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Galactic exploration by directed self-replicating probes, and its implications for the Fermi paradox

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Abstract: This paper proposes a long-term scheme for robotic exploration of the galaxy, and then considers the implications in terms of the 'Fermi paradox' and our search for extraterrestrial intelligence (ETI). We discuss the 'Galactic ecology' of civilizations in terms of the parameters T (time between ET civilizations arising) and L, the lifetime of these civilizations. Six different regions are described.

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Introduction

The proposal to explore the Galaxy by self-replicating probes goes back at least as far as Freitas (1980a) and Tipler (1980). Numerous criticisms have been made, notably by Sagan and Newman (1983). A recent paper (Wiley 2012) reconsiders the topic, and finds some of these criticisms without much merit. This paper outlines in more detail one exploration scheme and its benefits, and then considers the implication for the galactic 'ecology' of intelligent species.

Exploration of the Galaxy by self-replicating probes

Our starting point is as in Freitas (1980b) and Tipler (1980). This relies on two technologies, which we do not have at present, but which it is reasonable to suppose we will attain within the next few hundred years:

(T1) A propulsion system capable of sending probes to nearby stars, at say $0.01c$.

(T2) An AI system which, in total, is able, with the resources found in most star systems, of replicating itself.

Propulsion systems. Although no existing system can reach these speeds, various proposals for 100 year probes to Alpha Centauri have been made, such as Project Daedalus. A speed of $0.01c$ does not seem unduly optimistic, and in fact many proposals for galactic exploration, such as Bjørk (2007), consider probes which travel at $0.1c$.

AI systems Again, we do not have self-replicating systems at present, and what such a system would be like must rely largely on conjecture. In this context, note the following remark in Wiley (2012):

> *One point we take issue which is an inherent and frequently unconscious biological bias that pervades consideration of computerized intelligence, including self-replicating space probes (SRPs).*

A common tendency has been to imagine a self-replicating machine as being rather like a bacterium: that is a single machine which (somehow, almost magically) is able to move around in its environment and replicate itself. If we start with present technology, we are forced to imagine something rather different. The system as a whole might consist of three parts:

(A) A number of robots and probes, of several different types, which are together capable of exploring a Solar System and gathering resources (metals, volatiles, etc).

(B) A 'slow assembler' which would be able to refine these materials into components, which would make the final factory (C).

(C) A large-scale factory, or collection of factories, which would be able to manufacture copies of (A) and (B), as well as additional surveying and communication devices.

The payload of the probe would consist of (A + B), together with enough raw materials (fuel, etc.) to get started in the new system. Once (C) was made, resources would be gathered for as long as was necessary, and a number of probes would then be sent to nearby stars. If we take this view, then a 'SRP' would not be a single machine, but rather a collection of different machines with an overall capability of replication.

See Freitas (1980b) for a much more detailed description of such a probe, with the probe (A + B) plus the fuel for the voyage having a mass of of around 10^{10} kg. The factory described there only makes one new probe every 500 years, but (see Section 7.1) using a longer period for the initial construction gives a larger factory that can create 1000 new probes in 1500–2000 years. For simplicity I will take the reproduction time, between the arrival of the initial probe in a star system, and the completed factory (C) sending out new probes, to be $T_R = 1000$.

The AI needed for such a system far exceeds what is possible at present. However, while the kinds of decisions necessary for the AI (e.g. 'what kind of material is present in this asteroid?', 'can it be transported to the factory?') would require a very high level of skill, this would be within fairly narrow parameters, and a human level of overall initiative and judgement would not be required. Even if machines with a human intelligence can be constructed, it might be desirable to limit the intelligence of the SRPs.

As Tipler (1980) notes, there are reasons other than stellar exploration to develop these technologies. Progress in AI has been far slower than supposed by early optimists, but it still seems reasonable to suppose that, within a few hundred years, we will be able to build such SRPs. The development of such machines would, at least for a while, introduce an age of plenty, since it would open up the resources of the Solar System for our exploitation. Some idealistic individuals or groups might then be willing to invest the resources in making a number of the probes (A + B), and send them to nearby stars. (See Mathews 2011 for another proposal to explore the galaxy by SRPs.)

