THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI)

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ABSTRACT. A brief review is presented of the hypotheses inherent in searches for extraterrestrial intelligence (SETI). Some of the problems associated with such work at radio wavelengths are discussed, such as the optimal choice of a search frequency. It is shown that pulsed laser signals sent from an extraterrestrial civilisation should be observed to be brighter than the parent star, even when conservative estimates are adopted for the laser energy generation and detector time resolution. This is still the case when the energy output from the parent star is summed over all wavelengths. As a result, optical SETI programmes may be more attractive than their radio counterparts.

1. INTRODUCTION

To a large extent, the reasoning for SETI is based on the expectations of the Drake (1980) equation, which gives the relationship between the number \( N \) of concurrent Electromagnetically Telecommunicating Civilisations (ETCs) and the lifetime \( L \) in years of an ETC, and is written

\[
N = R_s \times f_p \times n_e \times f_l \times f_l \times f_c \times L
\]

where \( R_s \) is the rate of formation of suitable stars (i.e. stars with large enough habitable zones and long enough lifetimes for the development of intelligent life); \( f_p \) is the fraction of these stars with planets; \( n_e \) is the number of “Earths” per planetary system (i.e. planets with the basic conditions for life as we know it); \( f_l \) is the fraction of these planets where life develops; \( f_l \) is the fraction of life sites where intelligence develops; and \( f_c \) is the fraction of planets where technology develops. SETI searches hypothesise that (a) the evolution of life and technological civilisation is an inevitable consequence of physical laws, and occurs profusely throughout the Galaxy, and (b) Earth is mediocre in its development, with civilisations far in advance of ours existing, and the ETC on Earth is not the first to have occurred.

Blair (1985) and others have argued that, within an order of magnitude or so, \( N \approx L \). A large value of \( L \) (for example, \( 10^8 \) years), would then imply that the mean separation between ETCs is \( \sim 50 \) light-years (Blair et al. 1992). However some authors have provided very powerful arguments that \( N \ll L \), or that \( L \) is very small (see, for example, Tipler 1982; Carter 1983; Crawford 1997; also Livio 1999 for some counter-arguments).

SETI searches also make other hypotheses (Blair et al. 1992), including

1. The physical laws, energy sources and physical phenomena known today represent a "complete approximation" to the laws of nature. Complete implies that there are no new laws, and approximation means that known laws may not be exact, and future science may refine our understanding of these. However, there is no radical new physics.

2. Since physical laws make interstellar travel impossible, communication and exchange of information is the means of exploring life in the Galaxy.

3. A Galactic "club" exists and welcomes members. Other civilisations have already developed communications, and chosen target stars based on advanced astronomy. Beacons are directed at likely ETCs, with the goal of spreading and/or acquiring knowledge.

However, none of these assumptions may be true. In particular, several authors believe that interstellar travel is possible, even at velocities which are only 10% that of light (see, for example, Crawford 1990; Crawford 1995, and references therein). As a result, it would be realistic for a civilisation to colonise the Galaxy in a timescale of only a few million years, which is short compared to the lifetime of the Galaxy (Tipler 1982; Crawford 1997). Point 3 also assumes that any ETC is similar in thought and behaviour to that of humans, which may be false. However, it is likely to be true for at least some ETCs, especially if there are a large number of these (Crawford 1997).

In spite of the debate as to whether ETCs even exist, many authors do believe that it is worthwhile to search for possible signals.
2. RADIO SETI

Cocconi & Morrison (1959) first suggested that the 21 cm (1420 MHz) line of neutral hydrogen (H i) could be used as an interstellar “beacon”. However, there are other beacon possibilities, such as the 1667 MHz hydroxyl line, the 8.66565 GHz hyperfine transition in $^{3}\text{He}^{+}$ and the 6.68 GHz methanol line (Blair & Zadinik 1993). Many such beacon frequencies are swamped by natural astronomical emissions, and it has been suggested that constants which arise from intelligence, termed Civilisation Signature Constants (CSCs; Blair 1986), such as $\pi$ and $e$, could be used to code fundamental frequencies to provide new Interstellar Communications Channels (ICCs). Unfortunately, there are many possible different combinations of CSCs and ICCs (Blair & Zadinik 1993).

