Beings on Earth: Is That All There Is?

This paper reviews the past, present, and future expectations of the systematic search for extraterrestrial intelligence or SETI, and discusses if we are any closer to detecting cosmic company or knowing at least whether it should be out there.

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ABSTRACT | The systematic search for extraterrestrial intelligence (SETI) has been ongoing for slightly more than half the century that this journal has been in print, and the topic has been of human interest through recorded history. Are we any closer to detecting cosmic company or knowing whether it should be there? This paper takes a look at what has been done, what we are currently doing, and briefly speculates about what the future of SETI research may look like as well as the implications of a successful detection.

KEYWORDS | Antenna arrays; antenna feeds; array signal processing; astronomy; interstellar communication; interstellar messages; receivers; search for extraterrestrial intelligence (SETI)

I. INTRODUCTION

The search for extraterrestrial intelligence (SETI) began as a scientific exploration with the publication of the first refereed paper in 1959 [1], and the first observational project in 1960 at the National Radio Astronomy Observatory [2]. Speculations about whether intelligent life on Earth represents the only form of sentience in the cosmos can be traced back to the early Greek and Chinese philosophers. Though admittedly some of these speculations seem quite unreasoned given the cosmology of the 21st century, they illustrate the abiding human curiosity about our place in the universe. Are we alone?

During the past half century, the vast majority of SETI searches have utilized the tools of astronomers and focused on radio and optical wavelengths. In recounting this history, Tarter [3] has cataloged searches at every wavelength that is accessible to instrumentation as well as searches for, and suggestions of searches for, information-bearing particles other than photons, artifacts on Earth, in the human genome, and in the solar system. Certainly the attention paid to these enterprises in the popular press would suggest that the searching has been exhaustive and comprehensive after all this time. Reality is quite different. The search space for electromagnetic signals alone is at least nine-dimensional (three-space, one-time, two-polarizations, one-modulation, one-frequency, and one-sensitivity, this last being a combination of unknown transmitter power and distance) and many of those dimensions are very large compared to the tools that our current technology can bring to explore them. By one numerical analogy [4], the combined efforts of SETI searching to date have been the equivalent of scooping one 8-oz. glass of water from the Earth's oceans in order to determine whether any fish live in the ocean. It is an experiment that could in fact succeed, but lack of success is not likely to convince many that the ocean is devoid of fish. Likewise, the search for evidence of other technological civilizations (technosignatures) has barely begun, and it is premature to draw any conclusions quite yet. This is why Fermi's Paradox is not, in fact, a paradox.

Fermi famously questioned "Don't you ever wonder where everybody is?" during lunch back in 1950 at Los Alamos National Laboratory [5]. By "everybody" it was understood he meant the extraterrestrials. Fermi assumed that interstellar travel was both possible and inevitable, so that if any other technological civilization had ever existed

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before us, then on a timescale that is short with respect to the age of the galaxy, every star system would have been colonized. Because they are not here, Fermi concluded that we must be the first. Leaving aside the sensational claims of alien abductions and encounters with UFOs that have steadfastly remained unsupported by tangible evidence, the glass of water analogy demonstrates that we have not yet conducted a significant enough search and cannot even conclude they are not here [6].

At least in terms of searches for radio signals, advances in analog and digital technologies have led to current programs that are 14 orders of magnitude more comprehensive than the first search in 1960. The exponential speed with which digital devices are still continuing to improve suggests that this will remain true for another 15 years [7], beyond which lies the tantalizing promise of manageable quantum computation. If this is indeed the case, and if radio signals are the correct thing to be searching for, then success could be within our grasp in the next decade or two, and is dependent primarily upon the average longevity of any technological civilizations, because that determines how many of the Milky Way's 400 billion stars need to be examined before the right one turns up [8].

II. TECHNOSIGNATURES

To some critics, radio signals seem parochial, not something an advanced technology would be using, or at least not for very long. Is this a fair criticism? Consider the alternatives.

We assume that the technological civilization utilizes some sort of technology deliberately to convey its presence and possibly information. While it may be enjoyable to think about accidently tuning in on the extraterrestrial (ET) equivalent of old television broadcasts, that is not realistic. The amount of power that is engineered into transmissions intended for local consumption is no more than is required for their intended purpose; probably sufficient to illuminate the next county, but not the distant stars. The easiest technosignatures to detect will be those intended for us to discover. The development and the application of extraterrestrial technology is subject to the laws of physics. Additionally, the reception of that technological signature is limited by the technology of the receiving entity, in our case a young emerging technology in a very old galaxy. It is outside the scope of this paper to discover new physics though some might be alluded to elsewhere in this Centennial Issue. What could we realistically expect, or be able to recognize?

A. Artifacts

One possible technological signal is to physically convey an artifact. This could range from beaming a stream of cosmic particles at near light speed to sending a delegation to post inscribed megaliths among unsuspecting primitives. The primary physical hurdle with this approach is just the sheer energy needed to do so. Accelerating a one kilogram mass to, say, half the speed of light takes more than three billion kilowatt hours of energy; 300 million dollars at \$0.10/kWh—a hefty power bill for sending one kilogram to one location. On arrival it will expend that energy as a four-megaton impact detonation, which would almost certainly be noticed by someone, should there be anyone with sentience at the time.

One can invoke faster-than-light travel or space-time warping, etc., but a central tenet of physics is that you cannot cheat on the energy budget. And these energy needs apply to a spacecraft with occupants, with the added complication of keeping them alive for the long journey, which also means you cannot accelerate or decelerate them too harshly and that you need the same amount of energy available at the end of the journey to slow them down. If you are going to take that route, you had better know exactly where you are going in the distant future and be really, really patient. This suggests that the spacecraft might be a nanoprobe and the occupants could be advanced forms of artificial intelligence. While not new physics, it is technology not yet in hand today. It does represent a type of technosignature that would have avoided detection in previous searches, and is a potential that should be considered. Such consideration will be inevitable as we get serious about cataloging the objects occupying the space surrounding our planet. As we develop means for monitoring and eliminating the threat of our own space debris and we scrutinize our solar system in greater and greater detail, searching for potential hazards posed by collisions with near Earth objects, the phase space available for any such probes to remain undetected will continue to shrink.

B. Neutrinos

Neutrinos are extremely light particles generated in thermonuclear reactions—the Sun generates copious amounts every second (about 10^{38}). Those generated at the European Organization for Nuclear Research (CERN) have recently fostered a serious discussion about whether they might be capable of superluminal speeds on their way to detectors in Italy [9]. Since they have little to no mass, they do not have such severe energy constraints. Since they are charge neutral, they will not be deflected by the galactic magnetic fields and could, in principle, be aimed at a target. One could imagine sending a sequence of neutrinos as a message. Unfortunately for the sort of neutrino communication that has been suggested [10], they are also incredibly hard to detect because their cross section for interaction with matter is so low. Currently deployed neutrino detectors such as Amanda and Ice Cube would have only marginal sensitivities to this form of interstellar communications, but the researchers involved with these experiments have indicated their awareness of this possibility.

C. Gravity Waves

All objects with mass generate gravity waves when accelerated, however, to be noticed, one needs very massive objects to do something dramatic, like two black holes finally devouring themselves. This then gets back to the energy argument of accelerating such large objects to large velocity, which you need to do repeatedly in order to transmit information that would be discernable above natural processes that are postulated.

