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Cosmology, Extraterrestrial Intelligence, and a Resolution of the Fermi–Hart Paradox

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SUMMARY

Cosmological constraints are considered on receiving signals from extraterrestrial civilizations. Attention is given especially to the argument, sometimes called the Fermi–Hart paradox, that extraterrestrials do not exist because we see no evidence of them and receive no signals from them, even though the presence of life on Earth might seem to imply its presence elsewhere. Evidence is reviewed which indicates that life in the Universe may be sparse. If this is so, the nearest civilization could be beyond our cosmological (particle) horizon, and therefore unable to communicate with us. This is a cosmological resolution of the Fermi–Hart paradox, which if valid implies that extraterrestrials exist but cannot be contacted.

1 INTRODUCTION

The absence of extraterrestrials on Earth has important implications for the search for other intelligent beings in the Universe. Enrico Fermi is reported to have started the discussion at a luncheon in 1950 by wondering out loud where the extraterrestrials could be. Michael Hart started the serious study of the absence of extraterrestrials in 1975 by suggesting that it is because we are the only advanced civilization in the Galaxy (Hart 1975). In recent years, the subject has grown in scope and come to be regarded as a paradox. There are several reasons for this. For example, a technologically advanced race could have colonized the Milky Way in a relatively short time if so predisposed, yet we see no evidence of this in the Solar System. Also, it appears to many people that if life exists on Earth then it should exist in other places both in our own galaxy and others, yet we have detected no intelligent signals from any other star or galaxy. (Potential sources should include other galaxies, since as noted below there are in principle as many of these visible to us as there are likely to be habitable planets in our own galaxy.) Of course, there is no paradox if extraterrestrial intelligent beings do not exist, a view held by some people and most notably by Tipler (1980, 1987; see also Barrow & Tipler 1986). However, if the Universe is infinite then even a tiny probability of the evolution of intelligent life must imply the existence of some extraterrestrials in some galaxy somewhere, as pointed out by Ellis & Brundrit (1979; see also Hart 1982, Gott 1982). The Fermi–Hart paradox has to be taken seriously, therefore, insofar as we see no evidence of extraterrestrials even though on a cosmological scale some should exist that are technologically capable of making themselves known. A lot of work has been carried out on the Fermi–Hart paradox, including the collections of papers edited by Hart & Zuckerman (1982) and Papagiannis (1985). But much of it is speculative and not quantitative. In the present article, straightforward astrophysical and biophysical data will be evaluated and combined to yield a cosmological resolution of the Fermi–Hart paradox.

The tone of this article is pedagogical. Much of what is said below is contained in some form in previous work by Ellis & Brundrit (1979), Hart (1982), Gott (1982) and Barrow & Tipler (1986). But it appears that many workers are unaware of how biophysics and cosmology fit together to provide a resolution of the Fermi–Hart paradox. Therefore this article aims to present the relevant data in a non-technical way, and to show how we are led to the conclusion that extraterrestrials may exist but cannot communicate with us.

2 COSMOLOGICAL CONSTRAINTS ON RECEIVING SIGNALS FROM EXTRATERRESTRIALS

Attempts to detect signals from extraterrestrial civilizations have been made by observing stars, globular clusters, galaxies and quasars (Tarter 1988). Most discussion presently, including that at a recent conference (McDonough 1988), appears to be concerned with stars. For example, NASA is currently preparing to conduct two surveys using radio telescopes, one of which is an all-sky survey while the other is an ambitious search of approximately 1000 stars out to a distance of about 100 lightyears. There are technical reasons for wondering if these searches have much hope of success (Bates 1988). But at a more fundamental level, a case can be made that it may be better to look for signals coming not from stars but from galaxies.

