Lecture 11: The Search for Extraterrestrial Intelligence

Aims of Lecture

(1) To explain the attempts that have been made to search for intelligent radio signals of extraterrestrial origin, and discuss the implications of the negative results to-date.

(2) To introduce the 'Drake Equation' and discuss its value in helping to quantify the issues relating the prevalence of intelligent life in the Universe.

(3) To discuss the 'Fermi Paradox' and proposed solutions.

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Fig. 1. The 300 metre diameter Arecibo radio telescope in Puerto Rico (NAIC/NSF).

1. Introduction

The first suggestion that it might be possible to detect extraterrestrial technological civilisations through their radio transmissions was made by Giuseppe Cocconi and Philip Morrison in 1959. The first search ('Project Ozma') was conducted by radio astronomer Frank Drake in 1960 who observed two nearby solar-type stars (τ Ceti and ϵ Eridani) for a total of 150 hours but detected nothing. Many much more sensitive searches have been carried out since then, all with negative results. The Arecibo telescope (Fig. 1), until recently the world's largest radio telescope, is an example of the kind of instrument used for SETI.
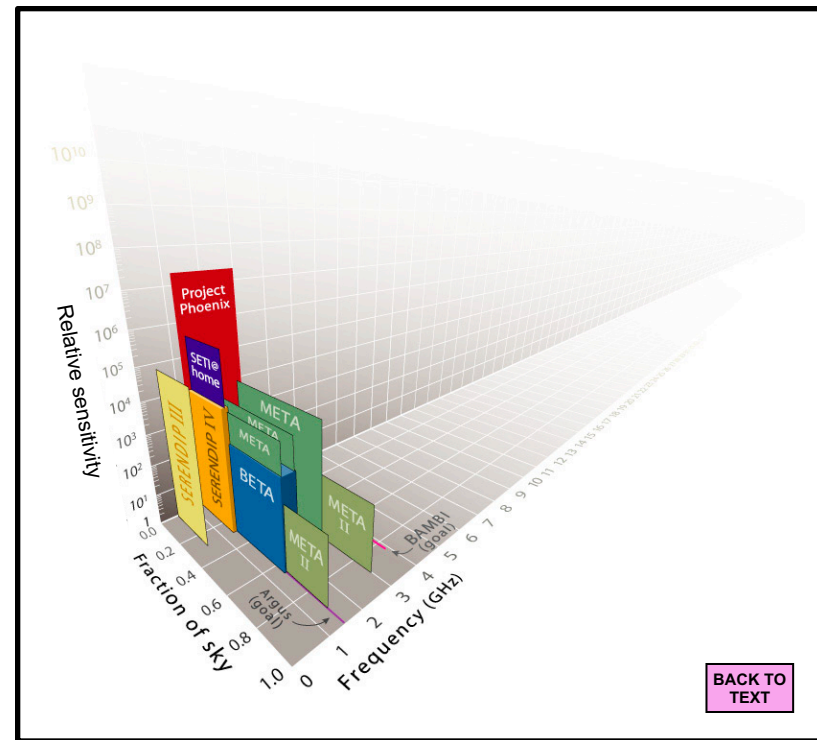
2. SETI searches

2.1 The SETI search space

Searching for extraterrestrial radio signals involves a trade-off between at least three parameters (see Fig. 2):

(a) Sky coverage: Here the choice is between trying to observe the whole sky or just a few individual stars. No radio telescope can observe the whole-sky all at once, so whole-sky observing is very time consuming. Also, a given star will only be observed for a short period of time, reducing the chance of a detection. On the other hand, choosing to target individual stars means that the chance of detecting a signal from those particular stars will be enhanced, but a signal from a neighbouring star that was not selected may be missed.

(b) Sensitivity: The sensitivity of a radio search defines the weakest signal that can be detected. In part, this depends on the technological capabilities of the receiver, but it also depends on the length of time that is spent observing a particular star: there is a trade-off between sensitivity and sky coverage – targeted searches are more sensitive than all-sky surveys, but cover far fewer stars.