D. Modulating Astrophysical Phenomena

Since so much energy is required to generate technosignatures, perhaps it would be more economical for an advanced technology to modulate a bright source of radiation that exists naturally. Consider this thought experiment: suppose an advanced technological civilization erects a large venetian blind 100 light years (LY) from Earth, obstructing our line of sight to a certain distant luminous quasar.[1] Like signal lanterns of old, the blinds could be rapidly opened/shuttered introducing artificial and easily detected fluctuations of the quasar luminosity. The quasar is 2 billion LY away, so at 100 LY the blinds could be only 100 m in diameter and produce a 1% modulation. Such a beacon might be difficult to aim as its beam is smaller than the Earth's radius, but highlights the concept that power modulation is cheaper than power generation. A specific modulation idea has been recently suggested [11]: modulate stellar radiation by placing a large oddly shaped object in orbit around a star. This orbiting artifact would be visible in the light curves being examined for planetary transit events by astronomers on a distant, fortuitously oriented receiving world. The higher order terms of the luminosity fluctuations during transit ingress and egress could distinguish this orbiting object from a natural planet that by definition must be round. Another idea (after Tommy Gold [12]) supposes that a civilization could use an astronomical maser as a "free" amplifier for low-power drive signals. A proof of concept for this amplification came with discovery of a maser that is modulated by a nearby pulsar [13]. Another method by which an advanced technology might modulate an astrophysical radiator [14] involves orbiting a neutrino factory around a Cepheid variable star.[2] By artificially advancing selected cycles of expansion, a short/long period binary code for sending information across interstellar, even intergalactic, distances could be created, albeit at a rather slow rate of bits per day or week. The modulation of a strong natural source has some limitations in terms of flexibility, but it has an important advantage in terms of discovery: as any emerging technology begins to examine its physical universe, it will inevitably discover this artificial modulation scheme. The transmitting technology can be assured that eventually its efforts will be successful, if only the modulation continues long enough. From the point of view of the receiver, a systematic examination of the cosmos, carried out to satisfy scientific curiosity, could be rewarded by detection of these deliberate signals.

E. Electromagnetic Waves

Electromagnetic waves are massless and travel at the speed of light (and only at the speed of light). They are inexpensive to generate (and inevitable if you happen to live at temperatures greater than 0 K). The physics of the interstellar medium suggests that at radio frequencies narrowband signals and long duration, narrow pulses can propagate over long distances with little or no distortion, and would appear obviously engineered to any receiver. As explained later, the average of the natural astrophysical sources of background radiation has a minimum in the microwave region of the spectrum further favoring these sorts of transmission. When spatial and temporal observing filters are considered, the background radiation can also be inexpensively reduced at visible and near-IR wavelengths making nanosecond pulses another candidate for obviously engineered technosignatures. While an advanced technology may in fact have evolved to using some other, as yet unknown to us, technology for the purposes of its own internal communications, the physics of the transmission medium we share may commend radio and optical transmissions over interstellar distances. In the event that our emergent technology has not yet understood that some presently unknown, putative *zeta-rays* (whatever they are) are, in fact, the technology of choice for this sort of long distance communication among advanced civilizations, then the only relevant strategy is to make sure that we survive long enough that we too can master *zeta-ray* transmission and reception. In the meantime, we should continue to employ the technologies we do understand because they may in fact be the right ones. Furthermore, in the process of exploring parts of observational phase space thought to be more appropriate to engineered technosignatures than to astrophysics, we might just learn something new about the universe that overturns these biases.

III. CURRENT DETECTION SCHEMES AND NEAR-TERM IMPROVEMENTS

We live in a glorious age of cheap signal processing. This makes a remarkable difference in which and how many ideas for SETI observations actually get pursued. In 1960, the output of an analog single-channel receiver could be displayed on a chart recorder, and data postprocessing was next to impossible. Today's telescopes look in multiple directions at once, observe millions of discrete frequencies

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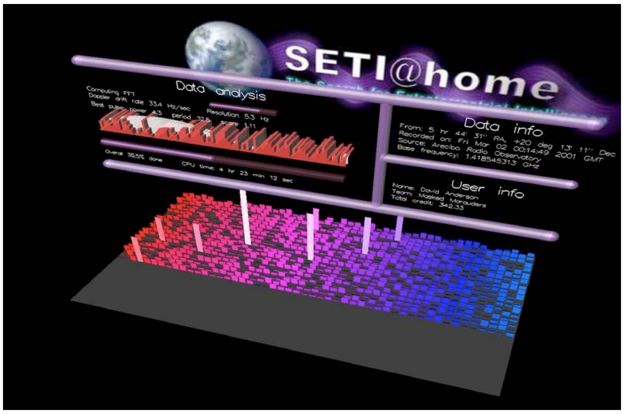
[1] Here we use 0716+714 as the prototype. It is about 2 billion LY away with an average spectral flux density of 1 Jy at 1.42 GHz (easily measured at most radio telescopes). The diameter of emitting regions in 0716 + 714 may be as small as 2 AU based on the fact that intrinsic time-variable fluctuations on a scale of 15 min are observed.

[2] A Cepheid variable is a very luminous, evolved star that alternately expands and contracts in a way that creates a precise relationship between its luminosity and its well-regulated period of oscillation. For this reason, these stars have been used as "standard candles" for determining the distance scale across our galaxy and to nearby galaxies.

at one time, pursue simultaneous data analysis using multiple projections, and even broadcast or store vast amounts of digital data for more complex processing that cannot be run in real time. The International Virtual Observatory Alliance (of which the U.S. National Virtual Observatory is a member) is now organizing access to astronomical data sets across the spectrum, and distributing web-based tools to process and curate them to professional and amateur astronomers [15]. SETI radio searches are likewise providing raw time series captured directly from the telescope and stored in the cloud [16], [17]. With the rise of well-scaffolded, web-based citizen science projects the rate of productive outcome is accelerating as a large army of volunteers swells the ranks of the professionals who can access and interpret these data.

SETI has benefited from this growth. When there is only one observing project at a time allowed on a single dish, competition for telescope usage is fierce. With modern, real-time processing, it is now feasible to build an advanced SETI detector and with small effort, plug it into the telescope to work in background mode without interfering with the primary observation plan. This continues to be done by the University of California Berkeley SETI@home program piggybacking at the Arecibo Observatory (illustrated in Fig. 1) using a second backend processor [18]. A similar example at the Allen Telescope Array (ATA) takes advantage of a system that generates radio images of the sky running in parallel with three pencil beams, and a prototype disk-capture system [19]. The ATA is shown in Fig. 2. Data capture and web publication are the best way to democratize the SETI search and our virtual observatories will grow in accordance with Moore's law. To summarize, today, any good idea for an ETI search can have its day, and multiple top-quality search schemes receive allocated opportunities at a few observatories in the world, but not nearly enough.



Computing FFT
Doppler drift rate 33.4 Hz/sec
Resolution 5.3 Hz
Best pulse: power 4.3 period 32.6 score 1.11
Overall 35.5% done
CPU time: 4 hr 23 min 12 sec

From: 5 hr 44' 31'' RA, +20 deg 13' 11'' Dec
Recorded on: Fri Mar 02 00:14:49 2001 GMT
Source: Arecibo Radio Observatory
Base frequency: 1.418545313 GHz

Name: David Anderson
Team: Masked Marauders
Total credit: 342.33

Fig. 1. ***SETI@home records data at Arecibo Observatory during sky surveys being conducted by the ALFA multibeam receiver. Those data are subsequently analyzed by distributed computing routines being run in the background of computers supplied by volunteers. Detected signals are sent to the University of California Berkeley for classification and further analysis. Credit: Seti@home.***

Fig. 2. ***Aerial view of the Allen Telescope array, now consisting of 42 antennas each 6.1 m in diameter, at the Hat Creek Radio Astronomy Observatory in northern California. The array can be used simultaneously for SETI observations and more traditional radio astronomy projects. Credit: G. Seth Shostak.***

In the rest of this section, we summarize the more widely adopted approaches to SETI and some interesting ideas that have received recent attention. Unless otherwise noted we will speak of detecting SETI beacons, which are specifically designed by a remote civilization to gain attention. While we do not specifically discuss the content of interstellar messaging until Section V, we briefly consider information containing signals that might be discovered without prior knowledge of the particulars of data encoding.

