Galactic Gradients, Postbiological Evolution and the Apparent Failure of SETI

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Abstract

Motivated by recent developments impacting our view of Fermi's paradox (the absence of extraterrestrials and their manifestations from our past light cone), we suggest a reassessment of the problem itself, as well as of strategies employed by SETI projects so far. The need for such reassessment is fueled not only by the failure of SETI thus far, but also by great advances recently made in astrophysics, astrobiology, computer science and future studies. Therefore, we consider the effects of the observed metallicity and temperature gradients in the Milky Way on the spatial distribution of hypothetical advanced extraterrestrial intelligent communities. While properties of such communities and their sociological and technological preferences are, obviously, entirely unknown, we assume that (1) they operate in agreement with the known laws of physics, and (2) that at some point they typically become motivated by a meta-principle embodying the central role of information-processing; a prototype of the latter is the recently suggested Intelligence Principle of Steven J. Dick. There are specific conclusions of practical interest to astrobiological and SETI endeavors to be drawn from coupling of these reasonable assumptions with the astrophysical and astrochemical structure of the spiral disk of our Galaxy. In particular, we suggest that the outer regions of the Galactic disk are most likely locations for advanced SETI targets, and that sophisticated intelligent communities will tend to migrate outward through the Galaxy as their capacities of information-processing increase, for both thermodynamical and astrochemical reasons. However, the outward movement is limited by the decrease in matter density in the outer Milky Way. This can also be regarded as a possible generalization of the Galactic Habitable Zone, concept currently much investigated in astrobiology.

Keywords: astrobiology, Galaxy: evolution, extraterrestrial intelligence, physics of computation, SETI

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

Heraclitus of Ephesos, *fragment B18* (cca. 500 BC)

1 Introduction

Fermi's paradox[1] 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 ~ 10 years:

- Discovery of more than 170 extrasolar planets, on almost weekly basis (for regular updates see `http://www.obspm.fr/planets`). Although most of them are "hot Jupiters" and not suitable for life as we know it (their satellites can still be habitable, however; cf. Williams, Kasting, and Wade 1997), many are reported to be parts of systems with stable circumstellar habitable zones (Noble, Musielak, and Cuntz 2002; Asghari et al. 2004; Beaugé et al. 2005). It seems that only selection e ects and capacity 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, the wealth of planets decisively disproves some 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, Brownlee, and Ward 2001). In particular, the important calculations of Lineweaver (2001; Lineweaver et al. 2004) showing that Earth-like planets began forming more than 9 Gyr ago, and their median age is 6.4 ± 0.7 Gyr, significantly more than the Earth's age.

- Confirmation of the *rapid* origination of life on early Earth (e.g. Mojzsis et al. 1996); this rapidity, in turn, o ers 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

[1] It would be most appropriately to call it Tsiolkovsky-Fermi-Viewing-Hart-Tipler's paradox (for much of the history, see Brin 1983; Kuiper and Brin 1989; Webb 2002, and references therein). We shall use the locution "Fermi's paradox" for the sake of brevity, and with full respect for contributions of the other important authors.

thought possible earlier (e.g. 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 (Lahav, Nir, and Elitzur 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 (e.g. Chernavskii 2000).

- Exponential growth of the technological civilization on Earth, especially manifested through Moore's Law and other advances in information technologies (e.g. Schaller 1997; Bostrom 2000).

- Improved understanding of feasibility of interstellar travel in both classical sense (e.g. Andrews 2003), and in the more e cient form of sending inscribed matter packages over interstellar distances (Rose and Wright 2004).

- Theoretical grounding for various astro-engineering/macro-engineering projects (Badescu 1995; Badescu and Cathcart 2000, 2006; Korycansky, Laughlin, and Adams 2001; McInnes 2002) potentially detectable over interstellar distances. Especially important in this respect is possible combination of astro-engineering and computation projects of advanced civilizations, like those envisaged by Sandberg (1999).

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 half a century later, but that it is more puzzling and disturbing than ever.[2] 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; Ćirković and Dragićević 2006, preprint). All this is accompanied by increased public interest in astrobiology and related issues (e.g. Ward and Brownlee 2000, 2002; Webb 2002; Cohen and Stewart 2003; Dick 2003). The list above shows, parenthetically, that

[2] One is tempted to add another item of a completely different sort to the list: the empirical fact that we have survived more than 60 years since 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 of part of the road toward safety for humankind is still in front of us.

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

Faced with the aggravated situation vis-à-vis Fermi's paradox the solution is usually sought in either (i) some version of the "rare Earth" hypothesis (i.e., the picture which emphasizes inherent uniqueness of our planet, and hence uniqueness of human intelligence and technological civilization in the Galactic context), or (ii) "neo-catastrophic" explanations (ranging from the classical "mandatory self-destruction" explanation, championed for instance by von Hoerner or Shklovsky, to the modern emphasis on mass extinctions in the history of life and the role of catastrophic impacts, gamma-ray bursts, and similar dramatic events). Both these broad classes of hypotheses are unsatisfactory on several counts: for instance, "rare Earth" hypotheses reject the usual Copernican assumption (Earth is a typical member of the planetary set), and neo-catastrophic explanations usually fail to pass the non-exclusivity requirement (but see Ćirković 2004a,b). None of these are clear, straightforward solutions. It is quite possible that a "patchwork solution", comprised of a combination of suggested and other solutions remains our best option for solving this deep astrobiological problem. This motivates the continuation of the search for plausible explanations of Fermi's paradox.

Hereby, we would like to propose a novel solution, based on the astrophysical properties of our Galactic environment on large scales, as well as some economic and informational aspects of the presumed advanced technological civilizations (henceforth ATCs). In doing so, we will suggest a radically new perspective on the entire SETI endeavor.