Fig. 2. Three-dimensional representation of the SETI 'search space' as defined by the fraction of sky observed, search sensitivity, and radio frequency. The volumes within this parameter space searched by various SETI surveys are indicated. As a guide to sensitivity, Project Phoenix, a targeted search of about 1000 nearby solar-type stars completed in 2004, had an absolute sensitivity of about 10^{-28} W m^{-2}. For a description of these surveys, and further explanation of this diagram, see this *Sky and Telescope* article: https://www.skyandtelescope.com/astronomy-news/seti-searches-today/. For an up-to-date summary of past and present SETI searches, see: https://technosearch.seti.org/ (Image reproduced with permission of *Sky and Telescope*).

(c) Choice of radio frequency: The radio spectrum is a very big place, and in practice no radio receiver can be sensitive to all frequencies simultaneously. Thus, the observer has to choose which frequencies to observe, which amounts to trying to second guess the frequencies at which an extraterrestrial civilisation will be transmitting! Most SETI searches have adopted a frequency at (or close to) 1.4 GHz, which corresponds to a radio wavelength of 21 cm (Fig. 2). This is the wavelength naturally emitted by hydrogen atoms in interstellar space, and routinely used for mapping the structure of the Galaxy. The idea behind using this frequency for SETI is that any civilisation wanting to be detected would transmit on this wavelength, knowing that all the radio astronomers in the Galaxy would probably be observing it.

Note that most SETI searches implicitly assume that extraterrestrial civilisations are deliberately transmitting in order to be detected – without this assumption there is no particular rational for choosing the 21cm wavelength (although it is also true that natural background radio noise is relatively low in this part of the radio spectrum).

2.2 On-going and future SETI searches

Fig. 2 summarises the most important past and present SETI searches (a comprehensive summary of all SETI searches to-date can be found on the SETI Institute's Technosearch website). These searches are now being expanded by the privately funded Breakthrough Listen Project which is using several major telescopes to perform the most comprehensive all sky survey to-date and a targeted search of ~1000 nearby stars over the very wide frequency range of 0.1-50 GHz (Fig 3). In addition, the new generation of professional radio observatories, such as the Square Kilometre Array (SKA) and its precursor, the South African MeerKAT telescope (Fig. 4), will also be used for SETI and will further increase coverage (although they will mostly be used for non-SETI radio astronomy).

Although, historically, SETI has been based on radio wavelengths, this is based on an assumption on our part, and other regions of the electromagnetic spectrum might be used for communication. This realisation has led to the growing field of 'optical SETI'. Here, the aim is to use optical telescopes to search for powerful lasers that may be being used by ETI to communicate, and the Breakthrough Listen Project has implemented an optical SETI programme to complement its radio searches. We should also keep an open mind to the possibility of signals being sent at other electromagnetic wavelengths, or even by subatomic particles, but no serious searches for these have been implemented yet.