A. The Cost of Power

Can a sufficiently luminous SETI beacon be constructed? Fundamental physics does not place a forbidding limit on beacon luminosity. If a transmitter is driven with too much power, it must eventually explode under its own radiation pressure (similar to the concept of Eddington luminosity in astronomy). This barrier can always be overcome, however, by replicating the transmitter. The real question is, can ET afford to run an interstellar beacon? A set of transmitters with 1-TW total power, coupled with Arecibo-sized collimators would permit signal detections with current Earth-based telescopes from the other side of the galaxy. At current prices, the electricity to drive this system would cost > \$10 trillion per year. SETI strategies usually assume a transmitting technology comparable to or better than our own strongest signal the ~2-MW transmitter at 2.38 GHz (associated with the Arecibo planetary radar system), whose 2×10^{13} W EIRP is easily visible from 100 LY (188 Jy[3] source localized to 1-Hz bandwidth) or with some challenge at 1000 LY (1.8 Jy).

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[3] The Jansky or Jy is a unit of spectral flux density equal to 10^{-26} W/m^2/Hz. Use of this unit makes it possible to discuss the extremely weak radio signals generated by natural sources in terms of numerical multipliers that are close to unity.

In the discussions below, we will consider SETI based on conventional assumptions of pulsed or narrowband transmitters, and then gradually relax these assumptions in a variety of ways to consider other scenarios.

B. Where to Look

With unlimited capabilities, the answer to the question "Where should we look?" for extraterrestrial (ET) signals is "all the sky, all the frequencies, all the time." An analysis of the requirements for an all-sky SETI survey at radio frequencies is detailed in [20]. Currently, just covering all look directions is a technological challenge: most telescopes magnify and concentrate EM radiation by specifically excluding radiation from all but a small region of the sky. This naturally serializes the SETI search (not all the time) and while some good "blind" surveys have been conducted [21], [22] and are still being pursued [18] many researchers choose to optimize their search strategy by targeting specific directions or stars, at certain times, and at special frequencies. A few straightforward principles are used to narrow the search.

1) Nearby: In the scenario where ET uses an artificial transmitter with limited power resources, distance is the most important factor in choosing which stars to observe. The detected power of a beam of EM radiation (light or radio waves) varies as the inverse square of the distance, and nearby transmitters require less power to allow detection with Earth's telescopes. Within 100 LY there are some 512 stars of the same spectral type or mass as our own Sun [23]. Stars much more massive than the Sun have lifetimes that are probably too short to support the evolution of technological civilizations. Stars much less massive than the Sun are by far the most numerous (260 of the 300 stars within 25 LY are small red dwarfs). Such stars have very long lifetimes, but they may be too dim and cool to foster life and the evolution of technologies, although that is an area of active debate and research [24]. As mentioned above, at 100 LY, a narrowband analog of the Arecibo radar presents 188 Jy in 1 Hz, allowing $> 10\sigma$ detection at the Allen Telescope Array in a 0.7-Hz bin with 100-s integration. Recent studies with the Allen Telescope Array used a spectral-imaging correlator; the spectral bin size was 3000 Hz, resulting in an effective signal spectral flux density of 60 mJy for an Arecibo transmitter at 100 LY.

Because life-as-we-know-it is a planetary phenomenon, nearby stellar systems that are known to contain planets are preferred targets. Radial velocity studies with ground-based telescopes have discovered more than 700 exoplanets around nearby stars, with the number growing larger each month [25]. However, since this technique infers the presence of a planet by the gravitational reflex it induces in the position of the host star, it favors the discovery of giant planets, in short period orbits close to the star, and such worlds are not likely to be habitable. The intrinsic precision of this observational technique is inadequate for the discovery of Earth-mass planets, but there may well exist smaller, undetected planets in these planetary systems that have been identified because of their giants. The Kepler spacecraft launched in 2009 [26] is the instrument that is intended to discover Earth-size worlds. Kepler is observing a group of 150 000 stars within a 100 square degree region of the sky between the constellations Lyra and Cygnus, looking for planets that transit in front of these stars. To date they have provided a list of 2321 candidate exoplanets, with an expected false positive rate of only a few percent [27]. By the end of the mission life, this list should grow to about 3000 planetary systems, with the expectation that Earth-like planets orbiting Sun-like stars at distances where the surface temperatures would support liquid water will be among them. At 880 LY (average distance to Kepler stars [28]) the Arecibo-analog flux density is $\sim$2.4 Jy. These flux densities are comparable to relatively bright astronomical sources in the radio-frequency range. Similar beacons launched from the opposite side of the Milky Way (50 000 LY) or from the nearest galaxy (2.5 million LY) would be below the capability of even the best radio telescopes. If the instrumental bandwidth is larger than the transmission bandwidth apparent source flux is diluted.

2) Habitable Zones: Lineweaver *et al.* [29] and references therein have suggested that there is an annulus within the galactic disk that is more likely to be supportive of life. At locations closer to the galactic center a planet would encounter higher hard radiation levels. Metallicity is suspected to vary with distance to galactic center, making the outermost regions of the galaxy too metal poor for the formation of rocky planets. Stars near Earth or roughly equal distance from the galactic center (as are Kepler stars) are in the region we call the Galactic Habitable Zone.

As already noted, another determinant for "habitability" for life as we know it, is whether liquid water could exist on some planet in a stable orbit around different stellar types. On Earth, the presence of liquid water is tightly correlated with the existence of life; life is found everywhere liquid water is found, and *vice versa*. Similarly, radiation levels reaching the planetary surface must be low enough to prevent destruction of early life before it can take hold and stellar flares and other energetic outbursts must occur at a rate conducive to driving evolution rather than extinction [30]. These notions imply the concept of a Stellar Habitable Zone; at best this is a very imprecise discriminant that is heavily biased toward our terrestrial chauvinism. The HabCat star catalog [31] was generated based on considerations of stellar habitability and serves as a reasonable finding list for selecting targets, including a small number of the M dwarfs.

3) EM Radiation: As noted in Section II, the search for extraterrestrial intelligence is primarily conducted as a search of the electromagnetic wave spectrum for reasons set out by Cocconi and Morrison in 1959 [1] and that still make sense today. Focusing on the electromagnetic (EM) spectrum, the constituents of the interstellar medium and Earth's atmosphere dictate that radio waves (1–10 GHz) and visible/IR light (120–800 THz) propagate with only modest absorption or scattering, and are accessible to ground-based observations. Other frequencies may be accessible from space platforms in the future. Radio SETI and optical SETI programs continue to coexist as both frequency ranges are considered plausible and have well-developed technologies for reception. The two frequency ranges are distinguished by two features: radio waves require relatively smaller energy to produce a detectable signal, but are subject to dispersion in the interstellar medium (ISM) which favors narrowband signals for SETI beacons. Comparatively, optical signals require more energy to generate but are affected very weakly by dispersion that favors short duration optical pulse searches. IR SETI has not yet been systematically employed primarily due to the higher costs of the fast photon counting detectors that are required, but this frequency range is preferred for interstellar distances in excess of $\sim$1000 LY because it suffers less absorption from interstellar dust. We will discuss these differences more below.