2 Digital perspective and the postbiological universe

In an important recent paper, the distinguished historian of science Steven J. Dick argued that there is a tension between SETI, as conventionally understood, and prospects following exponential growth of technology as perceived in recent times on Earth (Dick 2003):

> 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. In particular, we follow the *Intelligence Principle* of Dick (2003), stating that

> In sorting priorities, I adopt what I term the central principle of cultural evolution, which I refer to as the Intelligence Principle: *the maintenance, improvement and perpetuation of knowledge and intelligence is the central driving force of cultural evolution, and that to the extent intelligence can be improved, it will be improved.* [emphasis in the original]

Before we explore the logical consequences of the Intelligence Principle for SETI further, let us emphasize that the study of Dick (2003) is not an isolated instance. Very similar thinking is clearly emerging in various other fields and related to a plethora of di erent problems. Considerations of postbiological evolution are related to the *megatrajectory* concept of Knoll and Bambach (2000), who cogently argue that astrobiology is the ultimate field for verification or rejection of our biological concepts. In relation to the old problem of progress (or its absence) in the evolution of life on Earth, Knoll and Bambach o er a middle road encompassing both contingent and convergent features of biological evolution through the idea of a megatrajectory:

> We believe that six broad megatrajectories capture the essence of vectorial change in the history of life. The megatrajectories for a logical sequence dictated by the necessity for complexity level N to exist before $N + 1$ can evolve... In the view o ered here, each megatrajectory adds new and qualitatively distinct dimensions to the way life utilizes ecospace.

The six megatrajectories outlined by the biological evolution on Earth so far are: (i) from the origin of life to the "Last Common Ancestor"; (ii) prokaryote diversification; (iii) unicellular eukaryote diversification; (iv) multicellularity; (v) invasion of the land; and (vi) appearance of intelligence and technology. *Postbiological evolution may present the seventh megatrajectory,* triggered by the emergence of artificial intelligence at least equivalent to the biologically-evolved one, as well as the invention of several key technologies of roughly similar level of complexity and environmental impact, like molecular nanoassembling or stellar uplifting. ATCs can be regarded as instantiations of this seventh (or possible higher) megatrajectory. It is not necessary to assume that the seventh megatrajectory represents the complete or partial abandonment of the biological material substratum of previous evolution, although that is certainly one of the options. Rather, the mode of evolution is likely to change from the Darwinian one dominating previous six megatrajectories, to a sort of aggregative, intentional, quasi-Lamarckian mode characteristic for highly developed cultural entities. We shall repeatedly return to this important point, which in a sense obviates further rather superficial speculation about the *detailed* structure of ATCs.

A natural extension of the Intelligence Principle is what can be called the *digital perspective* on astrobiology: after a particular threshold complexity is reached, the relevant relations between existent entities are characterized by requirements of computation and information processing. It is related to the emergent computational concepts not only in biology, but in fundamental physics, cosmology, social sciences, etc. One particular consequence of the digital perspective, dealing with the thermodynamics of computation, we shall now argue, will allow us a glimpse of a novel view of the generic evolution of the intelligent communities in the Galactic context, including a new solution of the old Fermi's puzzle. The digital perspective also indicates that we should abandon or significantly modify Kardashev's (1964) classification of extraterrestrial intelligent communities, one of the mainstays of classical SETI studies.

What can limit the postbiological evolution guided by the Intelligence Principle? In order to answer this question, we need to consider limitations imposed by physics on the classical theory of computation. As almost anybody having practical experience with computers will have experienced, heat is an enemy of computation. In contrast to other obstacles and di culties facing highly imperfect computers of today (like limited storage space, dust, or ine ciency of their human operators), the problem of heat dissipation is a consequence of the laws of physics. Therefore, we conjecture that for advanced technical civilizations this problem will remain *the* enemy of e cient computation, and that it will have a dominant e ect on policy-making of such advanced societies.

Thermodynamics of computation has, historically, been motivated by Maxwell's demon "paradox" which led to great breakthroughs of Szilard, Brillouin, and Landauer. One of its most important results, often called Brillouin inequality is the fundamental property of the information content available for processing in any sort of physical system (Landauer 1961; Brillouin 1962):

$$I \leq I_{\max}, \tag{1}$$

where the limiting amount of information $I_{\max}$ (in bits) processed using energy ΔE (in ergs) on the processor temperature T (in K) is given as

$$I_{\max} = \frac{\Delta E}{k_B T \ln 2} = 1.05 \times 10^{16} \frac{\Delta E}{T}. \tag{2}$$

Here, k_B is the Boltzmann constant. Obviously, computation becomes more e cient as the temperature of the heat reservoir in contact with the computer is lower. In the ideal case, no energy should be expended on cooling the computer itself, since that expense should be added to the energy cost of logical steps minimized by (2). The most e cient heat reservoir is the universe itself, which *far from the energy sources* like stars and galaxies, has the temperature of the cosmic microwave background (henceforth CMB; Wright et al. 1994)

$$T_{\rm CMB} = 2.736 \pm 0.017 \text{ K}. \quad (3)$$

However, this is an ideal case, since ATCs cannot have their computers in thermal equilibrium with CMB for simple astrophysical reasons. In the rest of this paper we shall investigate how close approach to this ideal case is feasible.

It has already been repeatedly suggested that our descendants, in particular if they cease to be organic-based, may prefer low-temperature, volatile-rich outer reaches of the Solar system. Thus, they could create what could be dubbed ”circumstellar technological zone” as di erent and complementary to the famous (and controversial) ”circumstellar habitable zone” in which life is, according to most contemporary astrobiological views, bound to emerge. We propose to generalize this concept to the Galaxy (and other spiral galaxies) in complete analogy to GHZ (Gonzalez et al. 2001; Lineweaver et al. 2004). It is not necessary, or indeed desirable, for our further considerations to make the notion of ATCs more precise. The diversity of postbiological evolution is likely to at least match, and probably dwarf, the diversity of its biological precedent. It is one particular feature—information processing—we assume common for the ”mainstream” ATCs. Whether real ATCs can most adequately be described as ”being computers” or ”having computers” is not of key importance for our analysis; we just suppose that in either case the desire for optimization of computations will be one of important, if not the most important desire of such advanced entities. It is already clear, from the obviously short and limited human astronautical experience, that postbiological evolution o ers significant advantages (Parkinson 2005).

3 Galactic temperature gradient

The famous article by Freeman Dyson (1960) proposing searching for large-scale engineering projects (like eponymous Dyson shells) as the signposts of the presence of advanced extraterrestrial intelligence provoked much discussion henceforth. One very important contribution was the early suggestion of the distinguished computer scientist and AI pioneer Marvin Minsky (1973) in a debate following Dyson’s talk at the celebrated Byurakan conference in 1971, that advanced computers could operate at e ectively the temperature of cosmic microwave background (3).[3] This particular idea is wrong in the specifics, at least for the younger and most accessible ATCs, but it gives us an important hint as to what should we be searching for. Subsequently, other astro-engineering projects—sometimes called megaprojects or macroprojects—aimed at optimization of resources at ATCs' disposal have been proposed, notably Jupiter Brains (Sandberg 1999; for early history see Bradbury 1997; Perry E. Metzger, private communication to RJB May 20, 1998) and Matrioshka Brains (Bradbury 2001).