Finally, there is growing interest in searching for artefacts produced by ETI. This is sometimes called SETA ('Search for Extraterrestrial Artefacts') where, in principle, such artefacts might range from large scale engineering activities around other stars (e.g. Dyson spheres and the like), sometimes also called techno-signatures, to alien probes hiding (or abandoned) in our own Solar System.
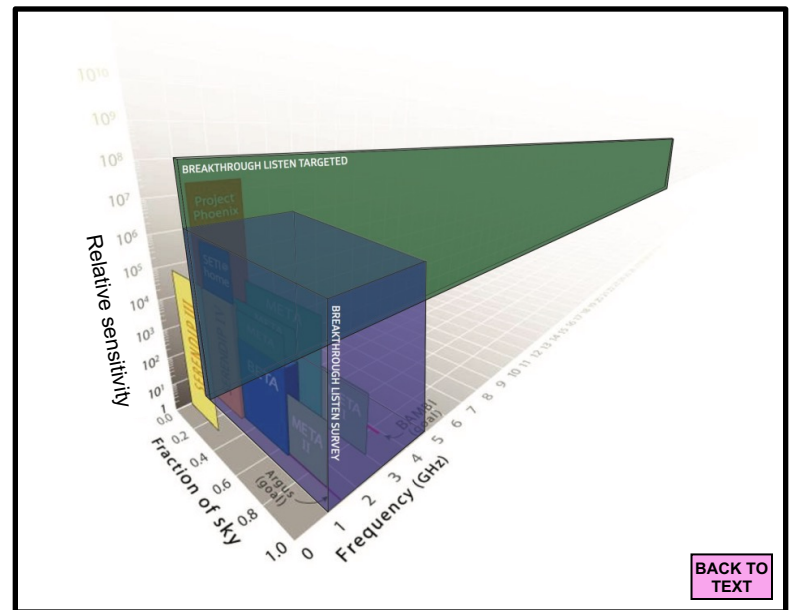
Fig. 3. The SETI search space to be probed by the Breakthrough Listen Project. Note, despite the large increases in sensitivity and frequency coverage, a large volume of the parameter space will still remain unexplored. (Image courtesy *Sky and Telescope/*Dr Steve Croft, University of California, Berkeley).

Fig. 4. The MeerKAT array of 64 13.5 metre telescopes in South Africa, and ultimately the SKA, will greatly increase the sensitivity of SETI searches (image: SARAO).

2.3 Summary of SETI results to-date

To-date, all SETI searches have been negative. However, because only a small fraction of the relevant parameter space has been searched (Fig. 2) this only sets loose limits on the prevalence of radio-transmitting ETI in the Galaxy. Based on the sensitivity of past and present SETI searches, and the non-detections to-date, the main points to note are:

• We can probably only hope to detect radio transmissions that are directly beamed in our direction. At present, we would barely be able to detect the random leakage of radio signals emitted by an Earth-like civilisation orbiting even the nearest star (although future large area detectors like SKA may extend this to ~10^2–10^3 light-years, but only for targeted searches);

• We should have detected any civilisations with our own level of radio technology within ~10^2–10^3 light-years if these choose to deliberately transmit in our direction at a wavelength of ~21 cm. Non-detections to-date can probably exclude any such nearby civilisations (which could reasonably be expected to know about us.....)

• We should already have detected any very advanced civilisations anywhere within the Milky Way Galaxy (or even the entire Local Group of neighbouring galaxies) that are prepared to invest much larger amounts of energy in interstellar communication than we are capable of.

The final point may be the most significant. Consider hypothetical ETI civilisations located in the Andromeda Galaxy, about 2 million light-years away and containing several hundred thousand million stars (Fig. 5).


Fig. 5. The Andromeda Galaxy (NOAO/AURA/NSF).

Any such ETI civilisation could point a relatively narrow (about 3° wide) radio beam at the Milky Way and know that their signal would sweep past all 10^{11} stars in our Galaxy. This would require a power of ~10^{16} W to be detected by us. This is a very large amount of power by our standards (about 4000 times the World's current electrical power consumption), but only 10^{-10} of the output of a solar type star and perhaps not impossible for an advanced ETI. The Andromeda galaxy contains several hundred thousand million stars, so the fact that there are no advanced civilisations within it, that have either the capability or the inclination to transmit signals in the direction of our Galaxy, is perhaps the most pessimistic conclusion that can be drawn from the SETI results to-date. It is also worth reflecting that this idea of beaming signals simultaneously to whole galaxies or star clusters to maximise the chances of reception has already occurred to us (Fig. 6), so would surely have occurred to ETI...

Nevertheless, it remains true that so far we have only searched a small fraction of the SETI parameter space (Fig. 2), and that the non-detection of extraterrestrial radio signals cannot yet be taken to imply that extraterrestrial civilisations do not exist. Hopefully, as SETI searches become ever more sensitive it will be possible to put ever tighter limits on the prevalence of radio-transmitting civilisations in the Galaxy (and beyond).

