The search for extraterrestrial intelligence

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As far as we know, humanity is alone in the Universe: there is no definite evidence for the existence of extraterrestrial life, let alone extraterrestrial civilizations (ETCs) capable of communicating or travelling over interstellar distances. Yet popular speculation about the existence of ETCs abounds, including reports of alien visitations either now or in the past. But there is a middle way. It is now possible to put limits on the existence of ETCs of varying capabilities, within arbitrary distances from the Solar System, and conceive of real-world strategies whereby we might communicate with ETCs, or they with us.

One of the intriguing aspects of astrobiology in all its forms is that matters once confined to science fiction are increasingly being discussed seriously by scientists. SETI — the Search for Extraterrestrial Intelligence — is perhaps the best example. Knowledge of the space environment gathered over the past 40 years, as well as improvements in our own technological capabilities, can now be applied to make plausible estimates of the number of ETCs in the Galaxy with technologies comparable to or more advanced than ours. Even so, these estimates vary greatly[1,2]. Recent developments and discussion could help constrain such estimates, including the discovery and characterization of planets around other stars[3]; reports of the discovery of possible past life on Mars[4]; and Ward and Brownlee's book *Rare Earth*[5], in which they argue that life is common in the Universe, but ETCs are rare.

A history of SETI

When modern considerations of SETI began, microwave radar and radio astronomy in the centimetre wavelength range were mature technologies. Thus it was natural to believe that an ETC might transmit signals with radio telescopes similar to those then in operation[6,7]. SETI began in 1960 with the targeted search of two nearby Sun-like stars, using the 25-metre-diameter radio telescope of the National Radio Astronomy Observatory[7]. This was Project OZMA, named after the queen in an imaginary land, "very far away and populated by strange and exotic beings"[8]. OZMA was soon followed by other initiatives, all using radio telescopes[9], and SETI programmes continue today, despite uncertain funding. NASA's programme, the High Resolution Microwave Search (HRMS) included both a targeted search (examination of selected stars) and an all-sky survey, but was cancelled by the US Congress in the early 1990s[10]. Funding for SETI initiatives today comes from non-profit organizations such as the Planetary Society[11] and the SETI Institute[12]. The SETI Institute has revived the targeted-search portion of the HRMS as 'Project Phoenix' using systems based on the NASA detectors. Meanwhile, SERENDIP (Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations) — a programme at the University of California, Berkeley — provides detectors for large radio telescopes so that ETC searches can be made while conventional astronomical investigations are carried out[13].

SETI that does not involve direct physical contact with ETCs (which I rule out for the purposes of this article) is based usually around three rather different scenarios. First, the detection of electromagnetic signals from an ETC, deliberately targeted at us with the expressed intention of communication; second, the detection of signals from an ETC targeted elsewhere, but still designed for communication (for example, a space navigational beacon); and third, the detection of stray electromagnetic radiation from an ETC, not intended for interstellar communication (for example, radio or television signals). These scenarios increase in plausibility as well as difficulty, and are not mutually exclusive, given the difficulty of judging the intentions of ETCs.

A SETI practical

Before we even begin a search, we must be clear about the physical limitations of the technology available to us, both for the reception of signals and their transmission by ETCs. But within these limitations lie certain strengths, for they allow us to set limits on the existence of ETCs capable of specific technological capabilities within arbitrary distances from the Earth.

Early SETI projects concentrated on listening for electromagnetic signals in the centimetre waveband, between around 3 and 60 cm. The reasons for this choice are purely practical: it is in this region of the radio spectrum that background noise from the Galaxy, the Earth's atmosphere and the receiving equipment is lowest. Figure 1 shows the contributions from various sources of naturally occurring noise. Some of the basic concepts of the single parabolic reflectors used conventionally in radio astronomy[14], and which could be used to transmit as well as receive signals, are summarized in Fig. 2. When used for receiving transmissions, large antennas have the advantage of greater collecting area, and parabolic reflectors reap the rewards of greater sensitivity when targeted to specific directions. For example, a parabolic reflector of diameter 100 m can detect signals that are ten-millionths the strength of signals detectable to a non-directional antenna.