There is a general evolutionary argument for this and a specific numerical one. Let us start with the general one, and for the moment ignore the Fermi–Hart paradox and adopt the common belief that there are many extraterrestrial races in the Milky Way which are engaged in signalling. Let us also assume along with NASA that some of them can make themselves 'heard' over distances of the order of 10^2 ly. Then the natural evolutionary spectrum expected among these races implies that some of them should be technologically advanced enough to make themselves heard over greater distances. Indeed, depending on how numerous they are, it is reasonable to expect that some should be able to signal over distances comparable to the diameter of the Galaxy, i.e. 10^5 ly. Many workers involved in the search for extraterrestrial intelligence appear to find this reasoning acceptable but then seem reluctant to take the next step, wherein one goes from considering signals from stars in our own galaxy to signals from other galaxies. However, there is no real impediment here. Hypothetical civilizations in other galaxies of the Local Group are only a factor of 10 further away (for example the large spiral in Andromeda is 2×10^6 ly away). So a modest degree of technological advancement would allow them to make themselves known to us as well. Civilizations in galaxies at large would have to communicate over intergalactic distances of the order of 10^7 ly, but among the numerous galaxies in our region of the Universe there is no reason why some should not harbour very advanced civilizations with this capability. Despite this, most researchers currently believe that the chances are higher of detecting signals from stars in our own galaxy than from other galaxies (though all-sky searches like the one planned by NASA might in principle be able to detect extragalactic signals). However, a notable exception is Gott (1982), who has given a detailed account that favours galaxies. And the general argument given here shows that if extraterrestrial races exist in significant numbers and have a spectrum of sophistication, a case can be made that communication with some of them in galaxies at reasonable distances is possible.

This case can be made more cogent by adding a numerical side to it. Consider the following statement: *an optimistic estimate of how many habitable planets there may be in our own galaxy is* 10^{10}, *but to order of magnitude the number of other galaxies from which we can in principle receive light signals is also* 10^{10}. This will be shown below as an incidental fact in another calculation. But for now, it can be noted that it makes just as much sense numerically to look for signals from galaxies as from stars. (Indeed, it makes more sense insofar as one galaxy in the field of view of a telescope might contain 10^{10} civilizations, and only one of them would need to be very advanced to make itself heard over intergalactic distances.) This argument can be carried further if the Universe is infinite in extent, since it then contains an infinite number of galaxies and habitable planets. An interesting study of the consequences of this, and in particular the inevitability of there being other creatures as similar to us as one cares to consider, has been made by Ellis & Brundrit (1979; see also Barrow & Tipler 1986). Perhaps the most important consequence is that *in an infinite Universe there must perforce be some extraterrestrials somewhere even if the probability of their evolution is tiny*. This brings the discussion back to the Fermi–Hart paradox: even if life in the Universe is sparse, as some biophysical data indicate (see below), it is still necessary to explain why we see no evidence of it.

The most natural answer to this can be found in the fact that while the Universe may be infinite in extent it is finite in time. Indeed, this is an answer irrespective of whether the Universe is spatially finite ('closed', containing a limited number of galaxies) or spatially infinite ('open', containing an unlimited number of galaxies). To see why, let us first do a simple exercise to get a few concepts straight, and then note some results from general relativity that can be used to yield a quantitative result.

We start with the usual assumption that the galaxies are distributed more-or-less uniformly over large distances with a mean density $\rho(t)$ that depends only on the time t measured from some chosen zero. (The origin $t = 0$ need not be the big bang, though this further assumption will be made below.) Let us imagine we observe a typical galaxy at a distance R from us, and that the photons from that galaxy have been travelling toward us at the speed of light c for a time τ. (The origin $R = 0$ is us, that is, and we receive some of the photons radiated isotropically from another galaxy.) Then we have the simple relation $R = c\tau$. The lookback time τ may be relatively small for a nearby galaxy (for example, $\tau = 2 \times 10^6$ yr for Andromeda), but τ is larger for more remote galaxies and if we observe more distant ones, the time-lag implies that we see them as they were at earlier stages in their existence. Now the galaxies have an age of approximately 15×10^9 yr, so when $\tau = 15 \times 10^9$ yr and $R = 15 \times 10^9$ ly, we can in principle see galaxies as they were at formation. (In practice it is very difficult to do this, though observations

