Fermi’s Paradox – The Last Challenge for Copernicanism?

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Abstract
We review Fermi’s paradox (or the ”Great Silence” problem), not only arguably the oldest and crucial problem for the Search for Ex traTerrestrial 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 a more than three quarters of a century old puzzle – and a quarter of century since the last major review paper in the field by G. David Brin – Fermi’s paradox has generated many ingenious discussions and hypotheses. We analyze the often tacit methodological assumptions built into 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 balance, the strongest justification for guarded optimism regarding our current and near-future SETI efforts.

Key words: astrobiology – extraterrestrial intelligence – Galaxy: evolution – history and philosophy of astronomy – observation selection effects

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 greatest challenge for any practical SETI activity, as well as one of the least understood of all ”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, Enriko Fermi: ”Where is everybody?” First discussed in print by the Russian space-science pioneer Konstantin Eduardovich Tsiolkovsky, and in recent decades elaborated upon 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 a 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 modern civilization. It is hard to conceive a scientific problem more pregnant in meaning or richer in connections 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):

\[ t_{FH} = 10^6 - 10^8 \text{ years} \]  

(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 contend that this timescale is well-defined, albeit not precisely known due to our ignorance regarding 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)

\[ t_\oplus = (4.46 \pm 0.02) \times 10^9 \text{ years} \]  

(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 system\(^1\)). 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 astro-engineering 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 the 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

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\text{sociotempestal 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

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\text{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

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\(^1\)In 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, Arkhipov 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.

\(^2\)Philosophical literature often calls this view *direct realism* or *common sense realism*. 

violate this realist view; an extreme and ludicrous 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 typically in play 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 a narrow sense tells us that there is nothing special about the Earth or the Solar System or our Galaxy within large sets of similar objects throughout the universe. In a 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 a century or so. We shall return to this issue in Section 7.

Finally, the role of the 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 a 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 a 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.

\(^3\)Note 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 long-standing confusion and the reason why Copernicanism is most fruitfully used in conjunction with some expression of observational selection effects, usually misleadingly known as the ‘anthropic principle’; for detailed treatment see Bostrom 2002.
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 advance occurring during the last two decades:

1. The discovery of more than 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 the capacities of present-day instruments stand between us and the discovery 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.

2. Improved understanding of the details of the 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 the age of the Earth. This means that the age difference

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

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 super-civilizations, in clear contrast with observations.

3. Confirmation of the rapid origination of life on early Earth (e.g., Mojzsis et al. 1996); this rapidity, in turn, offers strong probabilistic support to the idea of many planets in the Milky Way inhabited by at least the simplest lifeforms (Lineweaver and Davis 2002).
4. Discovery of extremophiles and the general resistance of simple life-forms to much more severe environmental stresses than 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.

5. Our improved understanding of molecular biology and biochemistry leading to heightened confidence in the theories of the 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).

6. 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.

7. 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.

8. Theoretical grounding for various astroengineering/macroengineering projects (Badescu 1995, Badescu and Cathcart 2000, 2006, Koryanskzky 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).

9. Our improved understanding of the 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. In addition, we have witnessed substantial research leading to a decrease in confidence in Carter’s (1983) so-called ”anthropic” argument, the other mainstay of SETI skepticism (Wilson 1994, Livio 1999, Ćirković et al. 2009). All this has been accompanied by an increase of 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 the quite widespread notion (especially in popular the press) 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 right at the beginning that it is not entirely surprising that several scientific hypotheses for resolving FP have been formulated, in a qualitative manner, in the recreational context 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 20th 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 of this mode of colonization leads to the lowest values for the Fermi-Hart timescales (1). It is important to understand, however, that although FP is aggravated with von Neumann probes, 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”

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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 greatest challenges on the road toward securing a future for humankind still lie ahead of us; see, e.g., Bostrom and Ćirković (2008).
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. This includes the misleading insistence on 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 a higher level of formal precision in these fields. Intuitive concepts of life and intelligence are sufficiently developed to enable fruitful research in these fields, in the same manner as the intuitive concept of life enables research in the terrestrial 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). The 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 species\(^5\) 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 significant than 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.

