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THE FERMI PARADOX: AN APPROACH BASED ON PERCOLATION THEORY

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Abstract

If even a very small fraction of the hundred billion stars in the galaxy are home to technological civilizations which colonize over interstellar distances, the entire galaxy could be completely colonized in a few million years. The absence of such extraterrestrial civilizations visiting Earth is the Fermi paradox.

A model for interstellar colonization is proposed using the assumption that there is a maximum distance over which direct interstellar colonization is feasable. Due to the time lag involved in interstellar communications, it is assumed that an interstellar colony will rapidly develop a culture independent of the civilization that originally settled it.

Any given colony will have a probability P of developing a colonizing civilization, and a probability (1-P) that it will develop a non-colonizing civilization. These assumptions lead to the colonization of the galaxy occuring as a percolation problem. In a percolation problem, there will be a critical value of the percolation probability, P_c. For $P<P_c$, colonization will always terminate after a finite number of colonies. Growth will occur in "clusters," with the outside of each cluster consisting of non-colonizing civilizations. For $P>P_c$, small uncolonized voids will exist, bounded by non-colonizing civilizations. For $P \approx P_c$, arbitrarily large filled regions exist, and also arbitrarily large empty regions.

1. Introduction

The galaxy contains roughly a hundred billion stars. If even a very small fraction of these have planets which develop technological civilizations, there must be a very large number of such civilizations. If any of these civilizations produce cultures which colonize over interstellar distances, even at a small fraction of the speed of light, the galaxy should have been completely colonized in no more than a few million years [1]. Since the galaxy is billions of years old, Earth should have been visited and colonized long ago. M.J. Fogg, for example, suggests that they should have already completed the expansion to fill the galaxy before the emergence of life from the ocean [2]. The absence of any evidence for such visits is the Fermi paradox. [A more proper name for this would be the Fermi-Hart paradox, since while Fermi is credited with first asking the question, Hart [1] was the first to do a rigorous analysis showing that the problem is not trivial, and also the first to publish his results].

Many proposals for solutions to the Fermi paradox exist, all of which are unsatisfactory in one way or another [3]. A bibliography of the discussion can be found in [4].

Proposed solutions to the Fermi paradox either deny the possibility of extraterrestrial civilizations [1, 5], an assumption as yet unwarranted, or accept the possibility of extraterrestrial technological civilizations and propose explanations for why such civilizations may nevertheless not have colonized the galaxy. Explanations include suggestions that such civilizations collapse or blow themselves up, run out of resources, choose not to colonize, or chose to colonize but leave us alone. The difficulty with all such explanations is that they must all assume an unwarranted uniformity of motive for extraterrestrial civilizations over extremely long periods of time. If even a single civilization choses to colonize the galaxy, the explanations fail. It is useful, therefore, to try to look for explanations of the Fermi paradox which do not rely on uniformity of motive.

I propose a model for the problem based on the assumption that long-term colonization of the galaxy proceeds via a "percolation" process similar to the percolation problem which is well studied in condensed-matter physics. Rather than assuming a uniformity of motive for extraterrestrial civilizations, the model assumes a wide variety of motives, with a mixture of civilizations interested in colonization and "stay at home" civilizations.

2. Assumptions

The analysis is based on two key assumptions. First, it is assumed that interstellar travel is possible, but difficult, and thus that there is a maximum distance over which colonies can be directly established. Hence, there are only a small number N of stars which are suitable for colonization and within reasonable travel distance of any given solar system. Any colonies farther away are settled as secondary colonies from other colonies. Second, any control of a colony by the parent civilization will at most be very weak, and the time scale for development of colonization capability by a colony is long; hence each colony develops its own culture which is independent of the culture of the civilization that originally settled it. I argue that these assumptions are reasonable in the light of what we currently know about possible technologies for interstellar travel at speeds far less than the speed of light.