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Fig. 6. The Arecibo message. In 1974 a message was transmitted by the Arecibo radio telescope (Fig. 1) towards the globular cluster M13 that lies ~22,000 light-years away in the constellation of Hercules and contains several hundred thousand stars (upper image). A colourised rendering of the image digitised in the message is shown in the lower image; a useful summary and explanation of the content is given in this Wikipedia article (image: Wikipedia Commons/ Arne Nordmann/CC BY-SA 3.0).
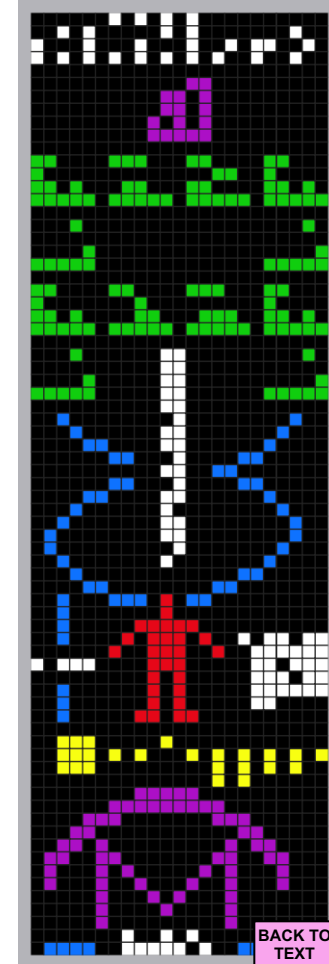
3. The Drake Equation

In 1961, Frank Drake produced a simple equation which may be used to estimate the number of "communicative" technological civilisations, N_{ETI}, present in the Galaxy at any given time:

$$N_{ETI} = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

Where:

R_* = Rate of formation of stars in the Galaxy ($R_* \approx$ 1-10 per year)

f_p = Fraction of stars with planetary systems ($f_p \approx 1$)

n_e = Number of planets within each system that have suitable environments for life ($n_e \approx 1$?)

f_l = Fraction of such planets on which life develops

f_i = Fraction of such life that evolves 'intelligence' (however defined...)

f_c = Fraction of such intelligent life that becomes 'communicative' (e.g. builds radio telescopes)

L = Lifetime of a communicative civilisation (in years if R_* is measured in stars per year)

The first six terms of the Drake Equation, when multiplied together, give the rate of formation of ETI civilisations per year. Multiplying this by the average lifetime, L, then gives the number that, on average, exist at any given time.

We can assign reasonable numbers to the first three terms, but the others are at present completely unknown. Nevertheless, the Drake Equation is still useful in breaking the problem up into easily analysed chunks.

For illustrative purposes, we can consider extreme 'optimistic' and 'pessimistic' solutions. In both cases we will assume $R_* = 1$ per year; $f_p = 1$; and $n_e = 1$ (perhaps actually somewhat pessimistic for both R_* and n_e).

3.1 Optimistic case

SETI-optimists, such as Frank Drake himself, tend to argue as follows:

• Given a suitable environment, life will always arise, so $f_l = 1$. They would argue that this is consistent with the early appearance of life on Earth.

• Given life, natural selection will 'inevitably' lead to the evolution of intelligence, as intelligence confers survival value. Therefore, $f_i = 1$.

• Given 'intelligence', technology will 'inevitably' follow, and this will ultimately lead to an interstellar communications capability. Therefore $f_c = 1$.