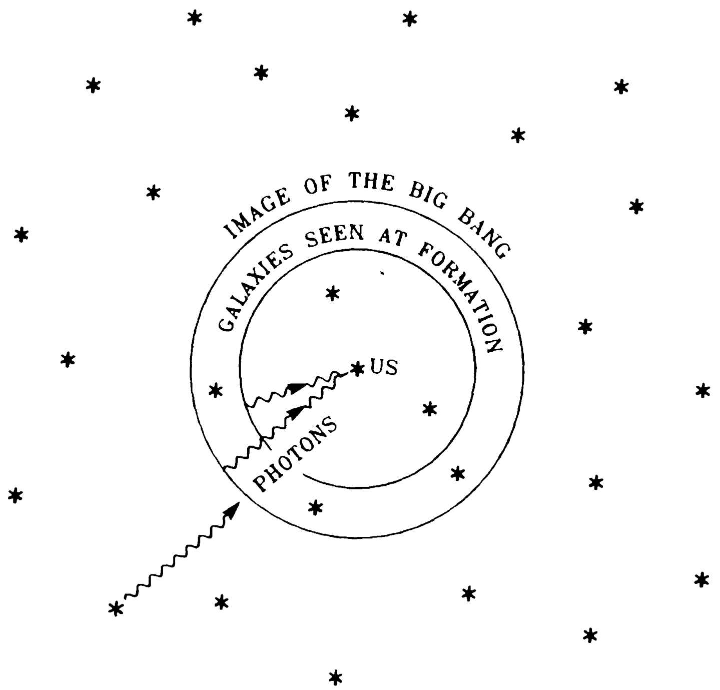

FIG. 1. A schematic representation of the surfaces which restrict our view of an unbounded uniform Universe.

of what may be galaxies-in-formation have been reported recently by Elston, Rieke & Rieke 1988, Tyson & Seitzer 1988, Cowie *et al.* 1988 and Cowie & Lilly 1989.) If we could look back farther in time and to greater distances in space, we would presumably only see the gas from which the galaxies are believed to have condensed. Suppose now that one adopts the standard big-bang cosmology in which all the matter in the Universe came into existence about 10^9 yr before the galaxies formed. Then the lookback time cannot be more than 16×10^9 yr, and the distance that can be penetrated cannot be more than 16×10^9 ly. Thus we arrive at a picture of the Universe in which, around us as origin, there are two concentric spherical surfaces: one at a distance of about 15×10^9 ly, where galaxies can in principle be seen at formation, and one at a greater distance of about 16×10^9 ly, which is a kind of image of the big bang.

These surfaces, illustrated in Fig. 1, are not physical boundaries. This can be understood by recalling that the mean density $\rho(t)$ contains no specification of such. Instead, the surfaces are imaginary ones, produced by the time-lag associated with the finite speed of light, that delimit our view of an unbounded Universe. This can be appreciated by noting that if the speed of light were twice as great the surfaces would be twice as far away and encompass greater volumes of the Universe (which in some sense exists 'now' outside of them). But while the surfaces at 15 and 16×10^9 ly from us are not physical boundaries, they *do* have real implications for the search for extraterrestrial civilizations. For if these exist, we expect to receive signals from them in the form of electromagnetic radiation. And if intelligent civilizations exist only around stars in normal galaxies, then we cannot hope to receive signals from further away than about 15×10^9 ly. Even if some hypothetical life-form can exist in a primeval gaseous medium, we cannot hope to receive signals from further away than about 16×10^9 ly. Basically, the Universe is circumscribed as far as we can expect to detect life in it using photons.

The above argument shows that there is a fundamental cosmological limit to the distance from which we can expect to receive intelligent signals, and also to the number of extraterrestrial civilizations we can expect to contact, even if such exist. The seeds of this argument were actually present in articles by Ellis & Brundrit (1979) and Gott (1982), but these appear to have been overlooked by people involved with the search for extraterrestrial intelligence. The argument is close to iron-clad, however, and is essentially the same as one used in a recent paper by Wesson, Valle & Stabell (1987) on the resolution of Olbers' paradox, in which context it is generally accepted. With regard to speculations about extraterrestrial civilizations, it ought clearly to play a central role because it provides an absolute limit for communication by photons. However, it also draws attention to the time-lag effect involved in communicating with extraterrestrials. One implication of this is that if life on a typical planet orbiting a typical star in a typical galaxy takes about 1×10^9 yr to evolve (as appears to have been the case on Earth), the size of the portion of the Universe in which we can ever hope to detect it shrinks from 15×10^9 ly to 14×10^9 ly. And if a technological civilization takes about 4×10^9 yr to evolve (as appears to have been the case for us), the size of the portion of the Universe in which we can ever hope to detect it is only 11×10^9 ly. In fact, the *longer* the time we allow a life-form to evolve, the *smaller* the size of the region in which we can expect to detect it.