What is the temperature of a solid body (like a Dyson shell, a Matrioshka brain, or a Jupiter brain[4] in thermal equilibrium with the surrounding interstellar space? The dominant factor influencing it is the spatial distribution of the interstellar radiation field (henceforth ISRF), especially at short wavelengths (optical and UV). It can be shown that in by far the predominant parts of ISM the most important way of energy transfer to a solid body is absorption of photons, while collisions with atoms and ions are unimportant. For example, ultraviolet flux close to the Solar circle of about 10^{10} photons m^{-2} s^{-1} nm^{-1} will deposit about a 10^{-20} J s^{-1} to a dust grain (with unity absorption factor, for simplicity), while collisions deposit $\simeq 10^{-26}\, n_{\rm ISM}$ J s^{-1}, where $n_{\rm ISM}$ is the ISM number density in cm^{-3}. Since on the average $\langle n_{\rm ISM} \rangle = 1$ cm^{-3}, we perceive how unimportant collisions which form our laboratory definition of the "thermal equilibrium" are in the interstellar space.

Neglecting collisions, the temperature will be given by solving the radiative equilibrium equation (e.g. Dyson and Williams 1980)

$$\int F(\lambda) Q_{\rm abs}(a, \lambda)\, d\lambda = \int Q_{\rm abs}(a, \lambda) B(\lambda, T)\, d\lambda, \qquad (4)$$

where $F(\lambda)$ is the energy flux of ISRF, $Q_{\rm abs}$ is the absorption coe cient, and the Planck black-body function is given as

$$B(\lambda, T) = \frac{2hc}{\lambda^3} \frac{n_\lambda^2}{\exp\left(\frac{hc}{kT\lambda}\right) - 1} \; . \qquad (5)$$

ISRF is created mainly by massive stars of Population I, concentrated in the Galactic disk. Typical value of the energy density of ISRF in vicinity of the Sun is $U = 7 \times 10^{-13}$ ergs cm^{-3}, which does not include the CMB contribution, which has $U_{\rm CMB} = 4 \times 10^{-13}$ ergs cm^{-3}. We use the conventional assumption

[3]Parenthetically, in the same debate Minsky presciently suggested infeasibility of conventional SETI due to the impossibility of distinguishing the signal from the Gaussian noise (cf. Lachmann, Newman, and Moore 2004).

[4]For the purpose of the present discussion, we use the placeholder "solid body" for any macroscopic body not made of gas or liquid. Thus, sizes of solid bodies we consider range roughly from 10^{-5} cm (an interstellar dust grain) to 10^{13} cm (a Dyson shell).

of the exponential disk (e.g. Binney and Merrifield 1998) with the luminosity density approximated by

$$j(R,z) = \frac{I_0}{2z_0} \exp\left(-\frac{R}{R_d} - \frac{|z|}{z_0}\right), \tag{6}$$

where I_0 is the central surface brightness, z_0 is the scale-height, and $R_d \approx 3$ kpc is the disk scalelength. From this, we obtain the disk surface brightness as

$$I(R) = \int_{-\infty}^{+\infty} j(R,z)\,dz = I_0 \exp\left(-\frac{R}{R_d}\right), \tag{7}$$

which agrees with observations in external disk galaxies. It seems clear that ISRF will decline with galactocentric distance, and thus the equilibrium temperature will decline too, enabling more and more e cient computation, as per (2). No detailed studies of the radiation field temperature distribution in the Milky Way disk exist so far, we suggest the following rough estimates.

Part of the answer can be gauged by comparison with the existent natural solid bodies in such thermal equilibrium, namely interstellar dust grains. In Figure 1, we see results of the detailed models of the Galactic temperature distribution of dust grains (Mathis, Mezger, and Panagia 1983; Cox, Krügel, and Mezger 1986). Using the same values of ISRF and correcting for the emission e ciency of larger solid objects give us the results presented in Figure 2, for computation e ciency defined as the maximal number of bytes processed per erg of the invested energy in terabytes (10^{12} bytes) per erg.

In reality, we need to take into account the inhomogeneities in the interstellar medium, especially giant molecular clouds. The interiors of molecular clouds are impenetrable to short wavelength radiation, and present some of the coldest locales in the Milky Way ($T \sim 10$ K). However, the interiors of giant molecular clouds are also sites of vigorous massive star formation, so these low-temperature locales are quite irregular and transient phenomena, assembling and dissembling on timescales of $\sim 10^6$ yrs, which is probably unacceptable from the point of view of most ATCs (which we suppose stable at larger timescales by definition).

There have not been any studies of the ISRF for distances larger than about 14 kpc (Prof. John S. Mathis, private communication). At some point for large galactocentric distances (larger than the Holmberg radius ~ 20 kpc), practically all sources of ISRF are located at smaller R, so we can use the simplest approximation of galaxy as a point source. If with $T_D(R)$ we denote the temperature of a large solid object (a Dyson shell, say) at galactocentric distance R, a simple scaling relationship

$$\sigma T_D^4(R) \propto L_* R^{-2}, \tag{8}$$

σ is Ste an-Boltzmann constant, $L_* \approx 4.9 \times 10^{10}\ L_\odot$ the Galactic luminosity in the absorbing bands. Taking into account both (2) and (8), we obtain the general scaling relation in the outermost regions:

$$\left(\frac{I}{E}\right)_{\max} \propto \sqrt{R}. \tag{9}$$

Other issues to be taken into account in a future more complete treatment of the problem of habitability of the Galaxy from the point of view of (probably postbiological) ATCs are the following:

- Cosmic ray heating, which is important even in the interiors of the densest molecular clouds (in fact it dominates heating mechanisms there and initiates all chemical reactions in cold environments); the cosmic ray energy density at the Solar circle is about $U_{cr} = 2.4 \times 10^{-12}$ erg cm^{-3} (Webber 1987), but falls o in a complicated manner with galactocentric distance (including Parker instability, etc.).