As a result of these assumptions, all the factors in the Drake Equation, except L, are equal to 1, so we get

$$N_{ETI} = L$$

No one knows what the lifetime of a technological civilisation might be. According to the definition used here, our own civilisation is currently less than a hundred years old. However, if the average lifetime of a technological civilisation were 1000 years, these optimistic assumptions would predict $N_{ETI} = 1000$. The nearest would then be about 2000 light-years away (on average), just on the limit of what is currently detectable by existing SETI searches. However, although this 'optimistic' case results in 'only' 1000 well-spaced civilisations in the Galaxy at any one time, it implies that a total of $\sim 10^{10}$ civilisations have existed over the age of the Galaxy. This huge number may be difficult to reconcile with the fact that we don't see any evidence for their activities (we will return to this point below when considering the 'Fermi Paradox').

3.2 Pessimistic case

For all we know at present, one or more factors in the Drake Equation might be _very_ small. For example, even if f_l =1, it does not follow that _intelligent_ life is also inevitable. At least on this planet, many seemingly chance biological, geological, and astronomical events have influenced the evolution of single-celled microorganisms, multicellular animals, and intelligent life. Thus, f_i might be $\ll 1$.

In his book _Man's Place in the Universe_, published in 1904, Alfred Russel Wallace (the co-discoverer of natural selection with Charles Darwin) gave some thought to the probability of evolving intelligent creatures by means of natural selection. He concluded that:

> _"[Given] the evidence as to the number of very complex, and antecedently improbable conditions which are absolutely essential for the development of the higher forms of life … the total chances against the evolution of man, or an equivalent moral and intellectual being … will be represented by a hundred million of millions to one."_

A probability of "a hundred million of millions to one" implies $f_i = 10^{-14}$. Of course, Wallace just plucked this number from thin air to illustrate his point, but if we put $f_i = 10^{-14}$ into the Drake Equation, even with all the other factors equal to 1, we get

$$N_{ETI} = 10^{-14} \times L$$

If we assume that L = 1000 years, as before, we get $N_{ETI} = 10^{-11}$, implying that there is only one communicative civilisation in the entire Universe!

There are actually three possible reasons for believing that Wallace may have been on the right track, and that technological civilisations are rare in the Galaxy:

• The history of life on Earth (Lecture 6)

• The negative SETI results (at least so far ...)

• The lack of evidence for space-faring civilisations (the so-called 'Fermi Paradox').

4. The Fermi Paradox

Sometime around 1950, during a discussion on extraterrestrial life, the physicist Enrico Fermi is said to have exclaimed "Where are they then?" in response to an assertion that technological civilisations must be common. It seemed to him that if the Galaxy is really teeming with technological civilisations then we would have seen them by now. The fact that we have not has become known as the 'Fermi Paradox' (although strictly it is only a paradox for those who believe that such civilisations must exist!).

At the heart of the Fermi Paradox is the fact that the Earth has not been colonised by an extraterrestrial civilisation at any time over the last 4 billion years. If it had been, terrestrial evolution would have been interrupted and we would not be here (note, this doesn't exclude the possibility that we have been visited, but otherwise left alone, which is a point to which we will return). Of course, the Galaxy is a very big place, so before we can lend much credence to the Fermi Paradox, we have to establish that technological civilisations, or at least some fraction of them, will have motives for wanting to travel between the stars, and, assuming that they do, that galactic colonisation is possible in principle.

4.1 Motives for interstellar colonisation

Despite the enormity of the undertaking, we can identify several reasons why technological civilisations might set out to colonise neighbouring stars:

- A possible genetic predisposition towards colonisation (natural selection might select for this – it has for many species on Earth, including, quite possibly, *H. sapiens*)

- Possible ideological motives for colonisation (human history is replete with these, so why should other intelligent species be any different?)

- A rational desire to escape the consequences of stellar evolution (no star lasts for ever (Fig. 7), so eventually even the most sedentary civilisations will be obliged to move)

- Scientific exploration (SETI searches conducted by the earliest civilisations to arise in the Galaxy would, necessarily, be negative, so they may set out for the stars in order to find out why).

