasinghe 1999)! Now, REH in strict sense avoids this problem by postulating ubiquitous simple life (actually implying a high probability of biogenesis *ceteris paribus*). However, if the continuity thesis applies further along "Haldane's ladder" – specifically, to origin of complex metazoans and to noogenesis – an analogous argument is perfectly applicable to REH. Obviously, this necessitates further research in evolutionary biology, cognitive sciences and philosophy.

There are other hypotheses for resolving FP which violate Copernicanism. The idea of Wesson (1990) that it is cosmology which limits the contact between civilizations in the universe also belongs to this category. It implies that the density of civilizations is so low that only a few are located within our cosmological horizon. However, this is just begging the question, since such extreme low density of inhabited sites – less than 1 Gpc^{-1} , say – is not only un-Copernican, but clearly requires some additional explanatory mechanism. It may consist in biological contingency or rarity of the Cambrian-explosion analogs or any number of other instances invoked by the proponents of REH, but it is clearly necessary.

On the other hand, no further explanation is necessary for the **adaptationist version** of REH, which in this case could truly be dubbed "**rare mind**" hypothesis. It has been hinted at by Raup (1992), but developed in more detail in the novel *Permanence* by the Canadian author Karl Schroeder (2002). A detailed discussion of this particular solution of FP is given in Ćirković (2005). This intriguing hypothesis uses the prevailing adaptationist mode of explanation in evolutionary biology to argue that conscious tool-making and civilization-building are ephemeral adaptive traits, like any other in the living world. Adaptive traits are bound to disappear once the environment changes sufficiently for any selective advantage which existed previously to disappear. In the long run, the intelligence is bound to disappear, as its selective advantage is temporally limited by ever-changing physical and ecological conditions. The outcome of the cultural evolution in limits of very long timescales is a reversion to the direct, non-technological adaptation – similar to the suggestion of Raup that animals on other planets may have evolved, by natural selection, the ability to communicate by radio waves (and, by analogy, at least some of the other traits we usually think about as possi-

¹¹Even smaller probabilities have been occasionally cited in the literature. Thus, Eigen (1992) cites the probability of random assembly of a polymer with a thousand nucleotides corresponding to a single gene as 1 part in 10^{602} . This sort of "supernatural" numbers have led Hoyle and Wickramasinghe (1981, 1999) to invoke either an eternal universe – in contradiction with cosmology – or a creative agency. The (in)famous metaphor of random assembly of "Boeing 747" out of junkyard, cited by Sir Fred Hoyle, nicely expresses this sort of desperation, which has, luckily enough, been overcome in the modern theories of biogenesis.

ble only within the conscious civilization). This form of downgrading the role of consciousness – present in many circles of the contemporary philosophy of mind and cognitive science – is beautifully exposed in the controversial book of Julian Jaynes (1990).¹²

There are many difficulties with the adaptationist hypothesis. For instance, its insistence on adaptationism at all times is a form of inductivist fallacy. As in earlier times inductivists argued that it is natural to assume a meta-rule of inference along the lines of "the future will resemble the past", thus there is a creeping prejudice that the present and future modes of evolution need to be the same as those leading to the present epoch. This is a consequence of the present-day idolatry of adaptation: almost reflex and non-thinking assumption that any evolution has to be adaptationist (e.g., Dennett 1995; for a criticism, see Ahouse 1998). In spite of such fashionable views like evolutionary psychology/behavioral ecology/sociobiology, there is no reason to believe that all complex living systems evolve according to the rules of functionalist natural selection, and not, for instance, in a Lamarckian, orthogenetic or saltationist manner. Besides, even if all Gyr-old civilizations are now extinct, what about their astroengineering traces and manifestations? For a detailed review of further problematic issues with this intriguing hypothesis, see Ćirković, Dragičević and Berić-Bjedov (2005).