- Supernovae, especially of the core-collapse Type II and Type Ic, which tend to be concentrated in spiral arms and other regions of intense star-formation (for the astrobiological significance of supernovae for planetary biospheres, see e.g. Tucker and Terry 1968; Ruderman 1974; Hunt 1978; Collar 1996).

- Much rarer and more dramatic events, Galactic gamma-ray bursts (the longer ones associated with hypernovae and perhaps also shorter ones caused by neutron stars' mergers), capable of adversely influencing planetary biospheres over a large part of the Galaxy (e.g. Thorsett 1995; Scalo and Wheeler 2002; Dar and De Rújula 2002; Melott et al. 2004; Thomas et al. 2005). Possible Galactic nuclear activity falls in the same category (see below).

- Other thermodynamical issues related to computational needs, notably bit-erasure costs, as well as bandwidth and latency issues (Sandberg 2000).

It is significant to note that both radiative and kinetic energy input from supernovae and related events are adverse to computation e ciency of ATCs. All these e ects are falling o with the galactocentric distance, and become very small for $R > 15$ kpc. In the inner parts of the Galaxy, the same factors which preclude habitability (mainly supernovae and gamma-ray bursts) act to preclude computation as well. In addition, the issue of the nuclear activity of the Milky Way and spiral galaxies in general, may be important for astrobiological evolution of those regions. It has been proposed by Clarke (1981) in an interesting early paper, as a mechanism of global regulation preventing life and intelligence from arising in the entire Galaxy; see also Clube

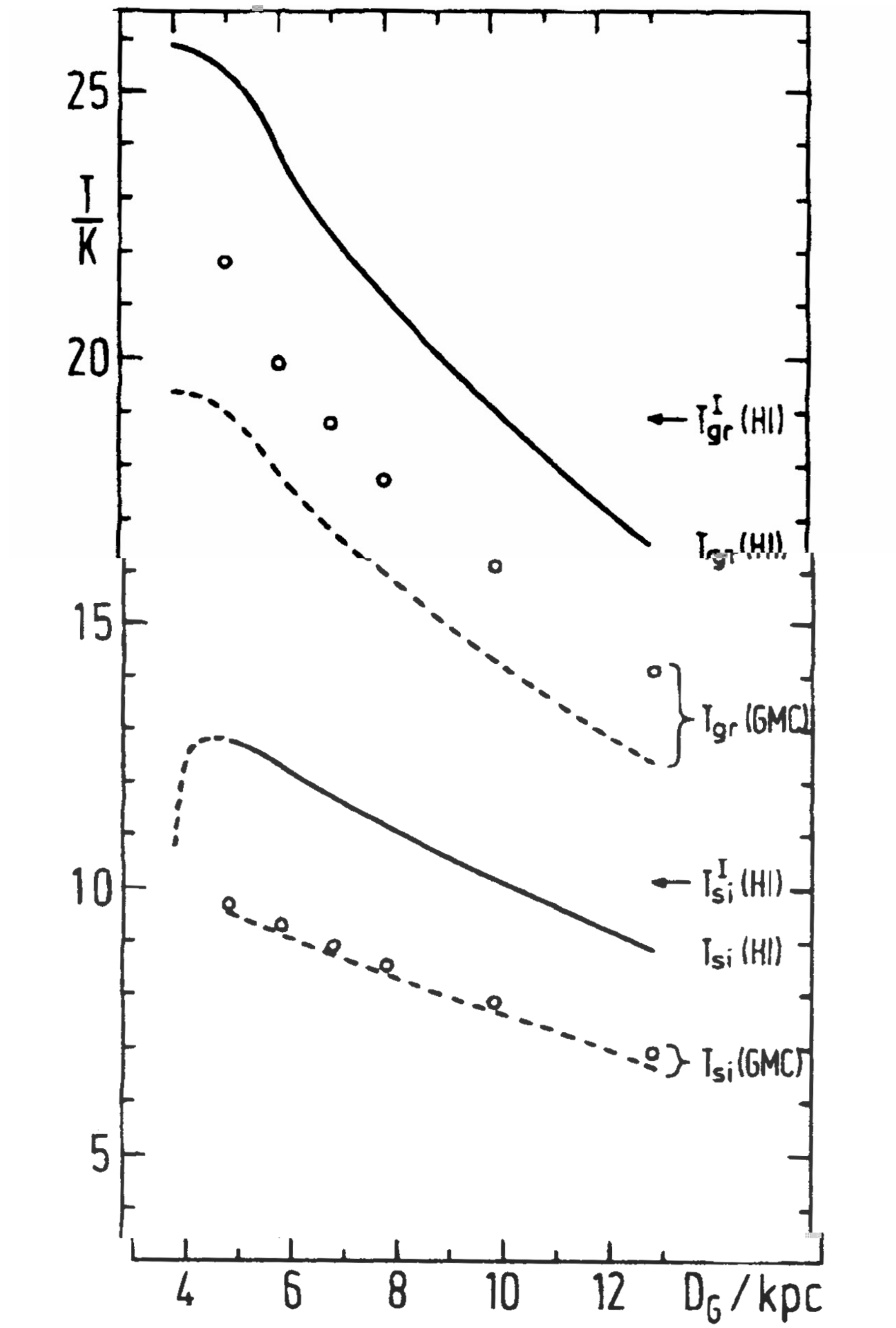

Figure 1: Temperature of interstellar dust grains in thermal equilibrium with ISRF for various galactocentric distances given by Mathis et al. (1983). Lines labeled with "(HI)" pertain to grains located in the di use neutral medium, while those labeled "(GMC)" are supposed to lie within giant molecular clouds. Several chemical models are used, determining the thermal capacities and albedo; the uppermost solid line corresponds to graphite particles is most relevant from our point of view (courtesy of Prof. John S. Mathis).

(1978) and LaViolette (1987). Although it seems now that the original idea is implausible in light of the specific conditions in Milky Way's nucleus, we should still be cautious, since the recent research unveiled similar tremendous nuclear outbursts in some distant objects (e.g. McNamara et al. 2005).