Exploration strategy

I now propose a scheme for galactic exploration, assuming that we do develop the technologies (T1) and (T2) described above. The first step would be to send probes to the 10–100 nearest stars, which are all within about 20 ly of Earth. (Long before the start of such a mission we will have very good data on the planetary systems of these stars.) The probes would arrive at their destinations 400–2000 years after the mission start. They would remain in radio contact with Earth (with a time lag of 40 years or less), would report on their discoveries, and would be able to receive updates on strategy. (Among the exploration devices (A) would be systems able to transmit and receive narrow band radio or laser communication over a distance of say 100 ly.)

I will call the initial star systems Level 1 'colonies', though there is no suggestion that they would have a human population. After the construction of the factory (C) on a Level 1 colony, the colony would send out SRPs (let us say about 1000–10 000) to create colonies at 'Level 2'. I have suggested an initial 'hop size' of 10–20 ly, since the number of probes that could be sent out from our Solar System might be limited by resource constraints. However, once a colony at Level 1 or higher had a working factory, there would be no such limit on the number of probes that could be sent out, and it would be sensible to send as many as was necessary to explore every star system within the second 'maximum hop size'. There are about 15 000 stars within 100 ly of Earth, so with some useful duplication the Level 1 systems would together be able to send probes to every star in this region.

The maximum hop size h_m would be the greatest distance such a probe could be sent with a probability greater than 90% of arriving. I will take $h_m = 100$; this also needs to be less than the maximum distance for radio or laser communication, but this is much greater than 100 ly.

The probes from the Level 2 colonies would then establish Level 3 colonies and so on. Each colony at Level n would report back to its Level $n-1$ ancestor, and receive updating instructions from it. While it would be desirable for the Level 1 colonies to produce many probes, as the radius of the exploration sphere became larger, and so the curvature of its surface became less, fewer new probes per colony would be needed.

Within a few thousand years of the mission start, our descendants on earth (if they still existed) would be receiving a flood of information from the exploration of hundreds of star systems. The Great Pyramid was built around 4500 years ago; 4500 years after its start, the mission would be well under way, and would have given us detailed data on every star system within about 30 ly of Earth.

The overall mission would continue until the planetary system of every star in the galaxy had been explored. Let $v_p = 0.01c$ be the speed of the probes, and v_e be the propagation speed of the exploration front. Then

$$v_e = \frac{h_m}{T_R + h_m/v_p} = v_p \frac{1}{1 + v_p T_R / h_m}.$$

So $T_R = 1000$ and $h_m = 100$ give $v_e/v_p = 10/11$, the exploration front travels at nearly the same speed as the probes, and the total time to explore the galaxy is around 10^7 years. This compares with exploration times of the order of 10^8 years given by Bjørk (2007), using probes that travel at $0.1c$, but do not replicate.

Refinements

Although strategy is as above, it is necessary to consider a number of refinements.

(a) *Resource use within system.* The best place for the construction of the factory (C) might be the moons of a planet in the outer reaches of the star system. Assuming a mass of 10^{10} kg for the probes (A + B) and fuel, the construction of (C) plus say 10 000 probes would use at most a handful of minor planets and comets. This would leave plenty of material behind, even on the Level 1 colonies, and it would not be necessary to to 'strip mine' the Galaxy in order to complete this exploration. One would only need a few probes per star – one plus a margin for accidents.

(b) *Systems with planets with life.* In systems with planets with complex life, a different procedure should be followed. Two possibilities would be:

(i) Report, build a factory (C), explore the system thoroughly, and then await instructions from Earth.

(ii) Report, do nothing, and await instructions from Earth.

The first- and second-level probes would provide enough data to refine this strategy at an early stage of the overall mission. In the very unlikely event that more than 90% of systems have planets with complex life, a modification of (ii) would be needed so that a reasonable proportion of colonies did send out probes.

(c) *Extinction of the human race.* Once set in motion, the exploration could continue without any further human intervention. However, this proposal envisions continued interaction and direction: Earth would receive data from the probes, and based on this revised instructions on exploration (as well as possible system upgrades) would be sent out. What however if humanity becomes extinct, or just loses interest in the mission? There are many possible procedures, which could

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be followed, of which the simplest are: (i) continue anyway, (ii) abandon further exploration. For simplicity I propose (ii), and suggest that every 100 years the Level 1 colonies would ask Earth “Shall we continue?” If 1000 years went by with no positive response, the project would be mothballed, and instructions would be sent through the communication tree that no further SRPs were to be built.