Another possible problem is that one must restrict a radio search to a relatively narrow frequency coverage, to avoid contamination by astronomical and terrestrial background sources. Even multichannel arrays give a relatively small frequency coverage, with for example the Megachannel ExtraTerrestrial Array (META; Horowitz & Sagan 1993) having 8,000,000 channels, each 0.05 Hz wide, covering an instantaneous bandwidth of 400 kHz around the 1420 MHz line of H i. However this is only a velocity coverage of 85 km s$^{-1}$, and as we do not know the radial velocity of a potential ETC, any signal could be Doppler shifted out of our receiver’s spectral coverage. It has been suggested (Blair et al. 1992) that an ETC might send a signal to us in one of several reference frames, namely:

1. Solar Barycentric (SB) reference frame, where the ETC makes all Doppler corrections needed for us to receive their signal exactly on the ICC frequencies, apart from correcting for the Earth’s motion.
2. Geocentric (G) reference frame, where the ETC corrects for both relative stellar motion and Earth’s orbital motion. The only correction needed is for the telescope’s position on the rotating Earth.
3. Target Barycentric (TB) reference frame, where the ETC corrects their signal for their own orbital motion, but not the relative stellar motion.
4. Cosmic Microwave Background (CMB) reference frame, where the ETC Doppler shifts their signal so that it would appear exactly at the ICC frequency if detected by a receiver stationary with respect to the CMB. This is a truly universal reference frame. However the Earth’s velocity relative to the CMB (calculated from the observed dipole anisotropy of the blackbody radiation) is currently rather uncertain (365 ± 14 km s$^{-1}$; Fixsen et al. 1994), so that a large frequency coverage would still be required.

To date, radio SETI searches have had null results (see, for example, Horowitz & Sagan 1993; Airieau et al. 1998), which perhaps is not surprising, given the problems in choosing even the correct CSC and ICC. In addition, the choices of targets for searches have, on occasion, perhaps not been optimal. For example, Blair et al. (1992) have searched for signals from a number of globular clusters, such as NGC 6254. These objects are known to contain only small amounts of metals (used in the astronomical context, i.e. elements with atomic numbers greater than helium), with, for example, NGC 6254 having a metal content only 3% that of the Sun (Chaboyer, Demarque & Sarajedini 1996). Such metal deficiencies, one would imagine, would be a barrier against the development of a technological civilisation, which requires metals. Indeed, one might expect that a lack of elements such as C, N, O and Fe would significantly reduce the likelihood of life developing, or even forming an Earth-like planet. We are unaware of any research to investigate the effect of metallicity on planet formation or the development of life, but such work could be very interesting.

As a result of the null detections, there is currently little government funding for SETI, with most of the resources coming from organisations such as the Planetary Society and the SETI Institute. An excellent review of NASA’s efforts in this area over the last 40 years is given by Launius (1998).

3. OPTICAL SETI

As well as communications at radio wavelengths, Cocconi & Morrison (1959) first suggested the possibility of interstellar communications via microwaves, as there were no lasers at that time. However, lasers were invented within a year, and Schwarz & Townes (1961) published the first suggestion of optical laser SETI (OSSETI).

As we show below, OSSETI removes several of the problems associated with radio region work, such as choosing the correct CSC and ICC, the correct reference frame, and spurious signals due to background or interference. There are existing OSSETI programmes at, among others, the University of California (Berkeley), Harvard University and Ohio State University (Columbus). Current work includes, for example, searching through high resolution spectra of nearby stars, obtained at the Lick and Keck Observatories, for ultra-narrow band signals. Details of the various OSSETI projects may be found on the WWW sites

- http://sag-www.ssl.berkeley.edu/opticalseti/
- http://mc.harvard.edu/oseiti/
- http://www.coseti.org/

while an excellent review is provided by Kingsley (1993).