Similarly, we use the locution ”advanced technological civilization” along the lines sketched in Ćirković and Bradbury (2006), as denoting a community of intelligent beings capable of manipulating matter and energy on sufficiently large scale. Again, the precise and useful definition is impossible to get, but some of the properties of hypothetical advanced technological civilization

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\(^5\)The status of the 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).
Figure 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.
would be, for instance, that they are immune to natural hazards (like those threatening the survival of humanity at present, like impacts or supervolcanism) and that consequences of their industrial and computational activities could, in principle, be detected from interstellar distances. It is exactly the magnitude of difference in (3) that we naively expect at least some of the advanced technological civilization to have arisen in the Milky Way.

(II) A useful way of thinking about FP is by analogy with Olbers’ paradox in classical cosmology, as 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 now know (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 actually an almost negligible, minor effect to take into consideration 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 had been in the 1920s and 1930s (Kragh 1996, 2007, Dick 1996, 2003).

3 What’s Past is Prologue

It was 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 constrains, 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, Duric and Field 2003) that most of the members of the hypothetical ”Galactic Club” of communicating civilizations are significantly older than ours.6 This applies to the future as well – the status of extraterrestrial biospheres older than the Earth

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6The magnitude of the age difference has been, however, constantly underestimated, as was the case 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
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, leads 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 disenchanted SETI pioneers (in particular Iosif Shklovskii and Sebastian von Hoerner; see, e.g., von Hoerner 1978 and comments in Lem 1977) argued, the reason behind the 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), this would mean that humanity is also overwhelmingly likely to self-destruct. If natural hazards (in the form of, for example, impacts by comets and asteroids or supervolcanic eruptions; cf. Chyba 1997; Rampino 2002) are the main culprits beyond the absence of extraterrestrials – automatically implying that they are, on 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. Consequently, in such case we would have to ascribe our surviving thus far to sheer luck, which holds no guarantees for the future. 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 a hellish fate are negligible. In that sense, the astrobiological history of the Milky Way is a Shakespearian prologue to the 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

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is indicative of the optimistic bias on the part of the authors.
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 17th 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 that 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 a 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 the 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 scientists throughout history, but none did more to promote it than the great British 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 evolution. Haldane was a co-author of the famous Oparin-Haldane theory of biogenesis,

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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 contemporary astrobiology and in particular to the study of FP. Beside speculating on 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 by about three decades, he argued that naturalism cannot account for the fine-tuned structure of the universe. That was perhaps the last attempt at large-scale denial of naturalism in what can be regarded as a legitimate scientific context.

8Whether such an extension is legitimate, remains an open question, one 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.
Figure 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/manifesting yet”. Only a small subset of proposed hypotheses is shown as examples in each category.

which emphasized law-like aspects of the process. This was in complete accordance with his philosophical and methodological principles, and enabled him to lay down the foundations of what is today often called future studies as well (Clark 1968; Adams 2000).

An important novelty here in comparison to 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 the 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 redefining 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 subtitle 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 yet 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 long been the province of the 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 to give 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 Russell Wallace (1903), who argued for the key role of "cosmic mind" in the grand scheme of things and on the basis of a 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 the garb of 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 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.

- The Directed panspermia scenario/hypothesis of Crick and Orgel (1973) suggests that Earth was indeed visited in the distant past with very obvious consequences – 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 microorganisms 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 for 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

9 Special creation, however, possesses some methodological similarities to the "rare Earth" hypotheses as well; see Section 6 below.
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 include invoking Moore’s Law in order to suggest 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 simulations of the internal structure of the 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 at the 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 the entire scientific endeavor. Their proponents are likely to retort that the issue is sufficiently distinct from other scientific problems to justify a 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 the 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 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 happened with the other seeded planets? 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, then, are our interstellar siblings?