The same principle applies to the transmission of signals. Antennas directed at small regions are much more efficient (they have greater effective radiated power, or ERP) than antennas radiating isotropically, and transmission is better at shorter wavelengths. For example, targeted transmission at a wavelength of around 1 cm is 100 times as effective as transmission at 10 cm: power is more concentrated at shorter wavelengths, allowing more effective propagation of a signal through space. However, the optimal waveband for signal transmission does not coincide exactly with the 3–60-cm band used in early SETI projects, and it is easy to see why. The background noise generated by a receiver operating at 1 cm is tenfold that at 10 cm, and the Earth's atmosphere is more of an obstacle. The atmosphere becomes a serious problem at wavelengths shorter than 1 cm, but this could be circumvented by siting radio telescopes at high altitude or in space.

Which wavelength?

Since the days of Project OZMA, receiver sensitivity at centimetre wavelengths has improved 20-fold. In OZMA, 100-Hz 'windows' in the spectrum were searched sequentially[7]. Now, large wavelength regions are analysed simultaneously by parallel sets of detectors. This allows increases in the speed of searches by a factor equal to the number of channels, and soon it will be possible to analyse a billion contiguous, narrow channels simultaneously[15]. Expansion is possible in another direction — using an array of coupled radio antennas, rather than a single dish, to create a radio interferometer[14]. Such an array would be cheaper to build than a single telescope of the same size, and could also be used to receive signals from several different regions simultaneously. The Allen Telescope Array (ATA), funded by private sources and to be operated by the SETI Institute, is one such instrument. Both SETI and conventional radio astronomy projects could be carried out with this array, which will operate in the 3–60-cm waveband[16].

But the SETI searchers of the 1960s had one big advantage over contemporary scientists — they did not have to worry about the waveband they chose to examine. The 3–60-cm band was convenient, and within that band the choice was simple: in 1960, only one spectral line was known to be present in this region, namely the well known 21-cm emission line of neutral hydrogen. The hydrogen line is a prominent and universal feature, and proponents of SETI hope that ETCs would emit signals using carriers at or near this wavelength, taking advantage incidentally of the fact that it falls within the relatively radio-quiet 3–60-cm range. Since then, it has been found that the hydroxyl radical (OH) emits at 18 cm, so the 18–21-cm region — associated with the components of water — has been dubbed the 'water hole', a feature that might be exploited by ETCs seeking to communicate with life forms for whom water would be important[17].

Modern SETI is spoiled for choice: tens of thousands of spectral lines

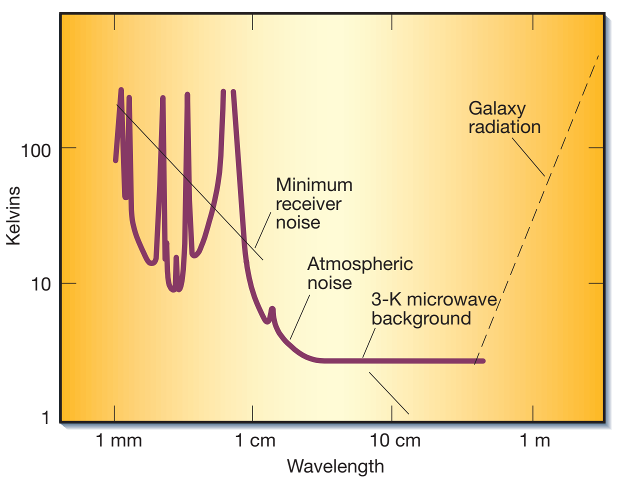


Figure 1 Noise from the Earth's atmosphere and the minimum noise from our Galaxy, versus wavelength. The vertical axis is in kelvins, which is proportional to power per unit bandwidth. The plot illustrates the low noise floor of the region between 3–60 cm, explaining its popularity among proponents of SETI. The curve marked 'minimum receiver noise' is ten times the theoretical minimum for radio-type receivers; the noise of many radio-type receivers approaches this value. The 3-K microwave background is the remnant radiation from the Big Bang[14]. Interstellar dust absorbs optical radiation, but not radio waves, so in the plane of our Galaxy radio signals can penetrate to great distances[14].