7. (NEO)CATASTROPHIC SOLUTIONS

This is the most heterogeneous group, containing both some oldest speculations on the topic and the newest ones. Before we review some of the main contenders, it is important to emphasize that the prefix "neo" is used almost reflexively with this mode of thinking for historical reasons. The defeat of "classical", 19th century catastrophism of figures such as Cuvier, Orbigny, de Beaumont, Agassiz or Sedgwick in the grand battle with the gradualism of Charles Lyell and his pupils (including Charles Darwin) imposed a lasting stigma on views which were perceived as belonging to this tradition of thought. This has clearly impeded the development of geosciences (see historical reviews in Raup 1991, Huggett 1997, Palmer 2003). In addition, the association of catastrophism with the pseudo-scientific (although often thought-provoking!) views of Immanuel Velikovsky has brought an additional layer of suspicion upon the label itself (for a review of the Velikovskian controversy, see Bauer 1984). Thus, the resurgence of catastrophism after 1980 and the discovery of Alvarez and collaborators that an asteroidal/cometary impact was the physical cause of the extinction of ammonites, dinosaurs and other species at the Cretaceous/Tertiary boundary 65 Myr ago (Alvarez et al. 1980) is often referred to as neocatastrophism.

- **Classical nuclear self-destruction hypothesis** was, perhaps more obvious during the Cold War era (cf. von Hoerner 1978) – but ephemeral cultural changes in our recent history should not really modify prior probability for this dramatic possibility. Problem with the exclusive nature of such a hypothesis – considering the fact that social and political developments on habitable planets throughout the Galaxy are quite unlikely to be correlated – are obvious.
- **Self-destruction options** have multiplied in the meantime, since the spectrum of potentially destructive technologies in human history have recently broadened. This now includes misuse of biotechnology (including bioterrorism), and is likely to soon include misuse of nanotechnology, artificial intelligence, or geoeengineering (see reviews in Bostrom and Ćirković 2008, Ćirković and Cathcart 2004). If most of technological societies in the Galaxy self-destructs through any of these – or other conceivable – means, this would be an explanation for the "Great Silence". Quite clearly, the same qualms about exclusivity apply as above.
- **Ecological holocaust:** Solar System and surrounding parts of GHZ belong to a "post-colonization wasteland", a bubble created by rapid expansion and exhaustion of local resources on the part of early advanced technological civilizations (Stull 1979, Finney and Jones 1985). Since colonization front is likely to be spherically symmetric (or axially symmetric when the vertical boundaries of the Galactic disk are reached), they will tend to leave vast inner area exhausted. If the parameters describing the rates of expansion and natural renewal of resources are in a particular range of values, it is possible that younger civilizations will find themselves in a This hypothesis has been recently revived in numerical models of Hanson (1998b), showing that in some cases fairly plausible initial conditions will lead to "burning of the cosmic commons", i.e. catastrophic depletion of usable resources in a large volume of space. This is rather controversial **as a solution to FP** since, apart from some fine-tuning, it still does not answer the essential question: where did the "precursors" go and why we do not perceive their immensely old astro-engineering signatures? They have either become extinct (thus begging the question and requiring another layer of explanation) or changed into something else (see the **Transcendence** item below). However, this hypothesis is non-exclusive (since the volume of space within the ancient colonization front is large) and it does make some well-defined predictions as far as renewal of resources and the traces of possible previous

¹²A particularly thought-provoking section (pp. 36-41) of the first chapter of Jaynes' disturbing book is entitled "Consciousness Not Necessary for Thinking".

cycle of their depletion in the Solar vicinity are concerned.

- **Natural hazards:** The risk of cometary/asteroidal bombardment (Clube and Napier 1984, 1990, Chyba 1997), supervolcanism (Rampino 2002), nearby supernovae (Terry and Tucker 1968, Gehrels et al. 2003) or some other, more exotic catastrophic process (Clarke 1981) might be in general much higher than we infer from the recent history of Earth. These natural hazards are much likelier to break the evolutionary chain leading to the emergence of intelligent observers, so we should not wonder why we do not perceive manifestations of older Galactic communities. For instance, one well-studied case is the system of the famous nearby Sun-like star Tau Ceti which contains both planets and a massive debris disk, analogous to the Solar System Kuiper belt. Modeling of Tau Ceti's dust disk observations indicate, however, that the mass of the colliding bodies up to 10 kilometers in size may total around $1.2 M_{\oplus}$, compared with $0.1 M_{\oplus}$ Earth-masses estimated to be in the Solar System's Edgeworth-Kuiper Belt (Greaves et al. 2004). It is only reasonable to conjecture that any hypothetical terrestrial planet of this extrasolar planetary system is subjected to much more severe impact stress than Earth has been during the course of its geological and biological history.¹³
- **Phase-transition hypotheses** (Annis 1999a, Čirković 2004b, Čirković and Vukotić 2008) offer a plausible astrophysical scenario for a delay in the emergence of intelligent observers and their technological civilizations based on the notion of a global regulation mechanism. Such a mechanism could occasionally reset astrobiological "clocks" all over GHZ and in a sense re-synchronize them. This is a prototype **disequilibrium** astrobiological 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 or the age difference in (3). 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 Galaxy. Astrobiological significance of GRBs has recently been subject of much research (Thorsett 1995, Scalzo and Wheeler 2002, Thomas et al. 2005, 2008, Galante and Horvath 2007). The discussion of other conceivable regulation mechanisms is given by Vukotić and Čirković (2007, 2008). In general, this hypothesis leads to the situation schematically envisioned in Fig. 3: where we