(d) *Communication and direction.* A key part of this exploration scheme is that the SRPs are not autonomous, but that the whole exploration process is directed, ultimately from Earth. The first requirement here is that Level n colonies be able to communicate (over a distance of say 100 ly) with their Level $n-1$ ancestors. Even with the present technology, we could build transmitters and receivers capable of working over these distances.

While all the Level 1 colonies would send out probes, this would not be necessary for higher level colonies, and stars could be divided into two groups. For the first, ‘end nodes’, a factory (C) would be built, the star system explored, but no probes would be sent out. The second, ‘branch nodes’ would send out probes. Among the pieces of infrastructure built in each colony would be telescopes to survey the stellar neighbourhood, and using this data, nearby Level n colonies would coordinate the exploration of their neighbourhoods. (Nearby colonies would be 10–100 ly apart, so communication time would be small compared with the time to build probes, or for the journeys.) Although the algorithm to coordinate this process may appear complicated, it is well within our current capabilities – unlike the AI needed for robotic exploration of a planetary system

(e) *Mission creep and machine mutation.* A widely voiced concern with SRPs has been that they might mutate, run amok and eat up the Galaxy – see Sagan and Newman (1983). However, Wiley (2012) argues that it should be possible to build in sufficient reliability to avoid this outcome – note also his comment above on inappropriate biological analogies. In the exploration scheme proposed here about 1000 generations would be needed to explore the Galaxy – fewer if hops longer than 100 ly are feasible. The total number of replicators (C) built would be of the same order as the number of stars in the Galaxy, that is about 4×10^{11}. Wiley (2012) points out that this is much less than the number of cell divisions within a human lifetime, which is of the order of 10^{16}.

If necessary, further steps could be taken to reduce the overall risk. In the initial stages of the exploration we would want every planetary system to be explored carefully. However, it seems likely that after the first million or so systems had been explored, we would have a good understanding of the processes underlying the formation and development of planetary systems, and might only be interested in those systems which had life, complex life or other exceptional features. The later phases of the exploration could therefore proceed as follows. Each ‘branch node’ would first send out about ten new full probes (A + B) to establish the next generation of colonies. Next, it would send out reduced probes, just consisting of (A), to all the stars in its exploration patch. These would explore the target system, and report back to the sending branch node. Without the reproductive capacity (B), these probes would ultimately run out of fuel and become inactive. A full probe (A + B) would then be sent to any system that merited further attention. Assuming that ‘interesting’ systems are rare, this modification would reduce the number of full replications by a factor of 1000 or so. Further safety mechanisms could also be built in, such as deeply embedded software constraints on the total number of probes that the factories (C) could make, or on the total number of permitted generations.

(f) *Crossing large spaces and percolation.* Landis (1998) has suggested a percolation model for the spread of a species through the Galaxy, and showed that in some cases this leads to large vacant (unexplored) regions. However, bond percolation on the lattice is a poor model for the type of exploration proposed above, since each ‘branch node’ would send out rather more than five probes. Further, the communication envisaged between colonies would mean that colonies would become aware of interstellar voids (with no or few stars), and regions that, perhaps because of the failure of a number of probes, were remaining unexplored. They could then send additional probes to explore these regions. If we consider the mathematical graph whose vertices are the stars, and join by edges all pairs of stars within 100 ly., then the exploration scheme proposed here will explore all stars in the connected component containing our sun, and it seems overwhelmingly likely that this spans most of the Galaxy.

(g) *System updates.* We would want to be able to incorporate updates into the systems (A, B and C). It is possible that this could be done by radio, but the available bandwidth might be too small for the necessary amount of data. One can imagine a system of ‘fast packets’ – small probes carrying data, which travel at say $0.1c$ between colonies with the infrastructure to send and receive them. However, one disadvantage of allowing such updates is that it would make the colonies more vulnerable to mutations or computer viruses.

(h) *Contact with extraterrestrial intelligence (ETI).* Detailed thought would need to be given on what course of action should be taken if either ETI were found, or traces of them. There would be time to refine strategies in the first few millenia of the mission, as data on frequency and type of life in other star systems accumulated. The number of possible actions the probes could take is large, and a full discussion of this is beyond the scope of this paper. The simplest (but not the quickest) option would be for the the probe to report back, and take no further action until instructed.

Implications for SETI and Fermi’s question

Let us now make the hypothesis (H) that the technolgies (T1) and (T2) can be attained, and explore the consequences. The exploration scheme outlined above, using these technologies is one which, if it survives long enough, the human race might adopt – no doubt with a number of improvements. The payoff is that with a relatively low initial cost our descendants would obtain detailed data about every star system in the Galaxy. In particular, they would learn how many planets support life, what kind of life it is, and just how rare complex or intelligent life is.