Observation selection effects are important ingredient in at least some of these hypotheses. The Directed panspermia scenario could, for instance, be linked with a curious puzzle posed recently by Olum (2004), which also helps to illustrate the 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). The spatial extent and amount of resources at the 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. 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 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. The 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 up with 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 a 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. The Directed panspermia hypothesis 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. 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 the 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 the 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. In addition, Ward and Brownlee break new ground by pointing out 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 mainstream astrobiology. Particular Rare Earth hypotheses (insofar as we may treat them as separate) are difficult to assess lacking first-hand knowledge of other Earthlike 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 the 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 had 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 it 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 – is astronomically small, say $10^{-100}$, but one still professes that it was completely natural event, 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

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10Even 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 "superastronomical" number has 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 the random assembly of a "Boeing 747" out of a junkyard, cited by Sir Fred Hoyle, nicely expresses this sort of desperation, which has, luckily enough, been overcome in the modern theories of biogenesis.
we know on the general fallibility of human cognition. According to the dom-
inant 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 ubiq-
uitous 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. If the probability
of evolutionary pathways entering a small region of biological morphospace
describing intelligent tool-making species is astronomically small, and one
still maintains that it has occurred on Earth naturalistically, as a ”happy
accident”, one is open to the same criticism as Fry brought forward in case
of biogenesis. 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 an 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 the 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 the
”rare mind” hypothesis. It has been hinted at by Raup (1992), but de-
developed in more detail in the novel Permanence by the Canadian author Karl
Schroeder (2002). A detailed discussion of this particular solution to FP is
given in Ćirković (2005). This intriguing hypothesis uses the prevailing adap-
tationist 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, intelligence is bound to disappear,
as its selective advantage is temporally limited by ever-changing physical and
ecological conditions. The outcome of cultural evolution at limits of very long
timescales is a reversion to 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 anal-
ogy, at least some of the other traits we usually think about as possible only
within the conscious civilization). This form of downgrading of the role of
consciousness – present in many circles of contemporary philosophy of mind
and cognitive science – is beautifully illustrated in the controversial book of Julian Jaynes (1990).\textsuperscript{11}

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: the almost reflex 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, Dragićević and Berić-Bjedov (2005).

7 (Neo)Catastrophic Solutions

This is the most heterogeneous group, containing both some of the oldest and newest speculations on the topic. 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 the "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 in 1950s and 1960s 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 by 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'.

\textsuperscript{11}A particularly thought-provoking section (pp. 36-41) of the first chapter of Jaynes' disturbing book is entitled "Consciousness Not Necessary for Thinking". See also Narretranders 1999.
• Classical **nuclear self-destruction hypothesis** was, perhaps more prevalent during the Cold War era (cf. von Hoerner 1978), but ephemeral cultural changes in our recent history should not really modify the prior probability for this dramatic possibility. Problems 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 geoengineering (see reviews in Bostrom and Ćirković 2008; Ćirković and Cathcart 2004). If most technological societies in the Galaxy self-destruct 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**: Our Solar System and surrounding parts of GHZ belong to a "postcolonization 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 cycle of their depletion in the Solar vicinity are concerned.

• **Natural hazards**: The risk of cometary/asteroidal bombardment (e.g.,
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’s 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.

- The **Phase-transition hypotheses** (Annis 1999a, Ćirković 2004b, Ćirković and Vukotić 2008) offers 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 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. The astrobiological significance of GRBs has recently been the subject of much research (Thorsett 1995, Scalo and Wheeler 2002, Thomas et al. 2005, 2008, Galante and Horvath 2007). The discussion of other conceivable regulation mechanisms is given by Vukotić and Ćirković (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 an essentially dead place, the Galaxy will be filled with intelligent life on a timescale similar to $t_{FH}$.

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12For a good recent introduction to the complex topic of the relationship between catastrophes and habitability, see Hanslmeier (2009).
• The **Deadly Probes hypothesis**: A particularly disturbing version of 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 would have 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 a completely different (and more hostile) ecological system than is usually assumed. Depending on the unknown mode of operation of destructive von Neumann probes, they might be homing in 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 is 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-destructing, 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. This 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.

• The **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, 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 cosmists, 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 terms of a "technological Singularity", the concept envisioned by Stanislaw Ulam and I. J. Good, and popularized in the 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. There are two reasons why this vague family of scenarios classified here, with other catastrophic hypotheses. First, the external appearance of a transcending event or process might be catastrophic; fictional precursor of the hypothesis, Vinge (1986) hints at such scenario. More importantly, one of the few common claims for the transcension scenarios is that of sudden, discrete change, obviously antithetical to gradualism.