are within the temporal window of a "phase transition" – from essentially dead place, the Galaxy will be filled with intelligent life on a timescale similar to t_{FH} .

- **Deadly probes hypothesis:** A particularly disturbing version of the Tipler's (1980, 1981) *reductio ad absurdum* scenario presumes that self-replicating von Neumann probes are not peaceful explorers or economically-minded colonizers, but intentionally or accidentally created destructive weapons. This might occur either due to malevolent creators (which in that case had to be the first or one of the first technological civilizations in the Galaxy, close to the Lineweaver limit) or through a random dysfunction ("mutation") in a particular self-replicating probe which has passed to its "offspring". In both cases, it seems that the originators of the probes have vanished or are in hiding, while the Galaxy is completely different (and more hostile) ecological system than it is usually assumed. Depending on the unknown mode of operation of destructive von Neumann probes, they might be homing on the sources of coherent radio emission (indicating a young civilization to be eliminated) or might be automatically sweeping the Galaxy in search for such adversaries. Brin (1983) concludes that this one of only two hypotheses which maintain wholesale agreement with both observation and non-exclusivity. In the realm of fiction, this hypothesis has been topic of novels by Fred Saberhagen (1998), Gregory Benford (1977, 1983) and Alastair Reynolds (2002).
- **"Freedom is slavery":** If all civilizations, instead of self-destruction, slip into permanent totalitarianism (perhaps in order to avoid self-destruction or other global catastrophic risks; see Caplan 2008), this could also dramatically decrease the contact cross-section. Orwellian state is quite disinterested in the external universe; even if it were willing to communicate, its paranoid nature would have made any opportunity for contact orders of magnitude more difficult. For a gruesomely dramatic description of this possibility see *Fiasco* (Lem 1987). On the other hand, it is conceivable that at least some totalitarian states would actually engage in aggressive interstellar expansion, even if through releasing the deadly probes sketched above. Here, as elsewhere, we might have a case for synergy of different FP solutions.
- **Transcendence hypothesis:** Advanced technological civilizations have neither destroyed themselves nor spread through the Galaxy, but have transformed themselves into "something else", not recognizable as a civilization and certainly not viable as a SETI target. Historically, this has been the first solution to FP,

¹³For a good recent introduction to the complex topic of the relationship between catastrophes and habitability, see Hanslmeier (2009).

offered by Konstantin Tsiolkovsky who posed the paradox in the first place. Tsiolkovsky, under the influence of his teacher, N. F. Fedorov and other Russian cosmoists, concluded that the only reason why we do not perceive manifestations of much older civilizations is their evolving into a form of "superreason" with near-godly powers and, presumably, inconceivable interests (Tsiolkovsky 1933; see also Lytkin et al. 1995, Lipunov 1997); the ideas of Tsiolkovsky have some similarities with the Zoo hypothesis of Ball (1973), discussed above. Today, it is often formulated in term of "technological Singularity", the concept envisioned by Stanislaw Ulam and I. J. Good, and popularized in 1990s by mathematician and author Vernon Vinge (e.g. Vinge 1986, 1991, 1993, Kurzweil 2005). Smart's (2007) concept of the "Universal Transcension" is a variation of this idea.