There is another large-scale gradient in the Milky Way recently firmly established by observations: the metallicity gradient. Average metal abundances of stars and ISM are rather well described by the radial gradient of $\nabla Z \simeq 0.07$ dex/kpc (Hou, Prantzos, and Boissier 2000; Tadross 2003). It could seem at first that this is adverse for ATCs in the outer regions of the Galaxy, thus counteracting the trend of increasing computing e ciency described above. But, the Intelligence Principle suggests something di erent, when we take into account that the chemical enrichment causing the gradient is entirely product of stellar nucleosynthesis; primordial composition was uniformly metal-free. Stellar nucleosynthesis is appallingly ine cient process by ATC standards; it converts $\sim 1\%$ of the rest mass to energy and even most of that created energy left the Galaxy long time before the emergence of first ATCs. Thus, baryonic matter in the primordial composition would, in principle, be required for advanced optimization of computation. ATCs would subsequently be able to create heavier nuclei by controlled fusion and minimize the energy leak per unit created entropy.

4 Migration hypothesis

Taking all this into account, we suggest the "migration hypothesis": ATCs will tend to move their computing facilities toward the colder regions of the Milky Way in order to make their information processing as e cient as possible. In general case, this would mean the outskirts of the Milky Way, but the interiors of the giant molecular clouds could also serve as local foci for the advanced information processing.[5] If the postbiological evolution is predominant, as suggested by Dick (2003) and other recent writers, this would mean that the entire ATC will tend to migrate outward from its original location in the GHZ toward a convenient location in the Galactic "technological zone" with temperature low enough to increase computing e ciency. Although such a migration will seem expensive at first glance, it is not necessarily so: postbiological civilizations are likely to be small, compact, stable over astrophysical timescales and would be able to travel as redundant information storages at small speeds with negligible energy expenditures. Almost all energy will be needed for acceleration and deceleration. Starting at particular galactocentric distances, it is not di cult to calculate that any

[5] Insofar as the other risks, from the point of view of ATCs and the Intelligence Principle, mentioned above can be avoided: notably star-formation bursts and associated Type II supernovae.

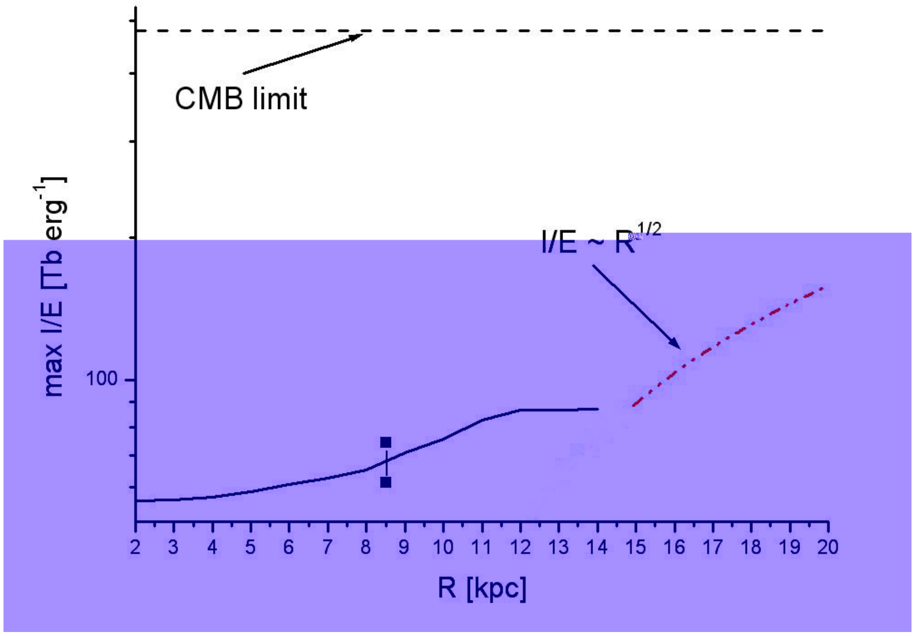

Figure 2: Maximal quantity of information per unit expended energy processed by a computer in equilibrium with the radiation field at various galactocentric distances in the Milky Way (with the location of the Solar circle indicated). The limit due to the cosmic microwave background is also given. We see that the e ciency limit rises considerably for $R > 10$ kpc. At large galactocentric distances, a simple scaling argument indicates that the e -ciency will tend to rise $\propto \sqrt{R}$ until it reaches the CMB limit in the "true" intergalactic space; however, those external regions are almost devoid of baryonic matter, and even the density of CDM particles becomes exceedingly small.

particular transportation cost will be covered by increased computation e -ciency on timescales short compared to the astrophysical timescales or even the timescale of the travel itself! Interestingly enough, suggestions for the possible technologies of such interstellar migrations already exist in the literature, notably in the form of ”stellar engines” (e.g. Badescu and Cathcart 2000).

What limits the outward migration of ATCs? This is largely a context-dependent issue, but the most plausible limit is set simply by availability of matter. Depending on whether ATCs get to use non-baryonic dark matter, whose density roughly varies in accordance with the isothermal profile ($\rho \propto R^{-2}$), or only baryonic matter, which falls o exponentially (6), the maximal distance a cost-mindful ATC may be located at will greatly vary. But in each case, it is a *well-defined value*, which limits the Galactic technological zone from the outside. The concept of the Galactic technological zone should not be understood as strict and immutable: it just indicate higher relative density of technologized matter than elsewhere. ATCs can arise and function elsewhere (in the same sense as life can arise outside of the classical circumstellar habitable zone; e.g. in Europa-like subglacial oceans), but the statistical weight of finding them is not uniform; on the present hypothesis, the maximum statistical weight will be located in the ring on the periphery of the Milky Way.

It is important to understand that while we do not doubt that ATCs will eventually have astro-engineering means to prevent any individual catastrophic occurrences like supernovae or GRBs,[6] we doubt that it can ever become worthwhile to manage and police the Galaxy in this manner. Energy/information and time cost are likely to remain too high in all epochs. On the contrary, it seems probable that any rational cost-benefit analysis would favor migration to the Galactic rim rather than the costly and risky ”policing” strategy.