If there have been technological ETI in the Galaxy, then they would also have had this option. So – this is Fermi's question "Where are they?" (This is often called the 'Fermi paradox', but it is only a paradox if one begins with the assumption that intelligent life is common. In fact, we have no information on this).

Let us recall the Drake equation, slightly modified for our purposes:

$$N = R^* \cdot f_{\rm p} \cdot n_{\rm e} \cdot f_{\rm l} \cdot f_{\rm ci} \cdot L;$$

here N is the number of existing civilizations sending out SRPs, R^* is the rate of star formation per year in the Galaxy, $f_{\rm p}$ is the fraction of those stars that have planets, $n_{\rm e}$ is the average number of planets that can potentially support life per star that has planets, $f_{\rm l}$ is the fraction of these that develop life, $f_{\rm ci}$ is the fraction of these that develop civilizations that send out SRPs, and L is the average lifetime of such civilizations. This lifetime is the time that either the civilization itself, or its SRPs, remain active. (From now on, I will use the term 'civilization' for 'civilizations that send out SRPs'.)

We do have estimates of at least the order of magnitude of some of the early terms in this expression: for example $R^* \simeq 7$, and data from the Kepler satellite suggests that $f_{\rm p} \simeq 0.5$, while $n_{\rm e}$ is quite small. (Out of about 10 000 systems surveyed, only a handful have planets which look really promising from the point of finding earthlike life.) At present $f_{\rm l}$ and $f_{\rm ci}$ are utterly unknown, though estimates of $f_{\rm l}$ may at some point become available via spectroscopic search for oxygen.

I have given the Drake equation in a simple form. A more realistic equation would take account of randomness, and the fact that these factors are not constant in time – see for example Glade *et al.* (2012). However, the uncertainty in our knowledge of the parameters in the equation is so great that these refinements seem to the author of this article to add little to what can be achieved with a simple 'back of an envelope' calculation.

Let us now set

$$\lambda = R^* \cdot f_{\rm p} \cdot n_{\rm e} \cdot f_{\rm l} \cdot f_{\rm ci} = N/L;$$

so that λ is the number of civilizations arising per year in the Galaxy. As an upper bound, if $f_{\rm l} = f_{\rm ci} = 1$ (surely very unlikely) and $n_{\rm e} = 0.03$, we obtain $\lambda \leqslant 0.1$. Let us set $T = 1/\lambda$ to be the average length of time in years between successive civilizations arising in the Galaxy; the estimates above suggest it is unlikely that $T < 10$.

Let us now consider the 'galactic ecology' in terms of the two parameters $T = \lambda^{-1}$ and L. Although a better model would allow for randomness of L, a simple mean model already yields useful insights. Figure 1 shows a plot of log L against log T. Since the Galaxy is about 10^{10}-years-old, we have $\log L \leqslant 10$, and it seems reasonable to take also $\log L \geqslant 2$. The estimates above give $\log T \geqslant 1$. We have no upper bound on T: it is not legitimate to use the Copernican principle to assert that because there is at least one potential civilization in the Galaxy (us) then $T \leqslant L$. Civilizations might only arise in one Galaxy in a billion, and those that arose would still observe themselves to be in a Galaxy. In the diagram I take $1 \leqslant \log T \leqslant 14$.

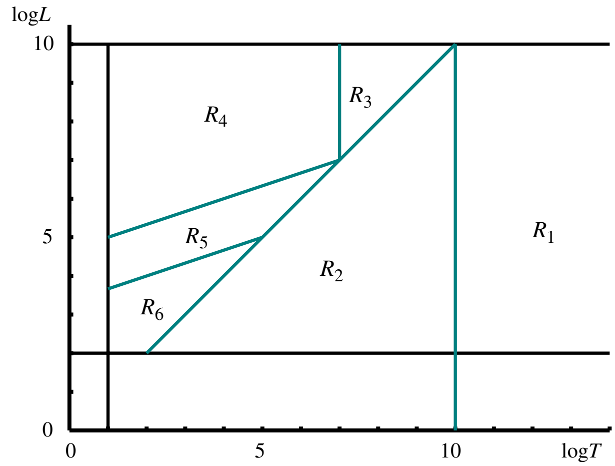

Fig. 1 Galactic ecology parameter space.