As the Cold War cultural pessimism retreated, neocatastrophic hypotheses obtained a strong boost from the resurgence of catastrophism in Earth and planetary science, as well as in astrobiology. Following the seminal work of Alvarez et al. (1980), we have become aware that global catastrophes played very significant role in the evolution of terrestrial biosphere (e.g. Jablonski 1986, Raup 1991, Courtillot 1999, Erwin 2006). Moreover, some of the actual catastrophes whose traces are seen in the terrestrial record are of astrophysical origin, emphasizing the new paradigm according to which the Solar System is an open system, strongly interacting with its 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). This neocatastrophist tendency is present in the modern 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. The major feature of these solutions is the abandonment of the classical gradualist dogma that "the present is key to the past" and acknowledgement that sudden, punctuated changes present a major ingredient in shaping both Earth's and Milky Way's astrobiological history (or "landscape"; cf. Vukotić and Ćirković 2008).

Intuitively, it seems clear that any form of catastrophic events affecting planetary biospheres in the Milky Way will reduce the hypothetical extraterrestrial civilizations' ages and thus reduce the tension inherent in FP. If such events are spatially and temporally uncorrelated – as in the "mandatory" nuclear self-destruction hypothesis or the totalitarian scenario – such an explanation is obviously low on the non-exclusivity scale. In contrast, hypotheses with correlated events – such as "deadly probes" or

phase-transition – fare much better here. In some cases, it is still impossible to estimate how tightly correlated some of the postulated events might be; this applies in particular to the transcendence-type scenarios, where the extent and the nature of "Singularity" remains a mystery.¹⁴

Among the non-exclusive hypotheses, the phase-transition model is in advantage in comparison to the "deadly probes", since we understand possible dynamics of the global regulation mechanisms. 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, in accordance with Annis' scenario. In both of these hypotheses, however, it is possible that pockets of old (in effective, astrobiological terms) habitable sites remain, either through purely stochastic nature of lethal regulation mechanisms, or through dysfunctional mode of operation of destructive von Neumann probes.

Predictions of these two hypotheses and their ramifications for the ongoing SETI projects cannot differ more dramatically. While the "deadly probes" scenario is particularly bleak and offers no significant prospect for SETI, punctuation of the astrobiological evolution of the Milky Way with large-scale catastrophes affecting significant fraction of GHZ will, somewhat counterintuitively, have the net effect of strengthening the rationale for our present-day SETI efforts. Namely, as the secular evolution of the regulation mechanisms leads to the increase in the average astrobiological complexity (Fig. 3), we might expect that more and more civilizations enter the "contact window" and join efforts in expansion towards Kardashev's Type III status.

8. OTHER SOLUTIONS

A small number of hypotheses have been proposed which do not fall easily into one of the broad categories described above. Although the total variation of approaches to FP is already stupendous, it is remarkable how small number of ideas escapes the general philosophical categories discussed.

For instance, Landis (1998) and Kinouchi (2001) have investigated the dynamics of interstellar colonization which, under some particular assumptions, can leave large bubbles of empty space surrounded by colonized regions. This phenomenon is in the context of condensed-matter physics known as *persistence*. An obvious weakness of this hypothesis is that it still implies cultural uniformity regarding the dynamical parameters of colonization, which violates the non-exclusivity requirement. In addition, we would expect to detect either extraterrestrial signals coming from outside of the local non-colonized bubble, or to detect manifestations of Gyr-older technological societies even in the absence of the direct presence of extraterrestrials in the Solar System or in its vicinity.

¹⁴Consequently, it is impossible to state confidently whether the transcendence hypotheses resolve FP, i.e., what additional assumptions are necessary for this rather vague concept to be a viable solution. On the other hand, obvious – and rather dramatic – importance of this scenario for future studies remains a strong motivation for further research.