The preceding discussion is conceptually informative. However, it needs to be quantified. This ought to be done on the basis of general relativity; but while some calculations have been made using this theory (Gott 1982), a full analysis would be complicated. It transpires, though, that an outline of the main relations and a couple of approximations will suffice for the main objective of this article, which is to give a cosmological resolution of the Fermi–Hart paradox.

The cosmological models of general relativity with uniform density are the Friedmann–Robertson–Walker (FRW) ones, and it may be useful for biophysicists and others who do not have a knowledge of the FRW models to review their essential properties here (those conversant with cosmology may skip the rest of this paragraph). The FRW models have expansion histories defined by a scale factor $S(t)$, which is proportional to the separation of any two typical galaxies at time t (measured from the big bang at $t = 0$). Derivatives of this define Hubble's parameter $H \equiv \dot{S}/S$ and the deceleration parameter $q \equiv -\ddot{S}S/\dot{S}^2$, and henceforth these and other parameters evaluated at the present time (t_0) will be denoted by the appropriate subscript. The spatial properties of FRW models are usually analysed in terms of spherical polar coordinates of which only the radius r is relevant here, and the curvature of space is described in terms of a constant k which is ± 1 or 0. Consider a photon that is emitted from a distant source at r_e at time t_e and is observed by us at $r = 0$ at time t_0. It is shown in introductory cosmology texts that the proper distance d of the source from us is given by

$$d = S_0 \int_0^{r_e} (1 - kr^2)^{-\frac{1}{2}}\, dr = S_0 \int_{t_e}^{t_0} S^{-1}(t) c\, dt.$$

This last relation effectively uses light-travel-time to measure distance. To maximize the distance out to which one can in principle detect photons from any form of life (irrespective of its stage of evolution), the lower limit of the time integral here has to be taken as small as possible. So for life in galaxies, t_e is the time of formation of these and $t_e \simeq 10^9$ yr. However, $t_0 \gg t_e$ because $t_0 \simeq 16 \times 10^9$ yr (see above). Thus the lower limit can be taken to a good approximation to be $t_e \simeq 0$, corresponding to a situation in which we can see back at least in principle to the time of the big bang. This choice of limit means d is now the distance to the *particle horizon*. This is the non-physical surface that separates things we can already see in the Universe from things whose light has not yet had time to reach us. (It is the general-relativity analogue of the outer circle in Fig. 1, and should not be confused with the event horizon, which is something else: see Rindler 1977.) To evaluate the distance to the particle horizon it is necessary to know $S(t)$. This can actually have different forms, as allowed by the field or Friedmann equations. These latter are normally simplified by assuming the intergalactic pressure to be zero, and some relevant relations have been derived under only this one restriction by Wesson *et al.* (1987). However, the Friedmann equations are often simplified more by assuming the cosmological constant to be zero, and horizon distances have been derived under this further restriction by authors such as Weinberg (1972) and Lawden (1982). To streamline the present calculation, let us make both assumptions. Then for the 3 different possible values of k, the horizon distances are

$$d_{k=+1} = \frac{c}{H_0(2q_0 - 1)^{\frac{1}{2}}} \cos^{-1}\left(\frac{1}{q_0} - 1\right), \quad q_0 > \tfrac{1}{2}$$

$$d_{k=0} = \frac{2c}{H_0} = 3ct_0, \quad q_0 = \tfrac{1}{2}$$

$$d_{k=-1} = \frac{c}{H_0(1 - 2q_0)^{\frac{1}{2}}} \cosh^{-1}\left(\frac{1}{q_0} - 1\right), \quad q_0 < \tfrac{1}{2}.$$

The value of k for the real Universe is not known, and the parameters H_0 and q_0 are only loosely constrained. However, an examination of the above relations and the assumption that q_0 does not have a value too far from $\frac{1}{2}$ shows that to order of magnitude we can take $d = ct_0 = 16 \times 10^9$ ly. That is, we will approximate the distance of the horizon in a curved Universe by the flat-space lookback distance considered above.