4.2 Colonisation timescales

Despite the vast size of the Galaxy (100,000 light-years across, containing ∼100 thousand million stars), it is actually possible for it to be fully colonised in just a few million years (that is, in a few hundredths of a percent of its present age). To understand this, consider Fig. 8, where the dots represent stars. Consider the star at the centre of the diagram, which let's say is the home of a spacefaring civilisation.
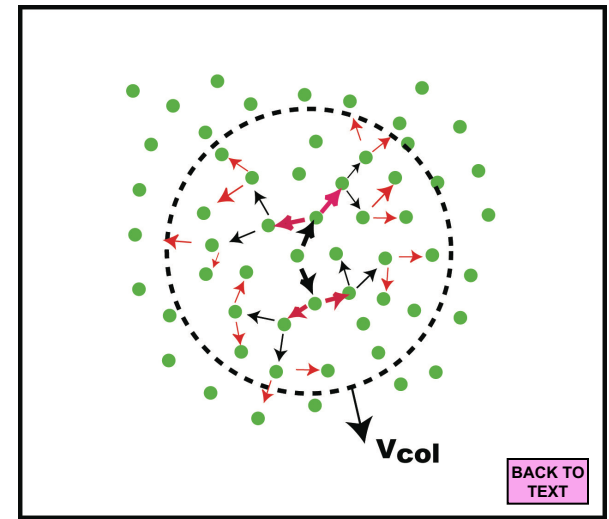

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Fig. 7. The Helix Nebula :a planetary nebula formed by a solar-type star at the end of its life (following the 'asymptotic giant branch' phase of its evolution; recall Lecture 1). The Sun will become a planetary nebula in ∼7 billion years' time, and life in our Solar System will have become impossible (NASA).

Suppose this civilisation sends out space missions to establish colonies around the two stars closest to it (thick black arrows). After sufficient time for these colonies to become established, each of them sends out two colonising missions of their own (thick red arrows), and so on. It is easy to see that the number of colonies rises exponentially: after the first step there will be 2, then 4, 8, 16, etc; in principle, after only 37 steps there would be 10^{11} colonies – equal to the number of stars in the Galaxy!

The speed with which this colonisation 'wavefront' moves through the Galaxy will be set by the speed of the spaceships (V_s), and the time it takes each colony to become established before it can send out colonies of its own (t_{est}). If D is the average distance between colony sites and and t_{travel} the time taken for the spaceships to move from one colony to another (i.e. $t_{travel} = D/V_s$) then the colonisation wavefront (dashed line in Fig. 8) will move through the Galaxy at a speed:

Fig. 8. A diagram to show how galactic colonisation might proceed: a 'home' planet (centre) colonises the two planetary systems closest to it, which then send out colonies of their own, and so on. The number of colonies grows exponentially (see text for further explanation).

$$V_{col} = D/(t_{travel} + t_{est})$$

If we assume D = 10 light-years (approximately the observed spacing of solar-type stars); V_s = 0.1c (technologically challenging, but not physically impossible); and t_{est} = 400 years (a reasonable guess), then we get V_{col} = 0.02 light-years per year. As the Galaxy is 100,000 light-years across, this implies a colonisation time of 5 million years, or only 0.05% of its present age. In principle, there could have been many such colonisation wavefronts sweeping through the Galaxy, from many different centres. However, if any ever came this way, they have not left any record of their passing -- this is the Fermi Paradox.

4.3 Anthropic Bias

We can recognise that there are several biases that may affect our ability to objectively assess the likelihood of life existing elsewhere. These can be summarised by the 'Anthropic Principle', a concept originally proposed by Carter (1983) in *The anthropic principle and its implications for biological evolution.*

We have just one example of a planet with life on it, and our own existence is dependent on the life having taken a very particular course. This imposes an "anthropic bias" on our observation of life on the Earth and our ability to extrapolate these observations to the wider galaxy, as we cannot be sure that the Earth is typical of other rocky planets. It is *probably* not typical of other planets on which life becomes established, but it might be reasonable to assume it is typical of a rocky planet that hosts complex, and intelligent, life ("observers").