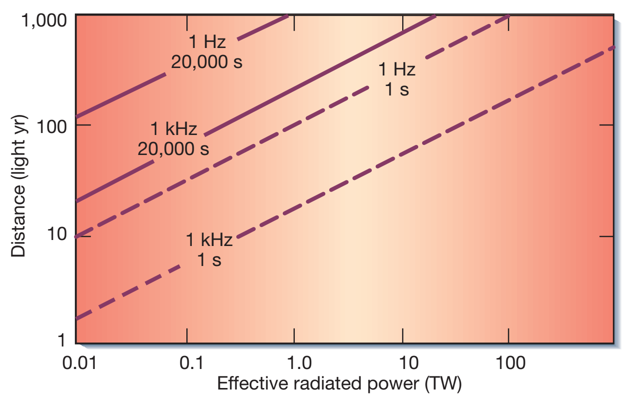
Box 1
Power requirements

The measurement of interest for a transmitter–antenna combination is the effective radiated power (ERP). ERP is proportional to the product of the effective power fed to the antenna and the squared diameter of the antenna in wavelengths. This can amount to a very large amount of energy: for example, if a 1-MW transmitter operating at 10 cm is connected to a 100-m antenna, the peak ERP is equivalent to the power used for all technological activities on Earth around 1970. And if there were another 100-m radio telescope receiving this signal at a distance of 100 light years, detection would occur in less than 30 s.

Spreading the bandwidth makes detection more difficult, as the figure below shows. A signal transmitted over a 1-Hz band can be detected from much further away than a signal having the same ERP but transmitted in a bandwidth of 1 kHz. If an ETC is sending a constant signal, then we increase our sensitivity by summing the result in time. Such a process increases the distance at which we can detect a given signal with a given ERP. Summing the signal for 20,000 s instead of 1 s allows us to detect a transmitter 12 times as distant.

All the above assumes that signals from ETCs would be sent intentionally for the purposes of communication. Much more problematic is the detection of 'inadvertent' signals from an ETC, such as from television transmitters[33], interstellar navigation beacons or the microwave emissions from orbiting satellites used for solar power production[34].

As an example, at a distance of just 10 light years, and using a 100-m telescope, we would need to sum a 6-MW signal for 10,000 years to detect it. We can shorten this time by increasing the size of the telescope. There was an ambitious proposal to build 'Project Cyclops', an array of up to 1,500 radio telescopes each of 100-m diameter[17]. With Cyclops, television broadcasts from ETCs could be detected by summing the signal for 4 h. But even in this optimistic case, detection of an inadvertent signal would not be easy.



Box 1 Figure Signal detection as a function of transmitter power, signal bandwidth and integration time. The diagonal lines represent the distance at which a given signal can be detected at five times the noise for a given bandwidth (in hertz) and a given integration time (in seconds). If, for example, a 200-MW transmitter operating at 3 cm is coupled to a 100-m radio telescope with an efficiency of 0.6, the ERP is 10^4 TW (10^{10} MW). The calculation is based on the assumption that the receiving antenna has a diameter of 100 m, an efficiency of 0.6, and is equipped with a 20-K noise temperature receiver. There are two sets of curves, for bandwidths of 1 Hz and 1 kHz. The dashed curves shown have shorter integration times than the corresponding solid curves[18].

Box 2
The Kardashev classification

Kardashev[21] classified possible ETCs according to the energy at their disposal (see table below). This scheme allows us to determine whether we are dealing with a civilization like our own (type I), a rather advanced civilization (type II) or a vastly more advanced civilization (type III). Humanity has sufficient resources at present to broadcast messages comparable to a type I civilization in a specific direction, although in practice the types of transmission are based on isotropic radiators. A Type II transmission might be transmitted by an ETC that had captured all of the power from its central star. These ETCs are referred to as Dyson civilizations[27]. Type III civilizations have captured the power of an entire galaxy.

In a recent survey of SETI results, it is reported that searches rule out type II civilizations to a distance of 10 million light years and type I civilizations to 1,000 light years (ref. 22). However, this is based on two assumptions. First, that ETCs transmit at centimetre-scale radio wavelengths, and second, that the bands surveyed include the transmitter wavelengths of nearby galaxies. Conservatively, one can state that for a sizeable part of our galaxy we can probably rule out the presence of type II and III civilizations, if these ETCs are broadcasting messages in the centimetre wavelength range. However, there exist sources of radio emission that are about a million times as powerful as those at the disposal of hypothetical type I ETCs. These arise from regions smaller than 1,000 times the distance between the Earth and Sun, although a detailed analysis of the noise characteristics of these signals shows that they are natural sources of radiation[35].

Box 2 Table Transmission power of ETCs

Civilization	ETC transmission power
Type I	The power expended by all technological activity on Earth. For a specific direction, this can be achieved by coupling the output of a 1-MW transmitter, operating at 10 cm, to a 100-m diameter telescope.
Type II	The power in the entire output of the Sun. This is equal to 10^{14} times a type I transmission.
Type III	The power from our entire Galaxy. This is 10^{11} times a type II signal.