The number of planets we can in principle expect to receive signals from can be estimated easily now that we have agreed to neglect the effects of curvature. (Some results with curvature included have been given by Gott, 1982, but they are not much different from the one found below.) And a rough calculation is sufficient, because we will see later that the probability of the evolution of life on a habitable planet is itself uncertain by many orders of magnitude. Thus if the horizon distance is 16×10^9 ly and the mean intergalactic distance is 1×10^7 ly (see above), the number of galaxies we can in principle expect to receive light from is of the order of $(16 \times 10^9/1 \times 10^7)^3 \simeq 10^{10}$. And if each galaxy has of the order of 10^{10} potentially habitable planets, the number of these we can in principle expect to receive signals from is of the order of 10^{20}.

We can expect to receive signals from extraterrestrials only if the probability of life evolving on a habitable planet is greater than 1 in 10^{20}.

At this point the discussion shifts from being astrophysical in nature to biophysical, and becomes more difficult to quantify. There appears to be a tendency among people working in the astrophysical domain, and especially planetary studies, to believe that the probability of the evolution of life must be significant because it exists on Earth. However, this belief is questionable (Hart 1975), and as it applies to intelligent life like us sounds suspiciously anthropic (Barrow & Tipler 1986). Although our own existence is a relevant piece of information, we should not allow it to bias us into believing that life will necessarily evolve everywhere that a suitable physical environment exists. The fact is that while Darwinian evolution of organisms is fairly well understood, the critical step from abiological molecules such as amino acids to something like a one-celled organism is a giant one that is not understood (Dickerson 1978; Schopf 1978). Perhaps the most crucial question is not so much how an abiotic environment can evolve life-building material like proteins, but how life gets organized through the evolution of information-carrying molecules such as nucleic acids. There have been many ideas about the origin and evolution of the genetic code, including ones based on physical and chemical properties of primitive planetary environments (Nagyvary & Fendler 1974) and ones based on chance events that can be simulated with a computer (Kuhn & Kuhn 1978), but none has been universally accepted. (A review of classical models for the origin of regularities in the codon catalogue has been given by Woese 1969.) However, while a definitive model for the origin and evolution of molecules like DNA and RNA is not available, some progress can be made by considering the information coded by these molecules and other structures (Hasegawa & Yano 1975; Ball 1985). To be specific, the information content of various life-forms and the probability of the evolution of that information from an initially abiotic environment has been considered by Argyle (1977) and Hart (1982), and their results deserve a closer look.

Argyle (1977) has considered a model of the prebiotic Earth with an appropriate complement of amino acids, and found that random interactions over a period of 500×10^6 yr would produce only about 194 bits of information. This is far short of the 120000 bits in a virus (which is not really living anyway) and very far short of the 6×10^6 bits in a bacterium like *E. coli*. Thus, on the basis of random interactions, the origin of life on any one Earth-like planet is highly improbable. Argyle has remarked that even with 10^9 Earth-like planets in the Milky Way, the potential for random generation of information rises only to 224 bits. (The low gain in information I from N random experiments is because the two things are related via $I = \log_2 N$.) Adapting this line of reasoning to the estimate given above of 10^{20} habitable planets within our cosmological horizon gives a potential information content of only 261 bits. If one asks, alternatively, how big a region of the Universe is necessary in order for random interactions on Earth-like planets to generate enough information for even one virus, the answer is far in excess of that associated with the horizon and quite mind-boggling. Argyle, on the basis of the implausibility of the origin of life on Earth by chance events, has also considered a non-random Darwinian kind of model for the generation of information. But while this possibility will be returned to below, it must be recalled that it is purely hypothetical. As far as chance and chemistry are concerned, there should be no other planet than Earth within the observable Universe where enough information has been generated to lead to life.

Hart (1982) considered models of Earth-like planets, particularly with regard to how the atmosphere is affected by changes in the mass of the planet, the semimajor axis of its orbit and the mass of the central star. He concluded that uncertainties in these astrophysical parameters are swamped by the uncertainty in the biophysical probability of the evolution of life, and that the latter is extremely low. He calculated that the probability of forming a single strand of DNA of modest length (600 nucleotide residues) by random interactions on the surface of an Earth-like planet, even over a period of 10×10^9 yr, is only 1 in 10^{30}. This is actually a very optimistic estimate, and includes a factor to account for the fact that at some positions in a strand of nucleic acid it is possible to replace one nucleotide residue by another without changing the biophysical effect of the strand. Without this factor, the probability is only 1 in 10^{300}. Irrespective of this, however, Hart considered other conditions that would have to be met for random interactions to produce a viable organism, and found the probability (for one planet over 10×10^9 yr) to be no greater than 1 in 10^{3000}. Even if the optimistic estimate of 1 in 10^{30} is taken, it is apparent that as far as evolution by chance is concerned, life should not exist on any of the other 10^{20} habitable planets within the observable Universe than Earth.