4) Magic Frequencies: Especially in the radio-frequency range, the limitations of our technology and channel impairments of the ISM lead us to focus on narrow frequency ranges. With limited observing budgets (funding and access to large telescopes), it is often suggested that searches should focus on certain "magic" frequencies to improve the likelihood of success. The first observations by Drake [2] were centered on the rest frame HI hyperfine transition frequency and to date, most radio SETI observations have focused on the "water hole" region bracketed by HI (1.42 GHz) on the low side and the OH maser lines on the high side (four lines between 1.612 and 1.72 GHz). Other transition frequencies, like the hyperfine transition of $^3\mathrm{He}^+$ (8.66 GHz) or the forbidden rotational transition of the H_2 molecule have also been suggested. To avoid interference with ordinary astronomy, artificial constructions based on spectral frequencies (multiples of HI frequency including $\sqrt{2}$, e, 2, π) have also been championed and tried [32]. Anthropocentric choices of absolute frequency values (e.g., π GHz) are avoided since the gigahertz unit depends on the human definition of one second, though frequency ratios (f_2/f_1) or combs of such ratios can make sense starting from any base frequency. It is appropriate to consider ratios of dimensionless quantities like π, the fine structure constant, the proton-to-electron mass ratio, or any of the other 23 dimensionless coupling constants of the standard model of particle physics.

The era of reliance on magic frequencies in radio SETI is coming to a close with better technology and dedicated instruments for SETI research. Currently, the Allen Telescope Array can perform a single-pass narrowband search covering the entire microwave frequency range with a resolution of 0.7 Hz in steps of 100 MHz in just over four hours on a single star, and frequency agnostic searches of thousands of exoplanets are now underway. This capability is made possible partly because the ATA offers "commensal" observing where two projects can operate on different intermediate frequency channels simultaneously. Future radio telescopes like the Square Kilometre Array, and its prototypes, are expected to be designed with similar capabilities [33].

C. Radio Versus Optical SETI

Technologies for optical and radio SETI searches have one critical difference: coherent digital processing is effective for radio but not for optical frequencies. The reason is simple: the amplitude and phase of EM radiation can be captured with a heterodyne system that converts the received frequency to baseband and samples it with a digital voltmeter (digitizer). Off-the-shelf digitizers are presently limited to capture of 0.1–10-GHz frequency bandwidths. Such detectors work equally well for radio or optical signals, but at optical, a 1-GHz fractional bandwidth captures only one part per million of the visible light resulting in unacceptably low sensitivity. At radio an analogous detector captures 10% of the microwave window, more than enough bandwidth for very sensitive measurements in radio astronomy or SETI. The result is that optical SETI is still limited to specialized analog processing systems (pulse detectors, narrowband spectrometers) while radio astronomy and SETI can benefit from almost arbitrary signal processing in the digital domain, greatly widening our horizons for signal exploration. Since the feed and receiver system of the ATA allows simultaneous access to the entire microwave window [19], Moore's law improvements in digital signal processing could potentially allow single-step exploration of this frequency region within the lifetime of the observatory.

In the optical domain, fast photon counters permit detection of optical pulses consisting of only a few photons with nanosecond duration, and optical interferometers give fractional resolution bandwidths (a.k.a. bin size) of 10^{-8} as used in the detection of exoplanets. The interstellar and interplanetary media contain free electrons that scatter and disperse (dramatically broaden) short radio pulses. This could be a fatal flaw if not for the fact that to first order, ISM dispersion is reversible and digital processing can de-disperse pulsed signals to a level close to that of their original width.[4] Digital radio spectrometers enable extremely high-resolution spectroscopy (e.g., 10^{-10} fractional bandwidth in radio SETI) with technology limits near 10^{-12} based on the stability of off-the-shelf clocks.

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[4] Unless the electron column density to a source has been measured, dispersion in the ISM is not predictable though it generally increases with distance from the transmitter. Therefore, radio pulse searches must be extended to search over dispersion measure. This increases the probability for false alarm in a SETI search since we are "fitting" signals with one more parameter. This drawback can be mitigated by targeting nearby stars and searching only for slow pulses.

Beyond this point coherent digital processing extends the realm of discovery to a very large number of signal types in radio observations, including signals with arbitrary phase modulation, signals with meaningful trains (patterns) of electric field values, and search schemes based on the most complex human-developed communication encoding. We will consider some imaginative detection strategies below. By comparison, postprocessing of optical power data for such signals is substantially less effective because of loss of phase information. Specialized analog optical detectors with fast electronic recorders can be competitive, but do not yet have the great flexibility offered by generalized digital processing. However, optical (and soon IR) SETI does have the advantage of broadband coverage with no need to search through individual channels in the frequency domain.

There are other factors, such as energy per photon, quantum noise, receiver sensitivity, space-borne telescopes, etc., that will all impact the optimization of SETI searches by Earthlings. "Optimal" is a moving target, and recent thinking suggests that we should spend at least some of our time looking for other feasible signal type while focusing the greatest energy on narrowband radio and short-pulse optical searches.

D. Conventional Optical and Radio SETI

The first step in SETI detection is to use a concentrator stage to increase the received signal amplitude. Mirrors for optical telescopes are of order meters in diameter, or 10^6 wavelengths. Radio concentrators (single dishes, interferometer arrays) have effective diameter of tens to hundreds of meters or 10^2–10^3 wavelengths.

Optical SETI (OSETI) searches typically use a photon temporal coincidence technique based on the idea that single optical photons from a star at 100 LY will arrive on average only about once per microsecond into a 1-m class instrument such as Harvard's purpose-built optical SETI sky survey instrument shown in Fig. 3. By comparison, analogs of strong lasers produced on Earth can increase the rate of photon arrival by 10 000 times during the sampling period of a fast optical detector ($\sim$1 ns). By searching for the simultaneous arrival of multiple photons in a nanosecond interval, an extremely unlikely event given stellar radiation alone, OSETI beacons may be discovered. Current systems [18], [34] also demand another form of simultaneity based on coincidence among multiple detectors. Scintillation in the glass of individual photomultipliers due to cosmic rays, ion feedback, and even radioactive decay of potassium (K40) located in the photomultiplier tube glass can cause an unacceptably high false positive detection rate [35]. In practice, the optical signal beam is split two or three ways, and the requirement for coincident detection drives the false positive rate down exponentially.

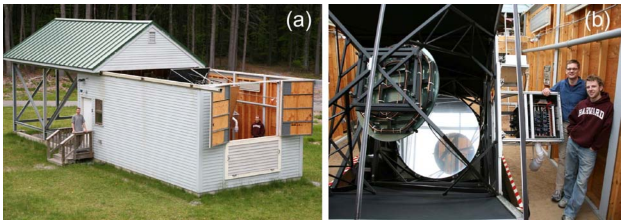

Fig. 3. ***The Harvard OSETI sky survey observatory. (a) The inexpensive facility features a rollback roof with a section of the south-facing wall that can be removed to accommodate drift scans. (b) The 72″ primary and 36″ secondary mirrors, the detector housing for an array of photodiodes, and two of the student builders. Credit: Paul Horowitz.***

Note that ISM dispersion of an optical pulse with 50% fractional bandwidth is less than 1 ps over a typical 100 LY journey, and may be neglected. A more generalized pulse search must also include a search over pulse duration, and if applicable, repetition rate. High-resolution optical spectroscopy data recorded during radial velocity exoplanet searches is also currently under study for detection of continuous ET laser signals [36]. Radio SETI is most conveniently carried out in a narrowband search to avoid ISM dispersion. Today a common resolution bandwidth is in the range of 1 Hz. A more generalized search should also include a search over resolution bandwidth, since wider bandwidth signals can be resolved out by a 1-Hz detector. With small additional effort, searches for narrowband pulses of relatively long duration ($\sim$1 s [37]) are also included. Shorter pulses could easily be detected in a targeted search of nearby stars since even at the low end of the radio range (1 GHz) the dispersion broadening for a 1-μs pulse (1 MHz wide) at 100 LY is less than 10 ns.