Migration in physical space will be analogous to the prior migration of the bulk of civilization’s interests and pursuits from physical to digital space. This presents an additional factor helping explain Fermi’s paradox: advanced civilizations based on an optimized computronium infrastructure have little need for conversations with human-level individuals or even entire civilizations whose thought capacities are trillions of times less than their own (cf. Ćirković and Radujkov 2001). In contrast, they may have an interest in leaving our civilization and other ”late comers” to their own unique development path so as to increase the potential diversity of, and information content in the Galaxy. As emphasized by Bradbury (2001), this is due to the large phase space of what can be constructed using molecular nanotechnology and the di culties in proving that the computational architectures

[6] This could be achieved through technologies already envisaged, like stellar uplifting and long-term orbit modifications.

previously adopted to support advanced civilizations are, in fact, ”optimal”. ATCs may need less developed civilizations for the ”dumb luck” they may have in developing an unexplored quadrant of the phase space of what may be designed and assembled in support of the evolution of intelligence.

As noticed by Gould (1989), the normative concept of ”progress through conquest and displacement” is intimately linked with the Victorian ”chain of being” fallacy. According to this view, all lifeforms have their exact position in the chain ranging from the most primitive *Archaea* to the gentlemen with white hats doing a noble job of conquering savages all around the world. This view has been abandoned in practically all fields—except, ironically enough, SETI studies. In general, SETI is mostly in the same shape and with the same set of philosophical, methodological and technological guidelines, as it was in the time of its pioneers (Drake, Sagan, Shklovskii, Bracewell) in 1960s and 1970s.[7] In contrast, our views of astrophysics, biology, and especially, computer science-arguably the three key scientific disciplines for SETI-changed revolutionarily, to put it mildly, since that epoch. The present study is an attempt to break this mold and point serious modern alternatives to the old-fashioned SETI philosophy.

The present approach is similar to the one favored by Dyson (2003), who suggests searching for life at distant objects of the Solar System (and other planetary systems). Although Dyson only considers primitive life, this can be easily generalized to life of higher level of complexity and even intelligence.[8] In our view, the migration hypothesis can solve Fermi's paradox, since the truly advanced societies, i.e. those who survive the bottleneck presented by the threat of self-destruction through warfare or accident will tend to be located at the outskirts of the Milky Way, outside of the main thrust of SETI projects so far. The very same traits making ATCs capable of migrating and utilizing resources with high e ciency (compactness, high integration, etc.) will tend to make them systematically hard to detect from afar. This is in diametrical opposition to views of many early SETI researchers—recently brought to a sort of the logical extreme by Weinberger and Hartl (2002)—that ATCs will indulge in extravagant spending in order to achieve interstellar communication, even if only nominal. The same applies *mutatis mutandis* to the large-scale interstellar travel to diverse targets; the nature of the postbiological megatrajectory is not likely to include any gain from the scattering of pieces of an ATC all over the Galaxy.[9] One of the SETI pioneers, Ben-

[7]For a prototype ”Galactic Club” optimistic—or naive—view of that epoch, exactly 30 years old, see Bracewell (1975). Early SETI literature abounds in such enthusiasm.

[8]Parenthetically, the same line of reasoning suggests that the search for extraterrestrial artifacts (SETA) should concentrate to the outskirts of the Solar System, notably the Kuiper belt objects and even Oort cloud comets. Low-profile digital approach would warrant maximization of the information processing for the hypothetical ATC probes also.

[9]This is related to the possibility of postbiological ATCs being what Bradbury (2001)

jamin Zuckerman proposed in 1985 that stellar evolution is an important motivation for civilizations to undertake interstellar migrations (Zuckerman 1985). Although arguments presented in that study seem outdated in many respects, it is significant that the migration idea has been presented even in the context of classical SETI studies, biological evolution and pre-digital perspective. It seems implausible that any but the most extreme conservative societies would opt to wait to be forced to migration by slow and easily predictable process like their star leaving the Main Sequence.

Not surprisingly, some of the ideas presented here have been forefathered in a loose form within SF discourse. Karl Schroeder in ”Permanence” not only formulated an unrelated answer to Fermi’s question, but, more pertinently, envisaged the entire Galaxy-wide ecosystem based on brown dwarfs (and halo population in general) and low-temperature environment (Schroeder 2002; see also Ćirković 2005). The idea of a new megatrajectory comprising ”mainstream” evolution of ATCs and containing the theoretical explanation of Fermi’s paradox has been profoundly and beautifully discussed by Stanislaw Lem (especially 1987, but see also Lem 1984). Most strikingly, the idea of ATCs 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 true ATCs inhabiting regions at the boundary of the disk and high above the Galactic plane. This is roughly analogous to the low-temperature regions we outlined as the most probable Galactic technological zone.

5 Discussion: failure of the conventional SETI wisdom

There is no meaningful scientific hypothesis for resolving Fermi’s paradox—or, indeed, any problem of importance in science—without a set of assumptions. In building of the migrational solution to Fermi’s puzzle, we have relied on the following set of assumptions:

1. The Copernican principle continues to hold in astrobiology, i.e. there is nothing special about the Earth and the Solar System when considerations of life, intelligent observers or ATCs are made.

dubs ”distributed replicated intelligence[s]”. Although elaboration of this admittedly speculative concept is far beyond the scope of the present study, it is enough to mention the intuitively clear picture in which, once a threshold of complexity is reached, it is very hard to separate an intelligent part from the whole of the ATC to any distance making the latency problems due to the finite speed of light important. This may pose problems for anything but the simplest, low-profile, interstellar drones or passive inscribed matter packages.

2. Laws of physics (as applied to the classical computation theory and astrophysics) are universally valid.

3. Naturalistic explanations for the origin of life, intelligence and ATCs are valid.

4. The Milky Way galaxy exhibits well-established gradients of both baryonic matter density and equilibrium radiation field temperature.

5. Habitable planets occur naturally only within GHZ (which evolves in a manner roughly understood), but ATCs are not in any way limited to this region.

6. We assume **local** influences both of and on ATCs. Thus, we disregard overly speculative ideas about wormholes, ”basement universes”, etc. Interstellar travel is feasible, but is bound to be slow and expensive (for anything larger than nanomachines) at all epochs.

7. Astro-engineering on the scales significantly larger than the scale of a typical planetary system (e.g., on the pc-scale and above) will remain di cult and expensive at all epochs and for all ATCs.

8. ATCs will tend to maximize e ciency of information-processing, no matter how heterogeneous their biological, cultural, etc. structures and evolutionary pathways are.