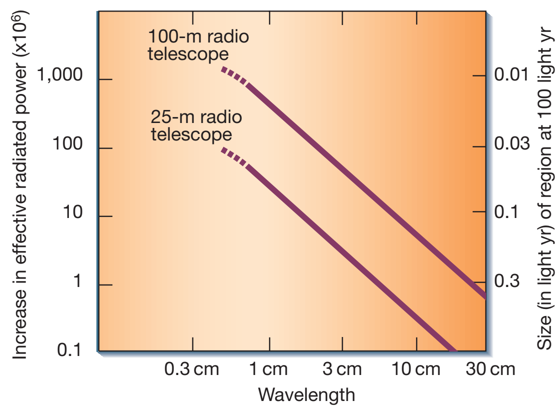


Figure 2 How increases in effective radiated power (ERP) of a transmitting radio dish are related to wavelength and the size and distance of the target. The increase in ERP is plotted on the vertical axis for two antennas as a function of wavelength. For a given antenna size, the power is increasingly concentrated into a smaller region as the wavelength decreases. When the antenna surface becomes comparable to the wavelength, this dependence breaks down (indicated by the dashed line). The 100-m diameter antenna has 16 times the effective power of a 25-m antenna for the same wavelength and target size. This advantage also holds when the telescope is used for receiving: the size of the region contained within the telescope beam at a distance of 100 light years is shown on the right-hand scale. For example, the 100-m radio telescope will include a region 0.14 light years across. Because this is about 4,000 times the diameter of the Earth's orbit around the Sun, we would certainly receive a transmission from an Earth-like planet when pointing towards a star at 100 light years.

from more than 115 known interstellar molecules are now known, so that the choice of a SETI wavelength has become complex. Many authors argue that the 18–21-cm 'water hole' range is best, but this in itself does not rule out other possibilities[7]. The intentions of ETCs are always a wild card: ETCs might choose to send messages at a wavelength obtained from various combinations of atomic constants. One such combination gives a wavelength of 11.72 cm (ref. 18), but there is no compelling argument for this wavelength either. Because agreement is lacking on which wavelength is the most likely, one approach is a systematic search through the range from 3 to 60 cm. An added advantage of using this range is that it is easier to build radio telescopes with large collecting areas. But as already noted, there are also arguments for specific frequencies outside this range. At shorter wavelengths, other choices would be 1.35 cm (a transition of water) or 1.47 mm (the analogue of the 21-cm line for a positron–electron 'atom'[19,20]).

Effective power

Successful transmission and reception are limited by available power (Box 1). If the distance at which a signal can be detected by a 100-m radio telescope is plotted as a function of transmitter power, signal bandwidth and integration time (Box 1 Figure), it is clear that the most effective radio transmission must use a narrow bandwidth. The drawback, familiar to any Internet user, is that the narrower the bandwidth, the slower the transmission of information[14]. Of course, we cannot know *a priori* the power at the disposal of any proposed ETC. As a way of addressing this, Kardashev[21] devised a scheme for the classification of ETCs according to the resources they might be able to command. A 'type I' civilization controls the resources of its home planet. Humanity is close to that point now. A 'type II' civilization can control the output of its home star, whereas a 'type III' civilization can dispose of the resources offered by its home galaxy (see Box 2). This classification can be used to set bounds on the existence of ETCs of specified technological capabilities within arbitrary distances of the Earth.

Given that we seek to receive and/or transmit signals from a specific direction, rather than isotropically, it should be possible in principle to exchange signals with a type I ETC using a 100-m radio telescope, together with a high-power transmitter to send narrow-band signals. These would be detectable with another 100-m radio telescope even out to a distance of 1,000 light years. A message from a type II civilization, on the other hand, would be detectable with a telescope of 10-m diameter from a distance of 100 million light years, which is 100,000 times further than the limit for a type I ETC. Type III ETCs, with galaxies of energy at their command, should be detectable to distances 10,000 times greater than the most distant type II ETC.