Arguments similar to those of Argyle and Hart outlined above have also been made by other workers. [For example, Hoyle (1980) has calculated that the probability of life evolving randomly on Earth is about 1 in $10^{40\,000}$, while Barrow & Tipler (1986) have calculated that in an infinite Universe creatures like us can evolve at other places but with an average separation of 10^{600} ly.] Irrespective of the details of these arguments and their numerical results, however, the same conclusion emerges provided the biophysics is based on chance statistics and the cosmology is based on standard theory: life should exist only on Earth within the (horizon-bounded) observable Universe.

3 CONCLUSION AND DISCUSSION

If extraterrestrial intelligent civilizations exist and send signals, there are good reasons for believing we could receive them not only from stars but also from galaxies. This gives a cosmological slant to the Fermi–Hart paradox, which in broad terms says we see no evidence of extraterrestrials even though we have grounds for thinking they exist. However, a reasonable and quantitative resolution of this paradox has been given that builds on astrophysical work by Ellis & Brundrit (1979) and Gott (1982) and biophysical work by Argyle (1977) and Hart (1982). The basic idea is that we can only receive signals from a part of the Universe bounded by the particle horizon and determined in size by its age, and if life evolves by chance chemical reactions it is so sparse that there is no planet within the horizon where it can be expected to exist other than Earth.

If this resolution of the paradox is valid, we are alone in the observable Universe. This will not be a very palatable result to many people, and especially to those involved in the search for extraterrestrial intelligence. In fact, it is not very palatable to the author. But before one begins to look for reasons to discount it, one should recall that at all stages during the calculation, data were taken that were optimistic to the idea of finding extraterrestrials. For example, galaxies were counted all the way out to the horizon, whereas if one could see the more remote ones they would appear early on in their histories, perhaps before they had evolved intelligent life, thanks to the time-lag associated with the finite speed of light. This illustrates that if one is to avoid the conclusion that we are alone in the observable Universe, some fairly drastic way of doing it is necessary. One way, suggested by what has just been stated, is that extraterrestrials may signal with something that travels faster than light. But this is pure speculation. A more reasonable idea is that one of the new cosmologies that have been developed in recent years may modify the horizon concept in such a way as to allow us to receive signals from a larger portion of the Universe. (See Wesson 1978 for a review of the alternative cosmologies, and Wesson 1986 for one that may have this potential.) Another possibility is that the Universe may be found to have some property which implies that, even though it is described by conventional general relativity, it has no particle horizon. But all non-empty, uniform big-bang models based on Einstein's theory have a particle horizon (Rindler 1977), so this way of avoiding isolation would involve a major revision of our beliefs about the Universe if not our theory of gravity. However, all of the suggestions made so far have been astrophysical in nature. And there is of course a way to avoid the conclusion arrived at above that is perhaps more realistic and is biophysical in nature: if life originates in a non-random manner, then the probability of life evolving on a habitable planet may be greater than 1 in 10^{20}, and there may be other intelligence within the observable Universe.

This possibility, while perhaps appealing, should not be accepted without careful consideration. First, it is speculative and will require great advances in molecular biology before it can be properly evaluated. Secondly, if the probability of life evolving is *too* high, then the Universe should be densely populated with life forms, and we find ourselves confronted with the Fermi–Hart paradox again.

Since the main objective has been to resolve this paradox without appealing to anything speculative (like the ideas suggested above), it may be appropriate to close by recalling what it means if the cosmological horizon argument is after all correct. We are then alone in the part of the Universe we can see and communicate with now. But if the Universe is spatially infinite and the probability of the evolution of life is finite, there must be creatures in other galaxies somewhere. That is, extraterrestrials exist but are beyond the horizon.

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