Our interest started in 1997, when we were approached with the idea of firing a continuous working (CW) laser beam from South Kensington to a nearby star, to celebrate the Millennium. However, calculations by one of us (Burgess) and Professor M. H. R. Hutchinson (Rutherford Appleton Laboratory) showed that a 40W CW beam with a wavelength of 1 μm gives a flux of about $2\times10^{20}$ photons/sec. A 5-m diameter telescope at 10 light-years distance will receive a fraction $\sim 2.9\times10^{-20}$ of the output (for a beam of width $5\times10^{-7}$ radians, limited by atmospheric seeing), and hence one could expect to detect about 6 photons/sec from the laser. However the background from the Sun at 10 light-years at the same wavelength, and into a 5 Å bandwidth, is about 2000 photons/sec. This implies that a CW laser is unlikely to be recognised by an ETC, even if substantially higher powers are used.

However, it is a different story for pulsed lasers. The VULCAN pulsed laser at the Central Laser Facility, Rutherford Appleton Laboratory (Central Laser Facility Annual Report 1998) has two modes of operation. In the long-pulse mode, it delivers 1 kJ at 5300 Å in 1 nsec (i.e. a power of 1 TW), while a short-pulse provides 40 J in 1 psec (40 TW). The short-pulse will be enhanced to 500 J in 500 fsec (1000 TW) in ~2.5 years, via a £3.5M upgrade from the EPSRC. Delivery of the long-pulse (nsec) laser energy is via 6 beams, and the short-pulse (psec)
Table 1. Comparison of energy generated, per unit solid angle, by laser pulses and stars.  *Energy generated in 5 nsec.

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy generated in 5 psec (10^{14} J/steradian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VULCAN laser (40 J in 1 psec)</td>
<td>2.0</td>
</tr>
<tr>
<td>VULCAN laser (500 J in 500 fsec)</td>
<td>25</td>
</tr>
<tr>
<td>Sun (0.3 – 1 μm)</td>
<td>1.0</td>
</tr>
<tr>
<td>Sun (1 – 2.5 μm)</td>
<td>0.3</td>
</tr>
<tr>
<td>Sun (total output)</td>
<td>1.5</td>
</tr>
<tr>
<td>F5V star (total output)</td>
<td>5.4</td>
</tr>
<tr>
<td>G0V star (total output)</td>
<td>2.3</td>
</tr>
<tr>
<td>G5V star (total output)</td>
<td>1.2</td>
</tr>
<tr>
<td>K0V star (total output)</td>
<td>0.6</td>
</tr>
<tr>
<td>K5V star (total output)</td>
<td>0.2</td>
</tr>
<tr>
<td>NIF laser (1.8 MJ in 3 nsec)</td>
<td>90,000*</td>
</tr>
<tr>
<td>Sun (total output)</td>
<td>1,500*</td>
</tr>
</tbody>
</table>

energy is via a single beam. One must wait 20 minutes between shots. However, progress in the development of high repetition rate laser systems (currently at smaller energies than are available with VULCAN) is rapid, and an advanced ETC might well have developed a laser with VULCAN’s output characteristics, but with a repetition rate in the kHz or even MHz range. An important point is that a narrow bandwidth pulse of a psec or so duration, or a modulated chain of such pulses, would of itself be a strong signature of an artificial origin.