Stars are concentrated in galaxies, and there are more than 20 galaxies within 3 million light years of the Milky Way. In principle, we should be able to receive a message from type II or III ETCs in any of these with technology currently available. With an average of 10,000 million Sun-type stars per galaxy, we could detect messages from ETCs even if the product of the last five terms in the Drake equation, which computes the number of communicating civilizations in a galaxy at a given time (see Box 3), were less than one part in a 100 million. These considerations provide a rationale for all-sky, untargeted searches: with the possibility of at least modest numbers of perhaps readily detectable ETCs (especially of type II or III), the extra sensitivity conferred by targeted searches would not be an absolute requirement for success. However, the fact remains that no confirmed transmissions in the centimetre wavelength range have been received[9,22], from which it has been claimed that type II and type III ETCs do not exist at the present epoch[22].

This claim is overstated: it may be valid for a sizeable part of our Galaxy, but only if the ETCs are broadcasting in the centimetre wavelength range without interruption — and if they wish their signals to be detectable. Signals in the centimetre range might be attenuated or

Box 3
The Drake equation

The Drake equation is an attempt to quantify estimates of the number of ETCs[7]. This relation is

$$N = R_* f_p n_e f_l f_i f_c L$$

where N is the number of ETCs communicating at any given time; R_* is the average rate of galactic star formation; f_p is the fraction of stars accompanied by planets; n_e is the number of planets per star system with conditions needed to support life; f_l is the fraction of habitable planets on which life actually arises; f_i is the fraction of the life-bearing planets which develop intelligent life; f_c is fraction of intelligent species which develop communication technologies; and L is the 'life span' of the communicating technological culture.

Astronomy is crucial in source selection for targeted surveys. We assume that ETCs need billions of years to develop, so only stars with such lifetimes would be suitable candidates for SETI. These stars must be similar to our Sun. There are approximately 1,000 such stars within 100 light years from the Sun[18]. More than 50 extrasolar planetary systems are currently known, but most of these are unlike our Solar System. At present we can detect planets that have Saturn-like masses with orbits close to the star, but because of limitations to measurements, we still have not found an Earth-like planet orbiting a Sun-like star. Finding these will require hundreds of times more accuracy than is available now; such searches will be conducted from satellites in the next decades. The value of N remains highly uncertain. Even if we had a perfect knowledge of the first two terms in the equation, there are still five remaining terms, each of which could be uncertain by factors of 1,000.

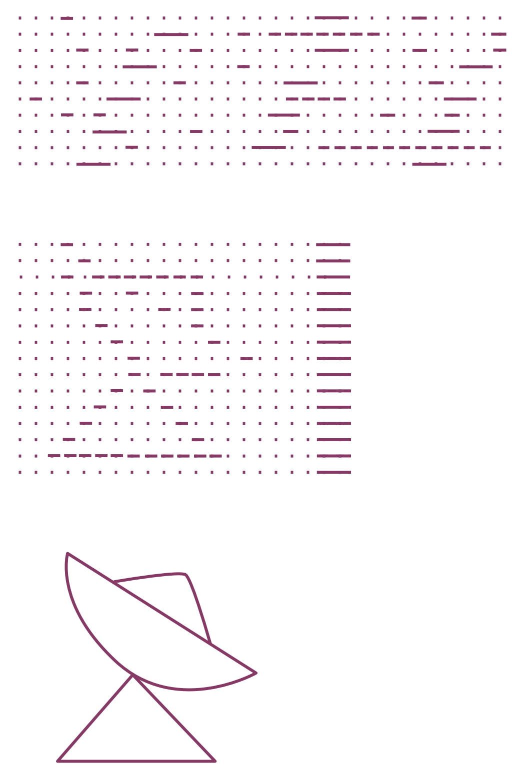


Figure 3 An example of a possible message from an ETC. **a**, A hypothetical signal pattern as received. The dots represent a short transmission and the dashes are transmissions of longer duration. The dashes of double length indicate the end of a line of dots and shorter dashes. **b**, The message has been arranged so that the longer dashes form the end of a row. **c**, Line drawing obtained by connecting the shorter dashes by a smooth line.

interrupted by the interstellar medium between an ETC and the Earth[23], so an otherwise constant signal might be detectable only occasionally. It is simple to imagine ways round this problem, such as redundancy, repetition or the transmission of a second signal at twice or one-half the chosen wavelength[24]. If the ETCs do not want to transmit signals deliberately, we may have to eavesdrop. One example of an unintended signal is the broadcast from a powerful television transmitter. But the reliable detection of unintended messages would require much larger telescopes, and in the case of television, the ETCs might use transmission via satellites or cable, in which the chances of finding broadcasts would decline still further.