E. Signal Detection

1) Compressible Signals: To obtain the best signal-to-noise ratio in detection, a SETI beacon should use a signaling scheme that allows the recipient to collapse all of the received energy into the smallest possible region of phase space. Signals of this type are called "compressible," and "processing gain" improves SNR by compressing signal energy into a single spectral bin of phase space while diluting background noise power over all other bins. For example, with a fast Fourier transform of length N, the noise-like background radiation (from sky or from receiver) gets distributed almost evenly over all the N frequency bins in the resultant spectrum. Meanwhile, the signal can be coherently concentrated into a single bin, resulting in a signal processing gain proportional to N^2. Since sine waves are also the eigenfunctions of the interstellar channel (pass without distortion, except for the Faraday rotation of linear polarization), a sine wave beacon is often considered the most natural approach for SETI transmissions.

Another possibility is transmitting very short, sharp pulses. Pulses can be collapsed to a single bin in the time domain, while diluting noise energy over a large number of bins corresponding to times when the pulse is not on. As mentioned, a search for nanosecond pulses is currently being conducted in the optical spectrum, but the dispersion of short pulses at radio frequencies introduces complications. Pulses can be thought of as a superposition of many sine waves having different frequencies where each one has a very specific phase value with respect to all others. The ISM contains a small number of electrons ($\langle n_e \rangle = 0.03\ \text{cm}^{-3}$), causing a frequency-dependent phase shift for any light passing through. This phase shift is very small at optical frequencies hence negligible, but at radio frequencies it must be corrected for. Since the ISM plasma density fluctuates and is not usually known, radio pulse searches require a search over dispersion measures, unless the bandwidth of the pulse is extremely small (e.g., slowly pulsed sine wave signals [37].

The effects of all likely dispersion measures can be calculated, applied to de-disperse the observed radio signals, and a systematic search for short pulses can be undertaken. A recent distributed-computing project follows the SETI@home model to provide the extensive central processing unit (CPU) capacity needed to search for ET pulses [38], [39]. The extension of these techniques to other sorts of compressible signals or matched filter searches should be straightforward.

2) Matched Filter Searches: Searches for signals with greater complexity (larger number of degrees of freedom) are limited only by compute power, and are now beginning to take place. Such searches avoid the biased assumptions that narrow frequency tones or short pulses are somehow natural choices for a beacon. From another standpoint, these signals are compressible only because we have guessed their encoding key. There are an infinite number of signal types that can be compressed provided you guess the correct key. While second-guessing another civilization might be difficult, we are already doing this in sine wave and pulse searches, so we consider other guessable encodings.

Suppose ET constructs a beacon that transmits N binary digits of π [40], which we refer to as PI. The choice of PI is very much like choosing a magic frequency, and a variety of special numbers ($e, \sqrt{2}$) or number series (primes) have historically been considered. To determine the presence/absence of PI in received data at a certain time, one computes the dot product of that data with the complex conjugate of the vector PI. Apart from conjugation, PI is its own "matched filter." This is also true for sine waves and pulse signals.

At optical frequencies, a matched filter search in a given direction and frequency band has two primary search parameters: start time and dilation. Because ET transmits a finite number N samples of PI, the signal is likely to repeat and the moment we choose to look may not coincide with the beginning of the series. So we must search over a variety of start times, much like the search for pulses. Similarly, we do not know the rate at which ET sends samples, and our search must test for uniform dilation (expansions or contractions) of the signal, similar to duration in a pulse search. At radio frequencies, dispersion also becomes important.

3) Incompressible Signals and Self-Referenced Detection: If the signal encoding is not perfectly compressible, as with any signal containing finite information per unit time, then its detectability is compromised. Messerschmitt and others have argued that despite this drawback, wideband signals may be preferred for other reasons: they contain nontrivial information and they are more resistant to radio-frequency interference [41].

The only use of an information-free SETI beacon is to announce a civilizations existence and perhaps give a clue about what frequencies the receiving civilization should study more carefully in order to discover encoded information. However, information-bearing signals themselves may be beamed across the galaxy to support slow-feedback communication between cultures or, given sufficient energy resources, be used with a simple modulation scheme that permits dual use as both a communication channel and beacon.

One detection scheme appropriate for modulated power signals is autocorrelation. In the framework of matched filters, this technique uses the received signal (or rather, a delayed copy of the received signal) as a matching filter. Autocorrelation has the distinct advantage that we need make no prior assumptions about the shape of the signal or its dispersion. If the signal has repetitive behavior, then autocorrelation will peak at delays corresponding to the repeat time. The disadvantage of this technique is that we cannot produce a noise-free copy of the signal until after it is detected. By comparison, we can compute a perfectly matched filter for sine wave signals. This difference results in a loss of sensitivity for signals with equal power. Given a sample of a signal, if a perfectly matched filter returns a signal-to-noise ratio $\langle s^2 \rangle / \langle n \rangle$, a self-referenced filter returns $\langle s^2 \rangle / \langle n^2 \rangle$ where $\langle n \rangle$ is a measure of the noise. This decreases the detection sensitivity for a self-referenced signal.

The need for communication reliability has produced many approaches for error detection/correction. If some fraction of a communication signal is corrupted, this can be overcome only by redundant transmission of the signal. Redundant does not always mean repeating the signal, but often it does. An effective beacon carrying arbitrary information is obtained by superposing a signal with a delayed version of itself [42], which is optimally discovered by simple autocorrelation. As another example, Global Positioning System (GPS) satellites encode each bit of information as a string of 1023 symbols in identical order, where the string is multiplied by ±1 representing 0 and 1. GPS signals and other cyclostationary signal types can be discovered by simple autocorrelation but are more effectively discovered with a variation called symbol-wise autocorrelation (SWAC) [43].

4) SETI Backgrounds and Mitigation: Many astronomical sources can potentially be confused with SETI signals. For example, when pulsars were discovered there was speculation that they could be extraterrestrial beacons [44]. An effective approach for dealing with natural radiation is to devise detection schemes that are sensitive only to signals that rarely or never appear in nature. For example, Cherenkov radiation from cosmic rays may generate optical pulses with microsecond durations, but no shorter. Optical SETI searches can avoid such backgrounds by selecting for pulses with timescales of nanoseconds. After adjusting the detection scheme to minimize such false alarms, researchers must deal with backgrounds that remain. The main backgrounds in pulsed optical searches results from detector pathologies as already noted, and can be mitigated by requiring coincidence in multiple detectors. In another example, the narrowest natural emission line sources of radio waves are saturated astronomical masers with linewidths of ~500 Hz [45]. Such confusing astrophysical lines are typically avoided by limiting searches to signals with line widths of a few hertz.

The EM spectrum is also valuable for human communication, and man-made artificial signals are a challenging background for narrowband radio SETI searches. A powerful method for excluding signals of terrestrial origin is to determine the direction of arrival of detected signals. With an interferometric telescope it is theoretically possible to estimate the signal's direction of arrival and distance from the telescope with 3-D Fourier transform of the signals detected in multiple antennas, but this is far beyond current computational capabilites and still contains some ambiguity.