The laser pulse duration will be increased because of its passage through the atmosphere, the solar system and finally interstellar space. Starting with interstellar space, for a typical electron density of 1 cm^{-3} over a 10 light-year pathlength, a 1 psec pulse would only be stretched by 1 fsec. Hence even after transiting the Galaxy, the pulse would still be sub-nsec in duration. Dispersion due to interstellar hydrogen will be negligible. Conditions in the near-Earth interplanetary medium are 1000-10,000 times denser than interstellar space, but as the radius of Pluto’s orbit is < 0.001 light-years, interplanetary effects should be smaller than interstellar ones. Finally, using standard formulae for the atmospheric refractive index (Allen 1983), a 1 psec pulse at a wavelength of 1 μm will be stretched by 100 fsec in the atmosphere. Even with the rapid increase in refractive index with decreasing wavelength, a 1 psec pulse at 5000 Å will be stretched by only 1 psec. Hence we see that, provided high density interstellar clouds are avoided, pulse-lengthening due to dispersion is not a problem, even across Galactic distances.

The divergence of the laser beam is limited by the atmosphere. The best atmospheric seeing achieved is about 2×10^{-12} steradians, and the laser will appear as a point source to distant observers. As an example, we will assume that an ETC is searching for pulses at a time resolution of 5 psec. In Table 1 we show the energy generated by various laser pulses over such timescales, as well as the output of the Sun and other stars in several wavebands (Colina, Bohlin & Castelli 1996). The energy generated is given as flux per unit solid angle, as both the laser and the parent star will be detected as point sources. These quantities can be directly compared, provided the detector is smaller than the size of the laser beam. The laser beam will be about 1 astronomical unit in diameter at a distance of 30 light-years, so that this is a reasonable assumption to make. In addition, it also implies that any laser directed at a distant star is likely to shine on a planet orbiting within the habitable zone of its parent star. For closer stars, one could de-focus the beam to ensure that it would cover the complete habitable zone of a star.

An inspection of Table 1 shows that the energy generated by the current VULCAN laser is larger than that from the Sun over optical (0.3 – 1 μm) and infrared (1 – 2.5 μm) wavebands, and is comparable to the total energy from the star in the timescale of the laser pulse. The energy from the upgraded VULCAN laser is much larger than from the Sun summed over all wavelengths. It is also greater than that from any star between F5V and K5V, the range of MK types expected for stars with ETC-bearing planets (Blair et al. 1992). For the National Ignition Facility (NIF) laser, due to come on-line in 2002 (Paisner & Manes 1994), we can see that the laser energy during the pulse duration is nearly two orders of magnitude greater than from the Sun during the same time interval, even at a time resolution of only 5 nsec, achieved in current OSET1 projects (see, for example, Kingsley 1996).

Given the fact that proposed pulsed laser signals, even adopting conservative estimates for energy generation and time resolution, can provide detections which are larger than that from a parent star summed over all wavelengths, it is understandable why OSETI searches are underway. However, one might ask why we are not currently sending such signals, with for example the VULCAN laser? Unfortunately, the plasma refractive index has a second-order effect, dependent on the intensity of the radiation, which becomes very important when the intensity is high, as for laser pulses. Our work has shown that this effect will lead to the breakup of the laser beam very quickly as it travels through the atmosphere, for a typical VULCAN beam diameter of 10 cm. The beam would need to be expanded in vacuum to several metres wide, to reduce the ef-
fect to the point where the beam could propagate through the atmosphere without breaking up. We note that as the beam would still be observed as a point source from a distance, it would not effect the calculations presented in Table 1. However, the cost to expand the beam is currently prohibitive. Of course, a space-based laser would not have this problem.

4. CONCLUSIONS

We have shown that pulsed laser signals sent from an ETC should be observed to be brighter than the parent star, even when conservative estimates are adopted for the laser energy generation and detector time resolution. This is true even when the energy output from the parent star is summed over all wavelengths. As a result, optical SETI programmes may be more attractive than their radio counterparts, where there are problems such as choosing an optimal frequency at which searches should be performed.

Acknowledgements

MEP acknowledges financial support from the Department of Education for Northern Ireland and the Rutherford Appleton Laboratory. We are grateful to Ralph Bohlin, Ian Crawford, Paul Horowitz and Roger Launius for copies of their work. This research was supported by the Leverhulme Trust.

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