Beyond radio

There is no reason why SETI should be restricted to radio wavelengths — it is possible that ETCs might transmit in other parts of the electromagnetic spectrum, such as the infrared or optical ranges[25,26]. The advantage of the latter is simply one of energy density: with optical systems, very high ERPs can be obtained with modestly sized optical telescopes. Indeed, optical SETI (OSETI) is just now beginning with 1-m class optical telescopes (ref. 27 and Box 4). The OSETI searches for type II and III civilizations should be finished quickly, but for type I civilizations, OSETI will require much more time. If type I ETCs are common, one can expect success from a complete survey of stars to a distance of 100 light years. A targeted survey would require a few years. If, however, there is an ETC for every million Sun-like stars, the time will be much longer. Using the ATA in the centimetre wavelength range or the modern OSETI detector systems in the optical or infrared ranges, it would be possible to examine a number of stars simultaneously. Such techniques should shorten the time needed for such searches to a few decades.

ET intentions

If signals are transmitted with the intention that they are detected, we would expect that ETCs would want us to recognize their signals as artificial. Broadcasts should have characteristics incommensurate with natural signals. The problem is that the characteristics of natural radio emissions vary over an extraordinarily large range. The narrowest spectral line has a width of 600 Hz, which is also a transition of the hydroxyl radical at 18 cm (ref. 14) in the 'water hole'. This line has a rather high intensity, but we are certain that it is natural as the noise statistics are typical of random processes and the time variability is very slow. At the other extreme are signals from pulsars, which show time variations on microsecond scales. At first, there was some speculation that pulsar signals were broadcasts from ETCs, but this was dismissed when measurements showed that the pulses were present over a wide frequency range. No ETC would be so wasteful, so the emission was taken to be natural. This emission has also been identified with rotating neutron stars[14]. In the near infrared, several stars were found to have large amounts of excess emission. Because such phenomena had already been discussed in terms of ETCs, this was taken as a signature of type II civilizations (ref. 28 and Box 2) in the course of shielding their parent star within a Dyson sphere. However, the radiation was found to be broadband, with only slow time variations, and these objects turned out to be dust-enshrouded stars[14].

In summary, we assume that any ETCs would be aware of astronomical phenomena and would construct signals that will appear to be anything but normal. If ETCs send messages, these would be sent at specific wavelengths. They would have widths of a few hertz or pulses of nanosecond duration, but not both. How can we differentiate between terrestrial interference and ETC messages? If the signals from ETCs cover a large bandwidth, these would be subject to greater time delays at longer wavelengths in travelling through the slightly ionized medium of interstellar space[14]. The actual ETC messages at shorter wavelengths would arrive earlier. Terrestrial interference would show no such delay, so we would be able to differentiate between broadband

Box 4
Optical SETI

There is an advantage in transmitting signals at short wavelengths. This explains the interest in optical SETI (OSETI) in which searches are done at optical wavelengths, which are very much shorter than radio wavelengths. In OSETI, receiver noise floor is very much lower, increasing receiver sensitivity. For transmission, it is simple to show that a 1-m telescope, operating in the optical range, can produce one hundred million times the ERP as a 100-m radio telescope operating at 50 cm. In addition, systematic effects such as interference should be less in the optical or infrared than the radio wavelength region and the rate of information transfer is faster because of the larger bandwidths. Filters in the optical range are less selective than in the radio range, but an advantage is that ETCs could send messages using nanosecond pulses designed to look artificial and thus distinguishable from natural sources of electromagnetic radiation.

OSETI proponents also make an argument based on properties of the interstellar medium. Ionized clouds in the interstellar medium[23] scatter and absorb light much less than radio signals. However, optical or infrared signals are absorbed by dust in interstellar clouds. The targets for OSETI are selected on the basis of visible light or near-infrared measurements, and so would not be affected by intervening material. Thus the overall effect of interstellar clouds on optical or near-infrared communications is smaller.

The following example illustrates the advantages of OSETI in regard to effective radiated power[27]. An ETC orbiting a Sun-like star could use a laser to illuminate a 1-m optical telescope through narrowband optical filters. The ETC could then produce a short pulse lasting a microsecond or less. This would produce a flash 300,000 times as bright as their Sun. Even without optical filtering, the flash would still be 30 times as bright as their Sun, and this factor would rise to 3,000 if the diameter of the telescope were increased to 10 m, as with the Keck telescope. Because of the short pulse length, such OSETI signals would not be found in conventional optical surveys.