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 a very significant role in the evolution of the 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 Vasish 1998, Shaviv 2002, Melott et al. 2004, Pavlov et al. 2005, Gies and Helsel 2005). This neocatastrophist tendency is present in modern research on biogenesis (e.g., Raup and Valentine 1983, Maher and Stevenson 1988), and even in the debates on the evolution of humanity (Rampino and Self 1992, Ambrose 1998, Bostrom and Ćirković 2008), but all of 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 the acknowledgement that sudden, punctuated changes present a major ingredient in shaping both the Earth's and the Milky Way's astrobiological history (or "landscape"; cf. Vukotić and Ćirković 2008).

Intuitively, it seems clear that any form of catastrophic event 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-transitions – 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 nature of the "Singularity" remains a mystery.\footnote{Consequently, 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, the obvious – and rather dramatic – importance of this scenario for future studies remains a strong motivation for further research.}

Among the non-exclusive hypotheses, the phase-transition model harbours an advantage in comparison to the "deadly probes" scenario, 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 the 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 would remain, either through the purely stochastic nature of lethal regulation mechanisms, or through the dysfunctional mode of operation of destructive von Neumann probes.

Predictions of these two hypotheses and their ramifications for the ongoing SETI projects could not 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 a significant fraction of GHZ would, 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.

\section{8 Other Solutions}

A small number of hypotheses have been proposed which do not fall easily into any of the broad categories described above. Although the total variation of approaches to FP is already stupendous, it is remarkable how a small number of remaining ideas defy inclusion within the general philosophical categories we have so far 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 appears in the context of condensed-matter physics as \textit{persistence}. An obvious weakness of this hypothesis is that it still implies cultural
Figure 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.
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-old technological societies even in the absence of the direct presence of extraterrestrials in the Solar System or in its vicinity.

A similar approach has been favored in the 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 the 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 timescale (3) it is clearly wrong as long as we do not postulate some additional reason for the delay in the initiation 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 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 intergalactic space). The logical conclusion is that most of the advanced technological species (which will be most likely postbiological, 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 the 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 an 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 an 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. A 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). A 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 speculative 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. Ć.]

In brief, the often-quoted cliché that life fills all available niches is clearly a 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, technologically-sophisticated “city-state” civilization, possibly slowly expanding, but at rates negligible in comparison to the expansion in either the Newman-Sagan-Bjork (no self-replicating probes) or Tipler (with self-replicating probes) regimes. Parkinson’s (2004) containment scenario offers a different rationale for the 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.14 This testifies to 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 contemporary developments in the geosciences, evolutionary biology and astronomy.

Gradualism, parenthetically, has not shone as a brilliant guiding principle in astrophysics and cosmology either. 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, since the “great controversy” of the 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 the ramifications of the 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 some extinct Galactic civilization (as per the 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,15 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 a phase transition. In any case, it is clear that our choice of hypotheses for resolving FP

14We have assumed naturalism throughout, in accordance with the proclaimed goal of investigating to what degree FP remains unresolved.
15The 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 to its capacity for cosmic colonization.
needs to impact our SETI efforts in a most direct way.

A related issue too complex to enter into here in more detail is the inadequacy of most of the orthodox SETI projects thus far. Radio listening for intentional messages, either intercepted or specifically directed to young societies, has been a trademark of orthodox SETI since the time of its "founding fathers" (Drake, Morrison, Sagan, etc.) and it has demonstrated quite a strong resilience to dramatic changes in other fields of learning over the past four decades. Several issues touched upon in this review strongly indicate that the conventional SETI (Tarter 2001, Duric and Field 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 the 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 explored more and more 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 the development of future, more detailed numerical models of the astrobiological evolution of the Milky Way (cf. Vukotić and Ćirković 2008, Forgan 2009, Cotta and Morales 2009). The overarching role played by observation-selection effects in a large part of the relevant hypothesis-space makes further research in this rather new field mandatory from both points of view discussed above: research in SETI and research on the future of humanity. Resolving FP is not a luxury; rather, it is one of the principal imperatives if we wish our scientific worldview to have even a remote prospect of completeness.
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