Weak Anthropic Principle (WAP):

"…our location in space-time is necessarily privileged to the extent of being compatible with our existence as observers." (Carter, 1979)

Strong Anthropic Principle (SAP):

"The Universe must be such as to admit the creation of observers within it at some stage." It implies that the 'purpose' of the Universe is to give rise to intelligent life, with the laws of nature and their fundamental physical constants set to ensure that life as we know it will emerge and evolve. (Barrow & Tipler, 1986)

Modified Anthropic Principle (MAP):

The problem does not exist until an observer species capable of formulating the paradox arises. Therefore the conditional probability of an observer finding themselves in a Universe compatible with their existence is **always 1**.

4.4 Proposed solutions to the paradox

Over the years there have been many proposed solutions to the Fermi Paradox, for example:

- That interstellar space travel is impossible. However, this seems very unlikely – although interstellar travel will doubtless be very expensive, and technologically challenging, it violates no known physical law (and in a sense we are already engaging in it, albeit very slowly, with probe like the Voyager spacecraft).

- That ETIs are not motivated to colonise the galaxy – but we have already identified several potential motivations, and there may be others we haven't thought of.

- That ETIs are constrained by strong ethical codes against interfering with primitive lifeforms (a suggestion known as the 'zoo hypothesis' – i.e. we are in the zoo!). However, it seems unlikely that *all* ETIs would subscribe to the *same* ethical codes – some might find colonising planets such as Earth was 2 billion years ago to be highly ethical, after all, they would be replacing bacteria with intelligence…

- That we are the first technological civilisation to appear in the Galaxy. This is of course consistent with the Paradox – if we are the first then there aren't (yet) any others. However, this requires an explanation, given that there are many stars older than the Sun, around which life could have had a head start.

Although it falls well short of a proof, careful consideration of the Fermi Paradox does seem to suggest that, even if we are not literally alone, ETIs are likely to be few and far between – the more there are (or the more there have been in the history of the Galaxy) the harder it is to explain away the Fermi Paradox.

Part of the reason could be due to the gradual increase in heavy element abundances in the Galaxy with time, biasing the appearance of planets, and life, to relatively recent Galactic history. However, many stars much older than the Sun are now known to have planets, and the *average* age of rocky planets in the Galaxy appears to be ~2.5 billion years older than the Solar System (Lecture 10). Biological evolution on such

planets could have had a 2.5 billion year head start on us! Possibly, these early-formed planets were not habitable for some reason, perhaps due to more energetic galactic processes (recall the GHZ concept).

The history of life on Earth (Lecture 6) suggests another possible explanation: even if $f_l \approx 1$ (as advocated by Christian de Duve, and consistent with life's early appearance on Earth), it may be that $f_i \ll 1$ (as suggested by Wallace, and consistent with the length of time it took to evolve multicellular animal life). Thus, the Universe may be teeming with life, but technological civilisations could still be very rare. This would be consistent with the negative SETI results to-date, and provide an explanation for the Fermi Paradox.

5. Conclusions

Much of the above is still speculation at this stage. What we really need are more facts, and the only way to get those is to continue with the exploration of the Universe around us:

- Expand the SETI programmes to cover more of the radio search space (Fig. 2), and broaden them to include non-radio wavelengths and to include searches for ET engineering activities (SETA, techno-signatures). Even if nothing is discovered, this will enable us to place tighter constraints on the prevalence of technological civilisations in the Galaxy.

- Search for evidence of past and present life on Mars, Europa, and elsewhere, to determine whether or not life really does appear rapidly given a suitable environment.

- Construct large space-based telescopes to study habitable planets orbiting other stars, and to search for biosignatures in their atmospheres.

- Eventually, we may ourselves have to construct interstellar space probes to explore extrasolar planets and their potential biospheres in more detail than will ever be possible from the Solar System ...