These assumptions are, of course, of varying validity and importance. Items 1, 2, and 3 are essential methodological guidelines of the entire scientific endeavor; although 1 has recently become controversial within ”rare Earth” theorists, there is still no compelling reasons for relinquishing it. Assumption 4 is an empirical fact, and 5 is quite close to it. Assumptions 6 and 7 are conservative extrapolations of our limited scientific and technological perspective, but in our view should be retained until the contrary positions can be verified. In particular, absence of the Galaxy-size astro-engineering e ects in external galaxies (cf. Annis 1999b) strongly supports the assumption 7.

Most controversial, of course, is the culturological (or meta-ethical) assumption 8. One way to justify it is to observe the alternative long-term strategies in a given cosmological setting. Ultimately, ATCs will face the limits of cosmology and fundamental physics (Ćirković 2004c; Adams and Laughlin 1997); their vastly improved predicting capacities will enable them to obtain high-resolution models of such situations far in advance. Two limits seem reasonable: evolving into either pure pleasure seeking and hedonism (a ”Roman empire” analogue) or onto a pathway toward the greatest accomplishments possible along their individual development vector (a ”Greek Olympics” analogue). In either situation they will seek the greatest computational capacity and e ciency possible to support these activities.

We wish to re-emphasize the absence of exotic physics or inconceivably advanced technology in our analysis. Its central piece, the Brillouin inequality is valid for classical computation. If much discussed (in theory) quantum computation becomes practical possibility, it might not be bound by it (although an analogous constraint, Margolus-Levitin bound might step in its place; cf. Margolus and Levitin 1998). On the more exotic/SF side of the story, one might imagine creating wormholes to non-local sources of usable energy, or even entire "basement universes" envisaged by Linde (1990, 1992; see also Garriga et al. 2000).

The migration hypothesis smoothly joins with the global catastrophic solutions, such as those proposed by Clarke (1981) and Annis (1999a; see also Norris 2000). In those scenarios, there is a *global regulation mechanism* for preventing the formation of complex life forms and technological societies early in the history of the Galaxy. Such a global mechanism could have the physical form of γ-ray bursts, if it can be shown that they exhibit su cient lethality to cause mass biological extinctions over a large part of the volume of the Galactic habitable zone (Scalo and Wheeler 2002; see also Thorsett 1995; Melott et al. 2004). However, since the regulation mechanism exhibits secular evolution, with the rate of catastrophic events decreasing with time, at some point the astrobiological evolution of the Galaxy will experience a change of regime. As long as the rate of catastrophic events is high, there is a sort of quasi-equilibrium state between the natural tendency of life to spread, diversify, and complexify, and the rate of destruction and extinctions. When the rate becomes lower than some threshold value, intelligent and space-faring species can arise in the interval between the two extinctions and make themselves immune (presumably through technological means) to further extinctions, and spread among the stars. The migration hypothesis complements such catastrophic solutions to Fermi's puzzle, since it adds another layer to the "Great Filter" (Hanson 1998) explaining the absence of ATCs or their manifestations. Annis' and related hypotheses suggest that ATCs are both rarer and younger than we would naively expect based on uncritical gradualism; the migration hypothesis presented here indicates that even those which exist at present would be hard to detect due to their peripheral distribution, as well as other di culties related to their postbiological evolution.

An objection that the proposed solution violates Occam's razor must be considered. As is rather well-known, parsimony, or Occam's razor, embodies an important logical principle when properly applied. William of Occam a 14th century English Franciscan, strongly espoused nominalism against the Platonic concept of ideal types as entities in a realm higher than material existence (a viewpoint conventionally known as realism). Occam devised his famous motto, *non sunt multiplicanda entia praeter necessitatem* (entities are not to be multiplied beyond necessity), as a weapon in this philosophical battle—an argument against the existence of an ideal Platonic realm (for nominalists regard names of categories only as mental abstractions from material objects, and not as descriptions of higher realities, requiring an additional set of unobserved ideal entities, or essences). Occam's razor, in its legitimate application, therefore operates as a logical principle about the complexity of an argument, not as an empirical claim that nature must be maximally simple. It is exactly this, often underappreciated point, which makes the present solution to Fermi's paradox actually simpler than most of the alternatives. Consider, for instance, the hypothesis that a hundred prospective (independently arising) ATCs randomly distributed over the Milky Way disk destroyed themselves through internal warfare before leaving their home planets. It is—apart from the appeal to a mystical and universal *fatum*—an excessively complex hypothesis, relying on explanation of observed "Great Silence" through a hundred both logically and spatio-temporally disjoint causes. Contrariwise, the migration hypothesis proposed here suggests that a fraction of these civilizations will, upon surviving the filter of natural and artificial catastrophes, essentially drop out of sight through optimization of computing resources (implying preferred peripheral distribution in the Galaxy, not wasting energy on ine cient communication, etc.). This can be, in turn, reduced to a small number of causes, essentially those presented as the assumptions 1–8 above.

Once adopted as a viable solution to Fermi's paradox, the migration hypothesis presented here has both theoretical and practical consequences. First of all, inconvenient location of most of ATCs as observed from the Solar system's position coupled with realization that distinguishing signal from noise is much harder than usually thought (Lachmann et al. 2004) and may even be completely substituted by inscribed-matter messages (Rose and Wright 2004) are su cient to explain the lack of results in SETI projects so far. Some of the SETI pioneers have been very well aware of this and warned about it (notably Sagan 1975); these cautious voices have been consistently downplayed by the SETI community. All in all, we conclude that the conventional radio SETI assuming beamed broadcasts from targets—selected exclusively on the basis of the old-fashioned biological paradigm—within Solar vicinity (e.g. Turnbull and Tarter 2003) is ill-founded and has minuscule chances of success on the present hypothesis. *It is a clear and testable prediction of the present hypothesis that the undergoing SETI experiments using this conservative approach will yield only negative results.*

The entire picture sketched in the present study undermines the prevailing SETI philosophy. Outward migration of advanced technological species should be taken into account in future practical SETI projects. Given the likely distances of an ATCs that began migration tens of millions to billions of years ago (Lineweaver 2001), they are not likely to know of our development. While their observational capabilities probably allow them to observe the Solar System, they are looking at it before civilization developed. It is doubtful, to say at least, that they would waste resources sending messages to planetary systems possessing life, but quite uncertain (in light of the biological contingency) to develop a technological civilization. Dolphins and whales are quite intelligent and possibly even human-level conscious (e.g. Browne 2004), but they do not have the ability to detect signals from ATCs, and it is uncertain, to say at least, that they will ever evolve such a capacity. By a mirror-image of such position, unless one has concrete evidence of an ATC at a given locale it would be wasteful to direct SETI resources towards them. Ironically enough, this can often a rationale to some of the SETI skeptics, but based on the di erent overall astrobiological picture and with di erent practical consequences.