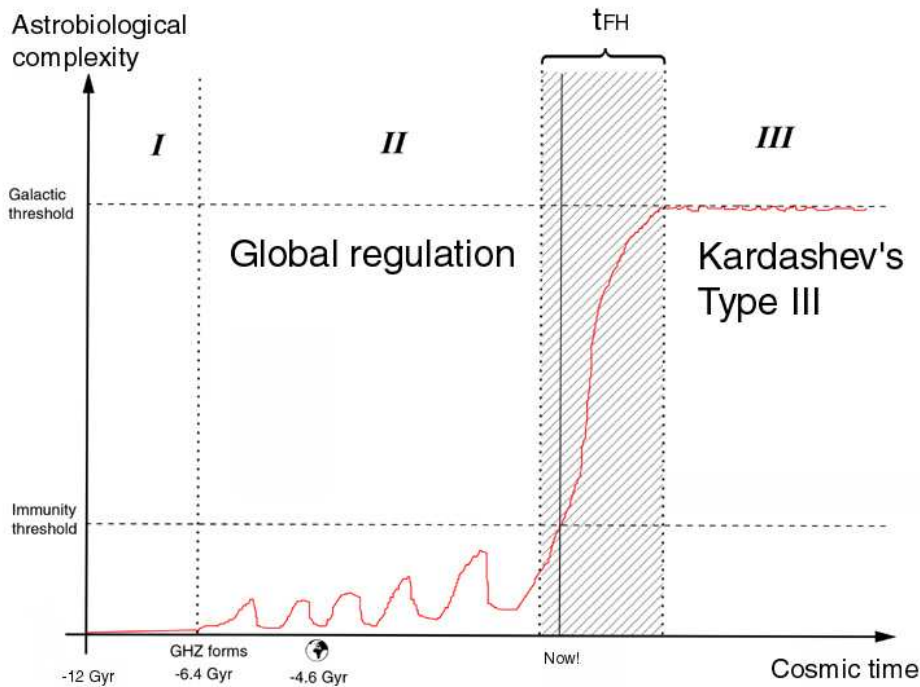


Fig. 3. Very simplified scheme of the phase-transition hypotheses (from Ćirković and Vukotić 2008): an appropriately defined astrobiological complexity will tend to increase with time, but the increase will not become monotonous until a particular epoch is reached.

Similar approach has been favored in numerical simulations of Bjork (2007), although the timescales obtained in his model are quite short in comparison with (3) even with his explicit rejection of self-reproducing probes, thus being more in line with the older calculations of Hart (1975), Jones (1976, 1981) and Newman and Sagan (1981). Bjork concludes, rather too optimistically, that FP could be resolved by through statement that "[w]e have not yet been contacted by any extraterrestrial civilizations simple because they have not yet had the time to find us." In view of the timescale (3) it is clearly wrong as long as we do not postulate some additional reason for the delay in starting the Galactic exploration.

The approach of Ćirković and Bradbury (2006; see also Ćirković 2008) offers an alternative solution based on the assumption that most or all advanced technological societies will tend to optimize their resource utilization to an extreme degree. It could be shown that such optimization will ultimately be limited by the temperature of the interstellar space – and that temperature decreases with increased galactocentric distance in the Milky Way (towards the ideal case of the CMB temperature of about 2.7 K achievable only in the intergalactic space). The logical conclusion is that most of the advanced technological species (which will be most likely post-biological, consisting of intelligent machines or uploaded minds; cf. Dick 2003) will migrate towards the outer rim of the Galaxy, far from the star-formation regions, supernovae and other energetic astrophysical events in order to process information

most efficiently. This solution modestly violates non-exclusivity requirement, depending on how universally valid is the assumption of resource-optimization as the major motivator of advanced extraterrestrial societies.

Not surprisingly, some of these ideas have been prefigured in a loose form within the discourse of science fiction. Karl Schroeder in *Permanence* not only formulated the above-mentioned adaptationist answer to Fermi's question, but also envisaged the entire Galaxy-wide ecosystem based on brown dwarfs (and the halo population in general) and a low-temperature environment (Schroeder 2002). Most strikingly, the idea of advanced technological civilization inhabiting the outer fringes of the Milky Way has been suggested—though without the thermodynamical rationale—by Vernon Vinge in *A Fire upon the Deep* (Vinge 1991). Vinge vividly envisages "Zone boundaries" separating dead and low-tech environments from the truly advanced societies inhabiting regions at the boundary of the disk and high above the Galactic plane. This is roughly analogous to the low-temperature regions Ćirković and Bradbury (2006) outlined as the most probable Galactic technological zone.