Travel over interstellar distances is not forbidden by the laws of physics, and several methods have been proposed by which it may be accomplished. Since it is possible, given a large enough number of extraterrestrial civilizations, one or more would have certainly undertaken to do so, possibly for motives unknowable to us. Colonization will take an extremely long time, and will be very expensive. Freeman Dyson, for example, estimates the cost for one type of interstellar ship as being on the order of the Gross National Product, and the voyage time to be on the order of 200 years for a trip of 4 light years [6]. It is quite reasonable to suppose that not all civilizations will be interested in making such a large expendature for a payoff far in the future. Human society consists of a mixture of cultures which explore and colonize, sometimes over extremely large distances, and cultures which have no interest in doing so [7].

The many light-year distance between a "home" system and its colonies makes it almost certain that the colony will develop a culture and civilization of its own. Over the many hundreds of years needed for the colony culture to develop to the technology level needed for it to be able to build its own interstellar transports, the colony civilization will likely be entirely independent of the parent.

An additional assumption needed is that a colony cannot be established on an already colonized world. Given the enormous unlikelihood of being able to carry out an invasion over interstellar distances, this seems to be a good assumption.

The percolation rule is as follows: A culture may have a colonization drive, or may not. A civilization which has a drive to colonization will establish colonies on any stars within reach. If it does not have any unsettled stars within its colonization radius, however, it will of necessity develop into one without a colonization drive. Thus, any given colony will have a probability P that it develops a colonizing civilization, and a probability (1-P) that it will develop a non-colonizing civilization.

3. Percolation

The percolation problem is well studied in physics (see, for example, references [8] and [9]). In a percolation problem, there will be a critical value of the percolation probability, P_c, which will depend on the dimensionality of the space (in this case, 3) and the connectivity N. For $P<P_c$, colonization will always terminate after a finite number of colonies. Growth will occur in "clusters," with the outside of each cluster consisting of non-colonizing civilizations. For $P>P_c$, on the other hand, clusters will grow indefinitely to fill all of space. However, small voids will exist, bounded on the inside by non-colonizing civilizations. The probability of any given point being a isolated unoccupied point is P^N; probabilities of larger clusters of isolated points existing are proportional to higher powers of P. Finally, for critical percolation, $P \approx P_c$, clumps grow into fractal structures of irregular shape. Arbitrarily large filled regions exist, and also arbitrarily large empty regions.

Figure 1 shows a typical percolation result, in this case for a cubic array in three dimensions with N=6. For this array P_c=0.311; the simulation is for P=0.333, very slightly over critical.

The percolation explanation of the Fermi paradox therefore suggests that one of three cases explains why colonizing extraterrestrials have not visited the Earth: either $P<P_c$, and colonization stops rapidly; $P \approx P_c$, and uncolonized areas of arbitrarily large extent exist, in one of which the Earth is located; or $P>P_c$, and the Earth is located in one of many small unoccupied void.

Before making estimates for values of the critical parameters N and P, it should be first emphasized that the main features of the model as a percolation problem do not depend on the values of the parameters or the details of the assumptions.

A baseline assumption for colonization would be that stars are suitable for a colony only if they are of a spectral type not too different from the sun, say F8 through G9 main sequence, and not binaries. From the 1969 Gliese catalog, the set consists of five possible stars within a distance of 30 light years from the sun. A reasonable guess for N, then, might be 5.

There is no way at all of making a reliable estimate of the value of P. For our own civilization, it seems equally likely that we may destroy ourselves, fail to destroy ourselves but not expand into space, or continue expanding until interstellar colonization is possible. A guess of P=1/3 is as reasonable an estimate as any. Interestingly enough, these values for N and P result in a model of the galaxy as being very near critical, and thus with extremely large "colonized" regions and equally large "empty" regions.

More complex models of interstellar colonization can be made on the same principles, incorporating such elements as the random positions of stars, the boundaries of the galaxy, the possibility of multiple civilizations colonizing the same star, etc. In general, it is not expected that such more detailed models will change the overall features of the result, although the details such as critical probabilities, will certainly be model dependant.

4. Discussion

Like all discussions of the Fermi paradox, solutions based on a percolation approach are dependent on the validity of its assumptions. Until we have either explored the galaxy or contacted extraterrestrial civilizations, all such assumptions can be challanged, however, I argue that the assumptions used are reasonable, and that in any case the assumptions made here are less universal and restrictive than those required by other analyses of the paradox. Critical assumptions: (1) existance of a distance horizon, (2) no recolonization of already colonized stars by new civilizations, (3) no relationship between parent and daughter civilizations, (4) colonization only possible to a limited set of possible stars, with small number of candidate stars inside the horizon.