While fully recognizing that patience is a necessary element in any search, cosmic or else, we still wish to argue 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 (META, ARGUS, Phoenix, SERENDIP/Southern SERENDIP, etc.), notably those conveyed by NASA and the SETI Institute, is fundamentally flawed. This is emphatically **not** due to the real lack of targets, us being alone in the Galaxy, as contact-pessimists in the mold of Tipler or Mayr have argued. Quite contrary, it is due to real physical reasons underlying flaws in the conventional SETI wisdom: in a sense the problem has nothing to do with the universe itself, and everything to do with our ignorance and prejudices. In this special sense, the flaws in the currently prevailing views on SETI is much less excusable.[10]

Instead, much stronger emphasis on the ATC *manifestations* is the only serious recourse of practical SETI. Even if they are not actively communicating with us that does not imply that we cannot detect them and their astro-engineering activities (cf. Freitas 1985). Their detection signatures may be much older than their communication signatures. Unless ATCs 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. The same applies to other un-natural e ects, like the 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). Search for mega-projects such as Dyson shells, Jupiter Brains or stellar engines

[10]It is not just the present hypothesis which leads to such a conclusion. Different views on the evolution of ATCs, not based on the Intelligence Principle and the digital perspective, lead to the same general idea. For example, this applies to the ingenious idea that ATCs will transfer their cognition into their environment (Karl Schroeder, private communication), following recent studies on the distributed natural cognition (e.g. Hutchins 1996). In these, as in other suggested lines of "mainstream" development of ATCs, the approaches currently favored by SETI projects will be fundamentally misguided, i.e. ATCs remain undetectable by such approaches.

are most likely to be successful in the entire spectrum of SETI activities (Slysh 1985; Jugaku, Noguchi, and Nishimura 1995; Jugaku and Nishimura 2003). Ironically enough, surveys in the infrared have been proposed by one of the pioneers of radio-astronomy, Nobel-prize winner Charles H. Townes, although on somewhat di erent grounds (Townes 1983). Bold and unconventional studies, such as Harris', Arnold's, Slysh's, or survey of Jugaku et al., represent still a small minority of the overall SETI research. We dare suggest that there is no real scientific reason for such situation: instead, it occurs due to excessive conservativeness, inertia of thought, overawe of "founding fathers", or some combination of the three. The unconventional approach with emphasis on search for ATCs' manifestations would lose nothing of the advantages of conventional SETI before detection (e.g. Tough 1998), but the gains could be enormous.

Of course, even those projects or proposals put forward so far are limited in the sense of being often too conservative with respect to the full range of parameters. For instance, the controlling parameter for detection of a Dyson shell is, ultimately, its temperature (the di erences in the intrinsic stellar output can be neglected in the first approximation). The searches thus far relied on the original Dyson's proposal that the shell would be the size of Earth's orbit around the Sun, and that its working temperature would, thus, be close to the temperature of a solid body at 1 AU from a G2 dwarf. Thus, the expected infrared excess from a partial (incomplete) Dyson shell could be expected at ~ 10 μm, and the di erence between the infrared K band and the magnitude at 12 μm could be used for screening of possible candidates (Jugaku et al. 1995). However, from a postbiological perspective this is quite wasteful, as elaborated above, and a natural follow-up could consist of surveys at ~ 100 μm, which have not been performed so far. Coincidentally, this lowering of the external shell temperature is also in agreement with the study of Badescu and Cathcart (2000) on the e ciency of extracting work from the stellar radiation energy.

The hypothesis presented here is falsifiable *inter alia* by extragalactic SETI observations. Extragalactic SETI has not been considered very seriously so far (for notable exceptions see Wesson 1990; Annis 1999b). The reason is, perhaps, the same old comforting prejudice that we should expect specific (and most conveniently radio) signals. Since these are not likely forthcoming over intergalactic distances (and two-way communication desired by SETI pioneers is senseless here in principle), there is no point in even thinking seriously about extragalactic SETI. From the preceding, it is clear how systematically fallacious such a view is: when we remove the cozy assumption of specific SETI signals (together with the second-order assumption of their radio nature), this view collapses. On the contrary, extragalactic SETI would enable us to probe enormously larger part of physical space as well as the space of possible evolutionary histories of ATCs. (Of course, part of what we get ensemble-wise we loose time- and resolution-wise.) In fact, the definition of Kardashev's Type III civilization should prompt us to consider it more carefully, at least for a sample of nearby galaxies, visible at epochs significantly closer to us than the 1.8 Gyr di erence between the average of Lineweaver (2001) and the age of Earth (Allègre et al. 1995). In fact, it could be argued (although it is beyond the scope of the present study) that the null result of extragalactic SETI observations so far represents a strong argument against the viability of Kardashev's Type III civilizations. While it remains a possibility, in the formal sense of being in agreement with the known laws of physics, it seems that the type of pan-galactic civilization as envisaged by Kardashev and other early SETI pioneers is either (i) much more di cult (suggesting that the sample of $\sim 10^4$ normal spiral galaxies close enough and observed in high enough detail is simply too small to detect even a single Type III civilization), or (ii) simply not worth striving to. (Another argument to the same e ect, based on the observation-selection e ects is presented in Ćirković (2006).) In contrast, the concept of spatially smaller, compact, e cient ATCs motivated by a convergent set of economic, ecological and/or ethical premises, inhabiting fringes of the luminous matter distribution presents to us more plausible alternative to the conventional Type III picture. This will remain valid even if (for some entirely di erent reason) the present hypothesis could not entirely account for Fermi's paradox in the Milky Way. The true test here would be to detect signs of astro-engineering e orts at the outskirts of nearby spiral galaxies (i.e. those which are seen at about the same epoch as the Milky Way is currently in), and in their immediate intergalactic vicinity. Observations of the edges of spiral galaxies are notoriously di cult (e.g. Bland-Hawthorn, Freeman, and Quinn 1997), but they are rapidly improving. It is quite conceivable that they will give us the first hint about the generic fate of advanced intelligent communities.

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