It has been claimed in the classical SETI literature that the interstellar migrations will be forced by the natural course of stellar evolution (Zuckerman 1985). However, even this "attenuated" expansionism – delayed by on the order of 10^9 years – is actually unnecessary, since naturally occurring thermonuclear fusion in stars is extremely inefficient energy source, converting less than 1% of the total stellar mass into potentially useable energy. Much

deeper (by at least an order of magnitude) reservoir of useful energy is contained in the gravitational field of a stellar remnant (white dwarf, neutron star or black hole), even without already envisaged stellar engineering (Criswell 1985, Beech 2008). Highly optimized civilization will be able to prolong utilization of its astrophysically local resources to truly cosmological timescales. The consequences for our conventional (that is, predominantly empire-state) view of advanced societies have been encapsulated in an interesting paper by Beech (1990):

[A] star can only burn hydrogen for a finite time, and it is probably safe to suppose that a civilisation capable of engineering the condition of their parent star is also capable of initiating a programme of interstellar exploration. Should they embark on such a programme of exploration it is suggested that they will do so, however, by choice rather than by necessitated practicality. [emphasis M. M. Č.]

In brief, the often-quoted cliché that life fills all available niches is clearly *non sequitur* in the relevant context; thus, interstellar colonial expansion should not be a default hypothesis, which it sadly is in most SETI-related and far-future-related discourses thus far.

The **sustainability solution** of Haqq-Misra and Baum (2009) is related to the compact, highly-efficient model of advanced extraterrestrial civilization postulated in Parkinson (2004), Ćirković and Bradbury (2006), Smart (2007), and Ćirković (2008). Haqq-Misra and Baum envision a situation in which large-scale interstellar expansion is infeasible due to sustainability costs (and perhaps dysgenic factors, similar to the ones in Schroeder's adaptationist hypothesis), so that the prevailing model would be a compact, "city-state" sophisticated technological civilization, possibly slowly expanding, but at rates negligible in comparison to the expansion in either Newman-Sagan-Bjork (no self-replicating probes) or Tipler (with self-replicating probes) regimes. Parkinson's (2004) **containment scenario** offers a different rationale for predominance of the "city-states" over the "interstellar empires", resulting in the same observed dearth of interstellar empires. These hypotheses meet with the same criticisms based on (i) the non-exclusivity and (ii) the lack of astroengineering detection signatures considered above.

9. INSTEAD OF CONCLUSIONS: A PUZZLE FOR THE 3. MILLENNIUM?

The very fact that **each wide class of answers to FP requires abandoning one of the great methodological assumptions of modern science** (solipsist solutions reject naive realism, "rare Earth" solutions reject Copernicanism and

neocatastrophic solutions – gradualism) should give us pause.¹⁵ This testifies on the toughness and inherent complexity of the puzzle. In accordance with the strong position of REH in contemporary astrobiology, our analysis shows that we should interpret it as a challenge to Copernicanism. In the view of the present author, by far the lowest price if paid through abandoning of gradualism, which is anyway undermined by the contemporary developments in geosciences, evolutionary biology and astronomy.

Gradualism, parenthetically, has not shone as a brilliant guiding principle in astrophysics and cosmology. It is well-known, for instance, how the strictly gradualist (and from many points of view methodologically superior) steady-state theory of the universe of Bondi and Gold (1948), as well as Hoyle, has after the "great controversy" of 1950s and early 1960s succumbed to the rival evolutionary models, now known as the standard ("Big Bang") cosmology (Kragh 1996). Balashov (1994) has especially stressed this aspect of the controversy by showing how deeply justified was the introduction—by the Big Bang cosmologists—of events and epochs never seen or experienced. Similar arguments are applicable in the nascent discipline of astrobiology, which might be considered to be in an analogous state today as cosmology was half a century ago (Ćirković 2004a).

This leads us to the practical issue of ramifications of various hypotheses sketched above for practical SETI activities. While solipsist hypotheses have nothing substantial to offer in this regard, Rare Earth hypotheses obviate the very need for practical SETI efforts. In the best case, we could expect to find archaeological traces of vanished Galactic civilizations (as per adaptationist hypothesis). In contrast, most neocatastrophic options offer support for SETI optimism, since their proponents expect practically all extraterrestrial societies to be roughly of the same effective age as ours,¹⁶ and to be our competitors for the Fermi-Hart-Tiplerian colonization of the Milky Way. The price to be paid for bringing the arguments of "optimists" and "pessimists" into accord is, obviously, the assumption that we are living in a rather special epoch in Galactic history—i.e. the epoch of phase transition. In any case, it is clear that our choice of hypotheses for resolving FP needs to impact our SETI efforts in a most direct way.