Let us now consider the various regions of the diagram. The descriptive statements for the regions apply to typical points in the region – naturally these will become weaker if the point (log T, log L) is close to the boundary between regions.

(R_1) ('Alone') If $\log T > 10$ then probably no other civilization has arisen in the Galaxy. (A more accurate statement would be that the mean number of such civilizations is less than 1.)

(R_2) ('Pompeii') If $\log T \leqslant 10$ and $\log L < \log T$ then $N < 1$ and there is no other civilization existing now. However, $10^{10}/T \geqslant 1$ civilizations have existed, and their ruins await discovery – except that we may not last long enough to find them.

(R_3) ('Galactic hegemony') $\log L \geqslant \log T \geqslant 7$. We have seen above that in a time of about $t_{\rm e} = 10^7$ years a civilization can explore the Galaxy via SRPs. If this civilization lasts longer than that, and no other civilization arises during the exploration period, then the exploring civilization would attain 'galactic hegemony'. It would know of the existence of any other civilization that might arise, and would be able to control their growth and activities.

In the remaining parts of the diagram there are many civilizations in the Galaxy. Assume for simplicity that the Galaxy is a uniform disc of thickness $h_{\rm G} = 1000$ ly and radius $R_{\rm G} = 50\,000$ ly, that civilizations arise uniformly in the Galaxy at rate λ, start exploring the Galaxy by SRPs with an exploration speed of $v_{\rm e} = 0.01c$, and continue to do so until the civilization (and the SRPs) end L years after the start of the exploration. (A more detailed analysis would take account of the likely existence of a galactic habitable zone described by Lineweaver *et al.* (2004).)

If a civilization starts at position x_0 and time t_0, then the space-time region explored will be the cone consisting of the points $(x,\ t)$ such that $t_0 \leqslant t \leqslant t_0 + L$, and $|x - x0| \leqslant v_{\rm e} t$. (This neglects for the moment the hard question of interaction

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between civilizations.) A point (x, t) will be explored by some civilization if any civilization starts in the space-time region

$$C_P(x, t) = \{(y, t-s) : 0 \leqslant s \leqslant L, |x-y| \leqslant v_e s\}.$$

The space volume explored will initially grow cubically with L, but with a transition to quadratic growth at the time $t_w = h_G/v_e$ taken to cross the thickness of the galactic disc. We have $t_w = 10^5$, and it turns out that it is the case $L \geqslant t_w$ which is of interest. The (space-time) volume of $C_P(x, t)$ is of the order of

$$W_C = \frac{\pi}{3} h_G v_e^2 L^3;$$

the exact value will depend on its location within the Galaxy. The volume of the Galaxy is $V_G = \pi R_G^2 h_G$, and so the mean number of civilizations arising in the region $C_P(x, t)$ is

$$M = \frac{\lambda W_C}{V_G} = \lambda \frac{h_G v_e^2 L^3}{3 h_G R_G^2} = \frac{L^3}{T} \frac{v_e^2}{3 R_G^2}.$$

Taking $3R_G^2 = 7.5 \times 10^9 \simeq 10^{10}\ ly^3$, we have $M \geqslant 1$ when

$$3 \log L \geqslant 14 + \log T.$$

(Note that $\log T \geqslant 1$ then gives $L \geqslant t_w$.) If $M \gg 1$ then a typical space-time point in the Galaxy will lie in the exploration cone of many civilizations, and so these cones will cover most of the Galaxy, while if $M \ll 1$ then there will be substantial vacant unexplored regions.

(R_4) ('Multiple zones') In the region $3 \log L \geqslant 14 + \log T$, $\log T \leqslant 7$ we therefore expect that the galaxy will covered by the zones of control of more than civilization. How these civilizations might interact is considered briefly below.

If $3 \log L \leqslant 14 + \log T$ then civilizations are too rare and short-lived for their SRPs to cover the Galaxy, but we can still ask about their radio signals. Let us begin by considering the conditions for 2-way communication by radio with an ETI. The same analysis as with the SRPs applies in this case, but with v_e replaced by the speed of light $v_c = 1$. Assume for simplicity that the time between a civilization starting to send out radio transmissions and sending out SRPs is small, and that radio transmissions continue for the lifetime of a civilization. Then the mean number of civilization still extant whose broadcasts can be accessed at a point (t, x) will be

$$M' = \frac{L^3}{T} \frac{v_c^2}{3 R_G^2} = \frac{M}{v_e^2}.$$

Thus, $M' \geqslant 1$ if $3 \log L \geqslant 10 + \log T$. (If $\log T \geqslant 1$ then this condition gives $L \geqslant 10^{11/13} > 1000$, so the case when we need to consider zones with radius less than h_G does not arise.)