ETC signals and local interference. For steady, narrowband signals, a fixed direction on the sky, modulation to transmit a message, and periodic Doppler shifts in wavelength caused by orbiting a star would be signs of extraterrestrial origin. However, short-lived, narrowband signals could be either interference from Earth or ETC signals.

What would be the content of an ETC signal? There have been many studies of the coding and content of hypothetical messages. The central problem of interpreting a message from an ETC is that we would have no idea about its language or syntax. The most reasonable communication mode would be mathematical and/or pictorial. Figure 3 shows a simple example of a possible ETC transmission, which consists of a picture from a rectangular array of '1's and 0's'[2]. Because the time delay would be decades or even centuries, there could be no 'conversations', but a message announcing 'we are here' and presumably 'this is what we look like'.

Where are they?

If ETCs exist, they are not making their presence obvious. This in itself suggests that type III and perhaps type II civilizations are at best extremely rare. There are, however, many possible reasons why we have not made contact with ETCs. First, there may simply be very few[5]. Second, there may be a number of ETCs, but these may be sending messages in optical or near-infrared ranges that we have yet to explore comprehensively[25]. Third, there may be ETCs, but these may not be interested in communicating[29] and choose to keep themselves hidden. This is more speculative since it depends on the cultural aspects of ETCs[30]. From searches so far, the lack of contact shows us that transmissions, if any, are weak or intermittent signals (or both). The detection of ETC messages will take time and effort.

As the Drake equation (Box 3) shows, SETI is a business full of imponderables, of unknowable answers to impossible questions. We can, however, take comfort in some of the near-certainties of physics. For example, there seems to be no hope for faster-than-light travel, so actual visits from ETCs are unlikely. Even with the most efficient propulsion systems, the energy needed to reach stars at 10 light years in 20 years would be the equivalent of the present world consumption for 1,000 years (ref. 31). Such expenditure of energy would hardly deter a type III ETC, but even then, broadcasts make more energetic sense than personal appearances. There have been suggestions that ETCs might populate space with self-replicating machines in space probes[32]. This would allow colonization of large regions of space in relatively short intervals of time, but it seems vastly more complex than communicating by means of electromagnetic radiation[6].

And what of ourselves? One can only speculate on the effect that contact with an ETC would have on humankind. Such a discussion exceeds the scope of this essay, which has been confined (deliberately) to technical matters. But the simple knowledge of the existence of ETCs would doubtless have far-reaching effects on our relationship with the Universe — as, no doubt, would be a persistent failure to detect ETCs, as this would confirm our uniqueness. □