In addition to these assumptions, the model ignores stellar drift. The time scale for star positions to change is on the order of a million years. It is impossible to project the sociology of extraterrestrial civilizations for time scales on this order. It is reasonable to suggest that a civilization that has existed for millions of years without colonizing would be likely to have evolved into a stable civilization that has no imperative to do so.

Finally, why haven't we heard them (e.g., via radio), or met their self-reproducing probes [5]?

One likely reason we have not yet detected extraterrestrial civilizations by radio is that we are likely simply listening at the wrong frequency. Arguments that we should listen at various fixed frequencies (*e.g.*, the "water hole" or multiples or sub-multiples of this frequency) are dependent on far too many assumptions about the psychology of the transmitting civilizations. It is also possible that a civilization interested in communicating across interstellar distances would not use high beamspread techniques like radio at all, but would use much shorter wavelength and hence more directed means: lasers. Unless the antenna size is unrealistically large (thousands of kilometers), across interstellar distances the overwhelming majority of any signal sent by radio will be broadcast to the empty space between the stars. The beam spread at target is proportional to the wavelength, and hence the power density at target proportional to the wavelength squared. As an example, compare a laser transmission at 500 nanometers with a microwave transmission at 5 mm. The laser has a wavelength 10^4 times shorter, and hence 10^8 times higher power density at the target star assuming the same transmitted power. Even if the bit rate is limited by the photon energy and thus the information transfer rate is proportional to the wavelength, laser communication is still preferable by a factor of 10^4.

Tipler argues that a extraterrestrial technical civilization will fill the galaxy with self-reproducing probes, which will not be subject to a distance horizon. Since we have not yet learned to design such machines, it is difficult to critique this reasoning in depth. However, I suggest that a self-reproducing probe would likely be more complicated than a dedicated probe, *e.g.*, by as much as an automobile factory is more complicated than an automobile. If this is so, then to produce maximum information return in any finite time (no matter how large) making self-reproducing probes which produce self-reproducing probes is not the optimum strategy. The optimum strategy is that after some number of generations G the factory probes will produce dedicated probes instead of self-reproducing probes. The number G will depend on the reproduction time, trip time, ratio of complexity, and information return time, but in general is quite small unless the required information return time is many orders of magnitude larger than the trip time, which is unlikely to be the case.

References

1. Hart, M.H. "An Explanation for the Absence of Extraterrestrials on Earth," *Q.J. R. Astr. Soc., Vol. 16*, 128-135 (1975), reprinted in *Extraterrestrials: Where Are They?*, Michael H. Hart and Ben Zuckerman, eds., Pergammon Press, 1982.

2. Fogg, M.J. "Temporal Aspects of the Interaction among First Galactic Civilizations: The 'Interdice Hypothesis,'" *Icarus 69*, 370-384 (1987).

3. Brin, G.D. "The 'Great Silence': The Controversy Concerning Extraterrestrial Intelligent Life," *Q.J. R. Astr. Soc., 24*, 283-309 (1983).

4. Kuiper, T.B.H., and Brin, G.D. *Am. J. Phys., 57*, 13 (1989).

5. Tipler, F.J., "Extraterrestrial Intelligent Beings Do Not Exist," *Physics Today*, Apr. 1981, pp. 9 and 70-71; and associated commentary in *Physics Today*, Mar 1982, 26-38.

6. Dyson, F. "Interstellar Transport," *Physics Today, Vol. 21*, No. 10, 41-45 (Oct. 1968).

7. Papagiannis, M.D., "Section VII, The Fermi Paradox and Alternative Search Strategies," in *The Search for Extraterrestrial Life: Recent Developments,"* International Astronomical Union, D. Reidel Publishing (1985).