It is far easier to prove that a signal does not arrive from the direction where the telescope is pointed. Because strong signals can be detected in the sidelobes of an antenna system even when the telescope is not pointed at their source, a simple method is to point the telescope in a different direction and see if the signal persists. With an interferometer it is possible to obtain signals from multiple directions at the same time with multiple synthetic beams, permitting directional anticorrelation without any physical motion of the telescope [46]. In a radio search for narrowband signals utilizing multiple antennas with a large separation (such as the Phoenix Project [37]), the differential Doppler due to the Earth's rotation and orbital motion can be precisely calculated from the antenna locations and the direction to the target source. Signals detected at the two sites, but without the correct Doppler characteristics, can be rejected. Earth satellites or ground-based transmitters cannot precisely mimic the behavior of a signal arriving from outer space, although distant man-made spacecraft can and have temporarily fooled researchers when this differential signature was not available [47]. Such unintended false positive events have given us a hint of what a real detection might be like.

IV. WHAT IF SETI SUCCEEDS?

Interest in the possible existence of extraterrestrial intelligence is widespread, as is easily inferred from the frequent presence of "aliens" in movies, television dramas, and a large body of written science fiction. It seems a reasonable conjecture that evolution has hard-wired us to be curious about other species with intellectual capability comparable to our own. After all, they could be potential competitors or possibly mates (viz., the Neanderthals).

This pervasive interest means that SETI experiments, although involving only a small number of scientists worldwide, incurs both notoriety and a great deal of inquisitiveness by the public. This is in contrast to much of today's other basic research topics, which are often too complex—or too poorly explained—to grab the attention of nonscientists. While many people have heard of the Large Hadron Collider, for example, few among them could give a simple explanation of its research goals. SETI's intentions, on the other hand, are completely comprehensible to the lay public.

While those with a more technical bent are keen to learn of SETI's strategies and technical approach, a broader group is intrigued by the question of what happens if this bit of hi-tech exploration actually succeeds. What sort of information would be garnered by the SETI scientists? Would the data be immediately shared, and what long-term societal consequences could we expect?

This curiosity about the implications of SETI has prompted some attention by academics. In the days of the National Aeronautics and Space Administration (NASA) SETI program, from the 1970s until 1993 (when funding was cut by the U.S. Senate), the program's lead, John Billingham, organized several conferences to address SETI's societal implications [48]. Billingham brought together not only academics from the physical sciences, but also anthropologists, sociologists, religious leaders, diplomats, and even media specialists to spend several days considering what the likely consequences of a SETI detection might be. In general, the experts concluded that some people would react with fear and concern to learning of intelligence elsewhere (paranoid), and a larger group would receive the news with enthusiasm and interest (pronoid).

In addition to this conference, the International Academy of Astronautics SETI Permanent Committee has held annual sessions for two decades on SETI's societal consequences, with approximately ten papers presented each year. A selection of these and other contributions to the matter of a response can be found in [49].

One difficulty encountered by all those who hope to accurately forecast the effects of finding a signal from cosmic intelligence is the lack of an appropriate historical analog. Is there a comparable event in our history that we can look to for guidance? Frequently cited candidates include the Copernican revolution and the publishing of Darwin's work on evolution. More recent analogs include the claims of a vast, hydraulic civilization on Mars made by Percival Lowell a century ago, or Orson Wells' 1938 radio dramatization of "The War of the Worlds." Copernicus and Darwin produced seismic paradigm shifts, and Lowell and Wells confronted us with a credible suggestion of intelligent aliens nearby. None seem entirely appropriate as models for what might happen if we were to find extraterrestrials at a great distance.

A more recent event, the 1996 announcement that fossilized Martian microbes had been found in a meteorite [50], was greeted with widespread interest and no disquiet. The story faded from the public's mind after several days, as astrobiology experts began to dispute the claims. This experience is offered as evidence against the idea that discovery of extraterrestrial life (albeit, dead microbial life in this case) would spawn panic.

A. What Could Be Learned Immediately?

As difficult as it is to predict societal consequences to finding evidence of cosmic intelligence, there are certain technical aspects of a detection that can be foreseen. The most obvious question that would be asked is "where is the signal coming from?" Assuming that the transmitting civilization is within 1000 or 2000 LY (there are millions of stars within this range), then existing radio astronomy arrays or large optical telescopes would be able to unambiguously determine from which stellar system the transmission originates. Straightforward astronomical measurement, based on the star's apparent brightness and spectral type, would then give its distance, if that was not already known. Planets in this system would be sought, although current instrumentation might not be able to find them if they were of terrestrial size and in an orbit comparable in extent to Earth's. If the detected signal is not coming from a planet in orbit around a host star, then its source of origin could remain in doubt for a long time.

However, there is little doubt that unending attention would be expended on any star system, or direction on the sky, that is sending a signal our way. If, eventually, a planet can be found, then simple monitoring of its brightness with time might inform us of the degree of cloud cover, and/or the distribution of continents [51]. If the transmitting planet is close enough then space-based instruments could make spectroscopic measurements that would allow an assay of the atmospheric components of the planet. Finding oxygen, for example, would be an extraordinarily interesting result, as that would indicate some similarity to terrestrial biochemistry.

As previously explained, most SETI radio experiments look for narrowband signals. These have the advantage (at least from the detection point of view) that the signal-to-noise ratio of the received transmission is maximized at any given level of transmitter power. There is a limit to how narrow the signals can be, however. The interstellar medium, which is suffused with highly rarified, ionized gas, will smear out any radio signal by at least a few tenths of a hertz. Consequently, SETI experiments typically use spectrometers with channel widths of 0.1–1 Hz. This high spectral resolution means that even slight changes in the frequency of the incoming signal can be registered. Indeed, if an extraterrestrial transmitter is located on a rotating planet, the changing Doppler shift seen from our position will cause the signal to periodically drift at the rate of, typically, a few tenths of a hertz per second. The possibility—indeed the inevitability, given the Earth's own rotation—of frequency drift clearly complicates the algorithms used to search for signals, but offers the advantage of easy discrimination against terrestrial emissions. If a signal is not drifting, then it is clearly coming from an antenna fixed to the Earth. As noted by Sullivan and Cordes [52], analysis of frequency drift would allow us to determine the diurnal rotation of ET's planet, and even the length of year. Other, subtler effects might give some insight into a planet's magnetic field.

B. Making the News Public

In the 1980s, when both the Soviet Union and the United States were actively engaged in SETI, a set of "protocols" was drawn up, largely due to the initiative of Michael Michaud, Jill Tarter and John Billingham [53]. This document had three major components, and was intended to address the question of what should be done immediately following a credible detection of a signal. In summary, the protocols stipulated that 1) the extraterrestrial nature of the transmission should be verified by additional observations; 2) other scientists, governments, the media, and the public should be notified (no order for this notification was indicated); and 3) no reply transmission in the direction of the signal should be made without first securing international consultation. The nature of this consultation was not specified.

Recently, the International Academy of Astronautics (IAA) SETI Permanent Committee has revisited these protocols, and rewritten them in simpler form, while removing some internal contradictions [54]. The basic intentions enumerated above remain the same, however.