(R_5) ('2-way SETI') If $10 + \log T \leqslant 3 \log L \leqslant 14 + \log T$ and $\log T \geqslant 1$ then a typical point will be able to receive radio signals from a civilization which is still extant, but will not be visited by SRPs. There is therefore the possibility of 2-way communication by radio between two civilizations, possibly continuing until one becomes extinct. This is the situation envisaged in much of the early SETI literature.

(R_6) ('1-way SETI'). If $3 \log L \leqslant 10 + \log T$ and $\log T \geqslant 1$ then a typical point can only receive signals from extinct civilizations. A point (t, x) will be able to receive signals from a civilization if that civilization arose in the region

$$C_S(t, x) = \{(y, s) : t - |x-y| - L \leq st - |x-y|\}.$$

This has space-time volume LV_G, and so the mean number of such civilizations is $\lambda L V_G / V_G = L/T$. Thus, $L \geqslant T$ is (not surprisingly) also the condition for there to be some civilization in the Galaxy within our light cone.

The space of galactic ecologies is therefore divided into six regions. For regions R_1 and R_2 there is little more to be said, but some other cases deserve further attention.

In region R_4 a typical point in the Galaxy could be explored by SRPs from many civilizations, and it is necessary to consider how such civilizations might interact. One can identify three broad possibilities:

(i) No interaction, and mutual interpenetration between explored regions of different civilizations;
(ii) Civilizations establish boundaries between their different 'zones of control';
(iii) Civilizations (or their SRPs) engage in warfare.

In case (i) we would expect to see many probes within our Solar System, and our failure to do so tends towards excluding this possibility.

For case (ii), consider the arrival of an SRP from Civilization X in a star system already containing infrastructure built by Civilization Y. The probe would need to decelerate from $0.01c$, and this would require the expenditure of large amounts of energy over a significant period, making the arrival detectable by Y. On arrival the SRP would have limited fuel and resources, and could be quarantined or neutralized by Y. A (lengthy) period of negotiation might then lead to agreed boundaries between X and Y.

If negotiation failed then war might ensue, which is case (iii). In the case of all out war, constraints on the number of SRPs built would be dropped, and all available material would be used. If it is the case that the material in stars and gas giants is too tightly bound gravitationally to be used to make SRPs, then the effects of such a war on other star systems might not be detectable to us at present. However, two pieces of evidence support the conclusion that such a war has never occurred in our Galaxy. The first is that the Solar System has not been mined in this way. Second, if SRPs can only utilize smaller planets then the total mass usable for SRPs in a typical stellar system would be around 10^{22}–10^{23} kg. However, a protostellar nebula contains a mass of around 10^{30} kg, which is not so tightly bound gravitationally. Such nebulae would be major military prizes, and their continued existence in our Galaxy, as well as that of recently formed stars, suggests that our Galaxy has seen neither an all out war, nor an arms race. (This applies also to other galaxies.)

Conclusion

Under our hypothesis that the technologies (T1) and (T2) can be attained, consideration of the points above, and

Fig. 1, leads to three broad categories of answer to Fermi's question:

(F1) They have not visited us because they do not exist. (Regions R_1 and R_2.)

(F2) The 'zoo hypothesis': their probes are watching us now. (Regions R_3 and R_4.)

(F3) They have not visited us because civilizations are all too short-lived. (Regions R_5 and R_6).

Of these, possibility (F3) relies all *all* civilizations being short-lived, while the zoo hypothesis appears to be deeply unpopular. (partly I suspect because it compromises human dignity.) The analysis above reduces the force of some of the objections that have been made to the zoo hypothesis, since in both cases R_3 and R_4(ii) we would lie in the zone of control of just one ETI.

If we exclude (F2) and (F3), then we are left with (F1), to which there are no objections except that it is uninteresting. It is worth noting that while astronomers have frequently given rather large values to f_{ci} – typically in the range 0.01–0.1, many evolutionary biologists have been much more pessimistic. Even if one is not convinced by all the arguments in Ward and Brownlee 2000, it seems very possible that the development of intelligent life requires evolution to pass through several gateways, and hence that f_{ci} is very small.

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