A related issue too complex to enter here in more detail is the inadequacy of most of the orthodox SETI projects thus far. Radio listening for intentional messages has been a trademark of orthodox SETI since the time of "founding fathers" (Drake, Morrison, Sagan, etc.) and it has demonstrated quite a strong resilience to dramatic changes in other fields of learning in the past four decades. Several issues touched upon in this review strongly indicate that the conventional SETI (Tarter 2001, Duric and Field

¹⁵We have assumed naturalism throughout in accordance with the proclaimed goal of investigating to which degree FP remains unresolved.

¹⁶A qualification "effective" is required here since in the case of arrested development (e.g., under the totalitarianism scenario, the age of civilization is almost irrelevant for its capacity for cosmic colonization.

2003, and references therein), as exemplified by the historical OZMA Project, as well its current counterparts such as META, ARGUS, Phoenix, SERENDIP/Southern SERENDIP—and notably those conveyed by NASA and the SETI Institute—are fundamentally flawed. Some of the alternatives have existed for quite a long time, starting with the seminal paper by Dyson (1960) and elaborated in Dyson (1966) and Ćirković and Bradbury (2006). What we can dub the Dysonian approach to SETI puts the emphasis on search for extraterrestrial technological manifestations and artifacts. Even if they are not actively communicating with us, that does not imply that we cannot detect their astro-engineering activities. Unless advanced technological communities have taken great lengths to hide or disguise their IR detection signatures, the terrestrial observers should still be able to observe them at those wavelengths and those should be distinguishable from normal stellar spectra. In addition, other bold unconventional studies like those on antimatter-burning signatures (Harris 1986, 2002, Zubrin 1995), anomalous lines in stellar spectra (Valdes and Freitas 1986), or recognizable transits of artificial objects (Arnold 2005) seem to be promising in ways conventional SETI is not. Search for megaprojects such as Dyson Shells, Jupiter Brains or stellar engines are most likely to be successful in the entire Spectrum of SETI activities (Slysh 1985, Jugaku et al. 1995, Timofeev et al. 2000, Jugaku and Nishimura 2003, Carrigan 2008).

All in all, considering the pace of the astrobiological revolution, these issues are likely to be more and more explored in years and decades to come. It is to be hoped that future missions like TPF (Howard and Horowitz 2001), GAIA (Perryman et al. 2001), or DARWIN (Cockell et al. 2009) will be able to offer further quantitative inputs for developing of the future, more detailed numerical models of astrobiological evolution of the Milky Way (cf. Vukotić and Ćirković 2008, Forgan 2009). The overarching role played by the observation-selection effects in a large part of the relevant hypothesis space makes further research in this rather new field mandatory from both dual points of view discussed above: research in SETI **and** research in the future of humanity. Resolving FP is not a luxury, but one of the imperatives if we wish our scientific worldview to have even remote prospect of completeness.

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ФЕРМИЈЕВ ПАРАДОКС – ПОСЛЕДЊИ ИЗАЗОВ ЗА КОПЕРНИКАНИЗАМ?

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Прегледни рад по позиву

У овом чланку правимо преглед Фермијевог парадокса (или парадокса "Велике тишине"), не само најстаријег и по много чему кључног проблема потраге за ванземаљском интелигенцијом (СЕТИ), већ и загонетке са дубоким опште научним, филозофским и културним значајем. Једноставном применом анализе посматрачких селекционих ефеката, коректно решење Фермијевог парадокса нам готово извесно говори нешто о будућности човечанства. Овај проблем, стар већ више од три четврти века - а прошло је више од четврт века од последњег кључног преглед-

ног чланка у литератури који је написао Г. Дејвид Брин - генерисао је многе домишљате расправе и ингениозне хипотезе. Овде анализирамо прећутне претпоставке уграђене у различите одговоре на ову загонетку и предлажемо нову класификацију бројних решења која се појављују у већ огромној литератури на ову тему. Коначно разматрамо последице различитих класа хипотеза на практичне СЕТИ пројекте. Донекле парадоксално, изгледа да (нео)катастрофичке хипотезе дају, кад се све узме у обзир, највише разлога за оптимизам у погледу наших садашњих СЕТИ подухвата и оних у блиској будућности.