While these protocols lack the force of law, they do define a "best practice" for SETI researchers who might trip across a signal. However, false alarms in SETI have shown that—in the case of a believable signal detection—the protocol recommendations are likely to be quickly overtaken by events. In particular, SETI researchers have not agreed to any secrecy regarding their work. For many, having a policy promoting a lack of candor would lessen the credibility of their enterprise among a public that—to a great extent—suspect that news of extraterrestrial intelligence would be suppressed. A 1997 CNN poll reported that 37% of the U.S. public agreed with the statement that aliens have contacted the federal government [55].

The actual lack of secrecy means that any signals that seem interesting are quickly brought to the attention of the media, and soon thereafter to the public. The story that SETI may have found the aliens will be widely known long before the researchers themselves are certain of the result [56]. It is safe to presume that there will be both confusion and, unfortunately, disappointment as some (or perhaps all) of these interesting signals turn out to be false alarms.

C. Messages

A common misperception by the public is that SETI practitioners will be able to recognize a signal from an intelligent source because it is marked by clearly nonnatural message components (e.g., prime numbers). In fact, for radio SETI experiments that look for narrowband signal components, there can be very little information conveyed at all (with the exception of very slow modulation, equivalent to leisurely Morse code). Information at radio wavelengths might be in sidebands, and if the signal is information rich, these sidebands will be broad. Simply understood, this means that the energy density of the "message" might be low compared to a carrier, and to retrieve the former will require far greater sensitivity (typically 10^4 times more) than to detect the latter. (Optical SETI experiments, which look for pulsed laser pulses, might see the "message" immediately.) Of course, some types of radio modulation, such as spread spectrum, might not have a strong, narrowband component at all, and most of today's SETI experiments would have difficulty in finding them.

It is important to note that generally SETI experiments are not attuned to messages. Finding a telltale, narrowband signal is the intention of these experiments; building the far larger instrument that would allow demodulation of embedded information is a follow-on activity. One can safely presume that both the motivation and the funding necessary to construct such an instrument would be abundantly available if a true, extraterrestrial signal were found.

What would happen then? To the authors' knowledge, there have been no deliberate discussions regarding the sharing of an interstellar message. The SETI protocols mentioned above specify that information about a signal detection will be made public. But as noted, a detection is merely prolog to the far larger effort that would be made once a detection is in hand. No one doubts that a discovery would be worldwide news, with information about its technical characteristics shared with others, if for no other reason than the necessity of obtaining independent confirmation. Would there be similar magnanimity concerning the sharing of the information-bearing signal components? One can hope so, for decoding a message—if possible at all—is more likely to occur if anyone with that ability can become involved.

D. Long Term

The long-term consequences of a SETI success would surely be profound. They are also extremely difficult to foresee. The practical consequences (other than the immediate transformation of SETI from a small, underfunded enterprise to a major research effort) depend on whether we can understand any signal content. On statistical grounds, it is generally assumed that any society we detect will be significantly more advanced than us. Clearly, if their signal is comprehensible, receiving it might give us a shortcut to knowledge that might otherwise take *Homo sapiens* centuries or millennia to acquire.

While this possible payoff in knowledge is occasionally cited as one of the strongest motivations for doing SETI experiments, there is no guarantee that it would occur. We might be as confounded by the aliens' message as chimpanzees trying to fathom a college textbook.

More certain to occur are changes in the way we see ourselves. Rather little research has been done on the effects a SETI detection would have on religion, although an early study by Ashkenazi [57] showed that theologians representing Christianity, Judaism, and Islam foresaw little difficulty in accepting the existence of intelligent beings elsewhere. But the change in long-term perspective is likely to be substantial. One only need think of the consequences of Copernicus' heliocentric cosmos, or the shift that European culture underwent following the discovery of the New World.

It is common to speak of the detection of intelligent life elsewhere as the greatest news story of all time. The grandiosity of that statement may sound like hyperbole. But in truth, and in the centuries that follow a detection, this florid description of the consequences of the SETI enterprise may very well prove to be understatement.

V. MESSAGES FOR INTERSTELLAR COMMUNICATION

If some day a SETI project detects conclusive evidence of extraterrestrial technology, humankind will be faced with a twofold question: Should we reply, and if so, what should we say, and who should say it? The protocols mentioned in the previous section foresee but do not answer these questions. Some have argued that it is premature to even ponder these queries in advance of signal detection, because the answers will depend largely on the specific context of the signal we receive. But a closer examination of likely detection scenarios suggests just the opposite.

As noted above, in radio SETI, search projects generally look for strong narrowband signals that stand out from the cosmic background noise. Even if contemporary searches find what they're looking for, they may well be limited in detecting only a beacon calling attention to another civilization. Any information encoded in sidebands would be several orders of magnitude more difficult to detect, and may need to await the construction of more sensitive telescopes.

At optical wavelengths, pulses could plausibly bear rich messages, conveying the equivalent of all the books in the Library of Congress in less than an hour [58]. Even if the modulation scheme is evident, however, the process of finding the correct format of the message, and then interpreting it correctly, could prove to be one of humankind's greatest intellectual challenges to date.

In the first scenario, we may know that a radio signal comes from an extraterrestrial civilization, but may have no way of knowing whether an encoded message is also being broadcast. In the second scenario, even if an optical signal is modulated in a way that could bear considerable information, it may not be evident what its message means. Even now, prior to contact, we can contemplate how we might respond to the detection of extraterrestrial intelligence (or at least the detection of the technologies they created), under these two scenarios, which assume that we will know that they exist (or at least that they existed at one time), but that we may not know much beyond that.

A. Searching for Universals

In what follows, we will speak as if biological ETI (the original inventors of the technologies that have generated the detected signal or artifact) still exist. But that might not be correct; they may have gone extinct or may have departed, being survived by their technologies, or they may in fact be postbiological products themselves.

If we receive a message from another technological civilization, it will not be written in English, or any other natural language used in everyday conversation on Earth. But it may be written in the language of mathematics and science. If we detect an electromagnetic signal from intelligence living around a distant star, at a minimum, we will know that they have the technology to transmit messages across interstellar distances. As a result, it is often argued that we can expect ETI to have among themselves engineers. For any civilization able to construct a radio transmitter or laser capable of targeted transmissions at interstellar distances, it seems reasonable to assume that civilization would know at least some mathematics, physics, and chemistry. Without an understanding of basic concepts from these fields, how would they have constructed their technologies?

Invoking the reciprocity between transmitter and receiver that is familiar to any communications engineer, humans have begun constructing messages in order to understand the potential content of any future messages we might receive. Basic mathematical and scientific concepts provide the subject matter for most conceptual interstellar messages that have been drafted to date.

Whereas cryptographers create codes to conceal the meaning of messages from unintended recipients, in interstellar communication we hope for the opposite—"anticryptographic" messages designed specifically to make their format and meaning as transparent as possible [59]. Typically, interstellar messages are created so their structure provides clues to the format of the message. Consider the message transmitted in 1974 from the world's largest radio telescope, in Arecibo, Puerto Rico, which also has a powerful radar transmitter (see Fig. 4) [60]. The target of this message is globular cluster M13, some 25 000 LY from Earth. The message consists of 1679 binary digits transmitted at 10 b/s at two slightly different frequencies near 2380 MHz, separated from one another by 10 Hz.