8. Feder, J., *Fractals*, chapter 7: "Percolation," 104-148, Plenum Press, NY and London, 1988.

9. Stauffer, D. "Scaling Theory of Percolation Clusters," *Phys. Reports, Vol. 54*, No. 1, 1-74 (1979).

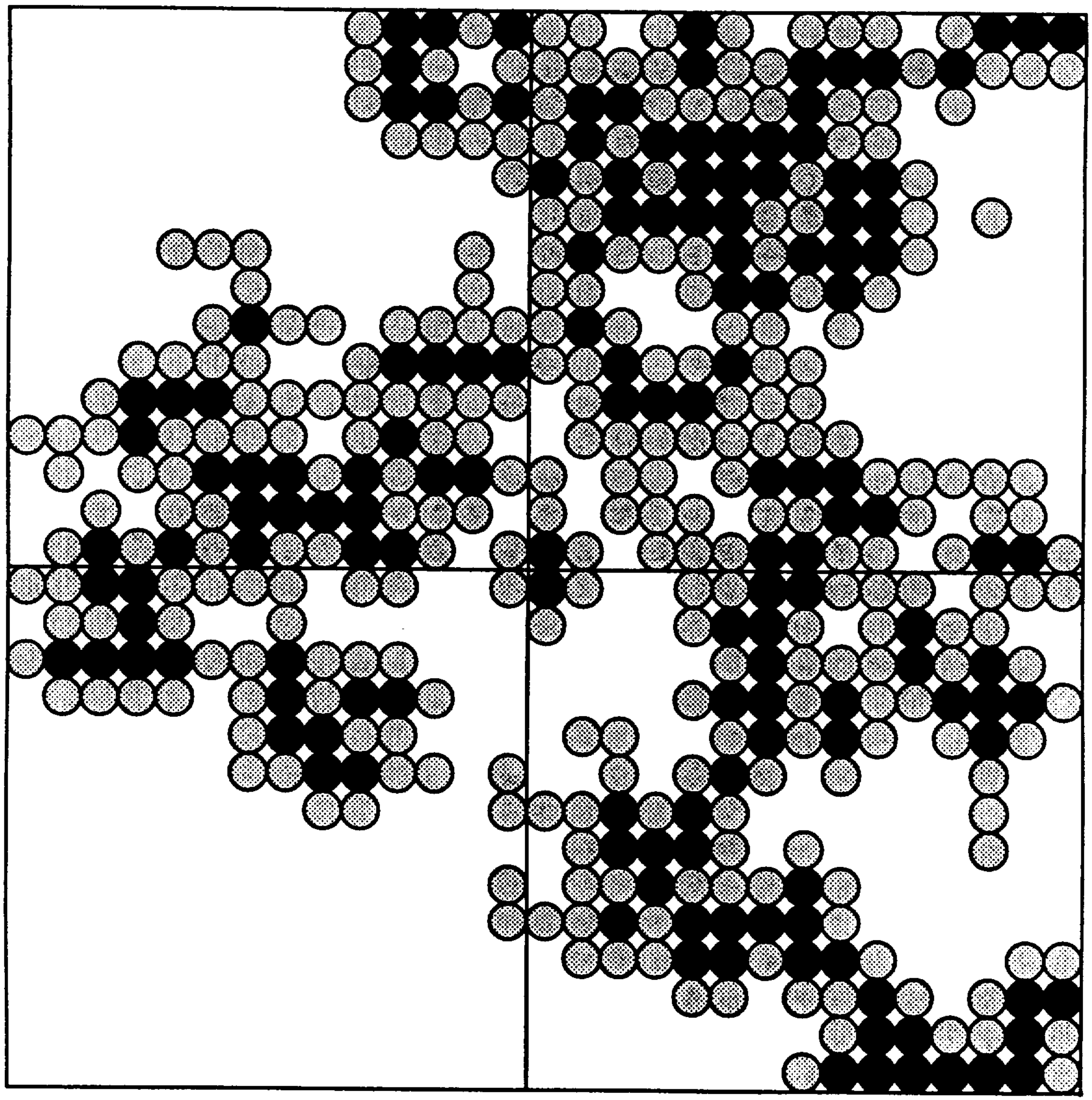

Figure 1. A slice from a percolation simulation on a simple cubic lattice in three dimensions. Here N=6 and P=1/3. Filled circles denote "colonizing" sites, open circles "non-colonizing" sites, and the absence of circles represents sites not visited. The irregular shape of the boundary and large voids in the percolation structure are clearly visible.