1. Hart, M. H. An explanation for the absence of extraterrestrials on Earth. *Q. J. R. Astron. Soc.* **16,** 128–135 (1975).
2. Sagan, C. & Drake, F. D. The search for extraterrestrial intelligence. *Sci. Am.* **232,** 80–89 (May 1975).
3. Vogt, S. S., Marcy, G. W., Butler, P. R. & Apps, K. Six new planets from the Keck Precision Velocity Survey. *Astrophys. J.* **536,** 902–914 (2000).
4. McKay, D. S. *et al.* Search for past life on Mars: possible relic biogenic activity in martian meteorite ALH84001. *Science* **273,** 924–930 (1996).
5. Ward, P. D. & Brownlee, D. *Rare Earth: Why Complex Life is Uncommon in the Universe* (Copernicus Books, New York, 2000).
6. Cocconi, G. & Morrison, P. Searching for interstellar communications. *Nature* **184,** 844–846 (1959).
7. Drake, F. D. in *Current Aspects of Exobiology* (eds Mamikunian, G. & Briggs, M. H.) 323–345 (Pergamon, New York, 1965).
8. Baum, L. F. *The Wizard of Oz* (Bobbs-Merrill, New York, 1900).
9. Tarter, J. in *The Search for Extraterrestrial Intelligence* (eds Kellermann, K. I. & Seilstad, G. A.) 79–98 (National Radio Astronomy Observatory, Greenbank, 1986).
10. Tarter, J. & Klein, M. in *Progress in the Search for Extraterrestrial Life* (ed. Shostak, G. S.) *ASP Conf. Ser.* **74,** 457–469 (The Astronomical Society of the Pacific, 1995).
11. McDonough, T. in *Progress in the Search for Extraterrestrial Life* (ed. Shostak, G. S.) *ASP Conf. Ser.* **74,** 419–422 (The Astronomical Society of the Pacific, 1995).
12. Pierson, T. in *Progress in the Search for Extraterrestrial Life* (ed. Shostak, G. S.) *ASP Conf. Ser.* **74,** 443–444 (The Astronomical Society of the Pacific, 1995).
13. Werthimer, D., Ng, D., Bowyer, S. & Donnelly, C. in *Progress in the Search for Extraterrestrial Life* (ed. Shostak, G. S.) *ASP Conf. Ser.* **74,** 293–301 (The Astronomical Society of the Pacific, 1995).
14. Rohlfs, K. & Wilson, T. L. *Tools of Radio Astronomy* 3rd edn (Springer, Heidelberg, 1999).
15. Leigh, D. & Horowitz, P. in *Bioastronomy '99—A New Era in Bioastronomy* (eds Lemarchand, G. & Meech, K.) *ASP Conf. Ser.* **213,** 459–465 (The Astronomical Society of the Pacific, 2000).
16. Welch, W. J. & Dreher, J. in *Radio Telescopes* (ed. Butcher, H. R.) *Proc. SPIE* **4015,** 8–18 (2000).
17. Oliver, B. M. & Billingham, J. (eds) Project Cyclops. NASA CR-114445 (1973).
18. Kuiper, T. B. H. & Morris, M. Searching for extraterrestrial civilizations. *Science* **196,** 616–621 (1977).
19. Mauersberger, R. *et al.* SETI at the spin-flip line frequency of positronium. *Astron. Astrophys.* **306,** 141–144 (1996).
20. Kardashev, N. S. Optimal wavelength region for communication with extraterrestrial intelligence—$\lambda = 1.5$ mm. *Nature* **278,** 28–30 (1979).
21. Kardashev, N. S. Transmission of information by extraterrestrial civilizations *Sov. Astron.* **8,** 217–221 (1964).
22. LePage, A. J. Where they could hide. *Sci. Am.* **283,** 40 (2000).
23. Cordes, J. M. & Sullivan, W. T. III in *Progress in the Search for Extraterrestrial Life* (ed. Shostak, G. S.) *ASP Conf. Ser.* **74,** 325–334 (The Astronomical Society of the Pacific, 1995).
24. Cohen, C. & Charlton, D. in *Progress in the Search for Extraterrestrial Life,* (ed. Shostak, G. S.) *ASP Conf. Ser.* **74,** 313–322 (The Astronomical Society of the Pacific, 1995).
25. Townes, C. H. At what wavelength should we search for signals from extraterrestrial intelligence? *Proc. Natl Acad. Sci. USA* **80,** 1147–1151 (1983).
26. Kingsley, S. A. in *The Search for Exterrestrial Intelligence in the Optical Spectrum* Vol. II (ed. Kingsley, S. A. & Lemarchand, G. A.) *Proc. SPIE* **2704,** 102–116 (1996).
27. Howard, A. *et al.* in *Bioastronomy '99—A New Era in Bioastronomy* (eds Lemarchand, G. & Meech, K.) *ASP Conf. Ser.* **213,** 545–552 (The Astronomical Society of the Pacific, 2000).
28. Dyson, F. J. in *Perspectives in Modern Physics* (ed. Marshak, R. E.) 641 (Wiley, New York, 1966).
29. Brin, G. D. The 'great silence': the controversy concerning extraterrestrial intelligent life. *Q. J. R. Astron. Soc.* **24,** 283–309 (1983).
30. Morrison, P. M. in *Interstellar Communication: Scientific Perspectives* 168–186 (ed. Ponnamperuma, C. & Cameron, A. G. W. (Houghton-Mifflin, Boston, 1974).
31. Oliver, B. M. Efficient interstellar rocketry. International Astronautical Federation IAA-87-606, 1–6 (1987).
32. Bracewell, R. N. *The Galactic Club* (Freeman, San Francisco, 1974).
33. Sullivan, W. T. III, Brown, S. & Wetherill C. Eavesdropping: the radio signature of the Earth. *Science* **199,** 377–388 (1978).
34. Glaser, P. E. Power from the Sun: its future *Science* **162,** 857–861 (1968).
35. Wilson, T. L. & Huettemeister, S. *Tools of Radio Astronomy: Problems and Solutions* p. 15 (Springer, Heidelberg, 2000).