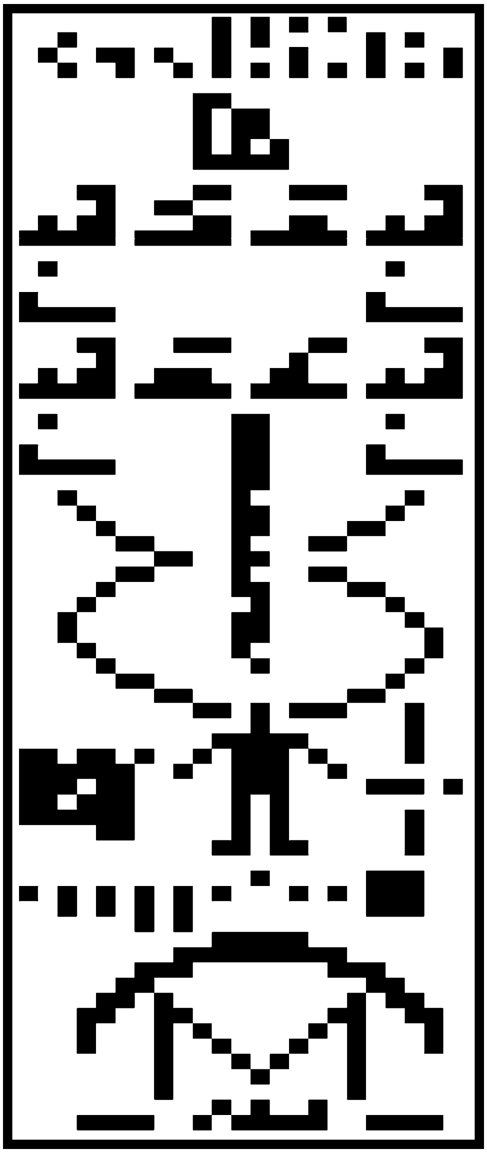

Fig. 4. ***The message sent to the globular cluster M13 using the S-band radar transmitter at the Arecibo Observatory on the occasion of the dedication of the new perforated aluminum paneled surface in 1974. The message consisted of 1679 b (73 rows and 23 columns). The message took less than 3 min to transmit and was repeated twice to ensure that the receiver would become aware of the correct number of bits. Credit: Arecibo Observatory.***

The designers of the Arecibo message hoped that the recipients would recognize 1679 as the product of two prime numbers, 73 and 23, providing a clue that the message has a rectangular format. The correct arrangement could be confirmed through standard cryptoanalytic procedures, which would detect repetitive patterns and symmetries [59]. The crux of interpreting the message lies in the recipient recognizing that some portions of the message refer to numbers, and that some of these numbers in turn refer to objects in the physical world. At the top of the message, the numbers from 1 to 10 are encoded in a binary format. Immediately beneath them, five numbers follow: 1, 6, 7, 8, and 15. Whereas the first ten numbers simply introduce our counting system in a binary format, the second set of five numbers makes a link to our terrestrial biochemistry. These numbers refer to the atomic numbers of five elements essential to life on Earth: hydrogen (1), carbon (6), nitrogen (7), oxygen (8), and phosphorus (15). To provide extraterrestrial recipients with insight into the biochemical basis for genetics on Earth, beneath these five numbers, the four nucleotides that are components of deoxyribonucleic acid (DNA) are described in terms of how many of each of these five elements each nucleotide contains. The rest of the message contains a pictogram of a human, with its height measured in wavelengths corresponding to the transmission frequency, linked to the third planet in a schematic of the solar system, and an estimate of the human population of that planet. Finally, there is a crude diagram of the transmitting antenna with its size rendered in the same wavelength convention—a cosmic boast.

A similar scheme was used in the picture sequence encoded in the Voyager interstellar recording, sent aboard two NASA missions launched in 1977 [61]. In this case, the same five elements were depicted with Bohr models of the corresponding atoms, with the different elements distinguished from one another by the number of electrons circling their nuclei (see Fig. 5). Subsequent pictures show how the nucleotide pairs combine to form the double helix of DNA.

Of course, interstellar messages that are more than symbolic demonstrations of the human capacity to send information-rich signals to other worlds need not be as concise as the 3-min Arecibo transmission. Several transmissions from the Evpatoria radar transmitter in the Ukraine included similar scientific content, but with more expanded explanations [62].

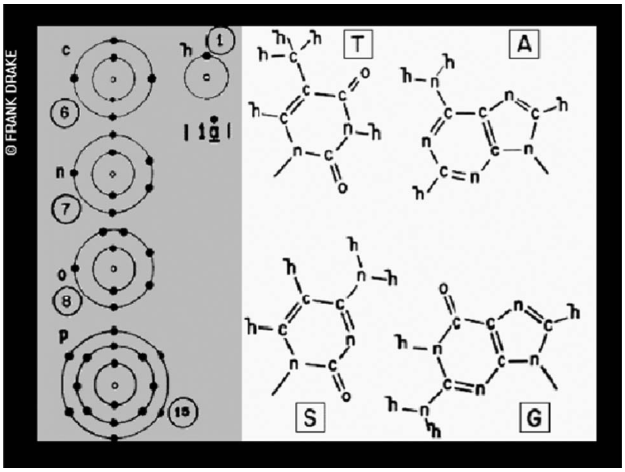

Fig. 5. ***Depictions of the atomic structure of several elements central to life on Earth, individually (on the left) and as found in deoxyribonucleic acid (DNA; on the right). From the Voyager interstellar recording. Credit: Frank D. Drake.***

B. It Is Only Logical

An alternative approach to designing interstellar messages was proposed by Freudenthal, whose *Lingua Cosmica*, or *Lincos*, is based on principles of logic [63]. For example, after communicating the concept of numbers, variables, equality, and inequalities, Freudenthal showed how these concepts could be combined to indicate logical implication. His first examples of this "if–then" deduction are as follows—rewritten here in a more accessible manner than the formalistic style that permeates *Lincos*:

$$\text{If } a > 4, \text{ then } a > 2$$
$$\text{If } a > 13, \text{ then } a > 1.$$

After an introduction to mathematics and concepts of time, Freudenthal introduces human beings—initially as agents capable of talking about mathematics. The descriptions of humans in *Lincos* are somewhat impoverished, with human cognitive development described in terms of the complexity of mathematics that children at different ages are capable of understanding.

In part, the truncated nature of Freundethal's depiction of humans is a reflection of the order in which he introduces basic concepts. Most importantly, the main chapter on human behavior precedes a discussion of space, motion, and mass, making most of these stories of humans relating to one another somewhat ethereal interactions between noncorporeal beings. Any system, however, must start somewhere, and it is noteworthy that Freudenthal had planned a second volume of *Lincos*, to focus on a more in-depth analysis of human behavior, but he never wrote it.

Others have proposed interstellar messages that "flesh out" the human actors. Letaw proposes setting the stage with depictions of objects understandable by extraterrestrials with a knowledge of basic mechanics and laws of physics, such as levers and pulleys [64]. From there, he would build up to depictions of humans interacting in their full embodiment, through 3-D animation sequences. As we attempt to tell extraterrestrial stories about ourselves, it will be important to unpack the many conventions we use in constructing our narratives, which we take for granted, but that may be opaque to unitiated ETI [65], and we hope that their messages will be constructed with the same anticryptographic care.

C. Not So Easy

Although any civilization capable of interstellar communication may need to possess sophisticated science, mathematics, and logic, some have argued that extraterrestrial and human efforts to characterize the same, shared natural world may not directly map onto one another. While we might expect advanced extraterrestrials to be familiar with natural numbers (1, 2, 3, . . .), the trajectories of their more complex mathematics may be quite divergent from the mathematics seen on Earth [66]. Even the topics deemed important by extraterrestrial scientists may be quite different from the concerns of their human counterparts. When combined with differences between human and extraterrestrial sensory modalities and ways of reasoning about the world, concepts that seem clearly relevant to humans may be elusive to ETI—and *vice versa* [67].

If in fact interstellar messages are not as transparent in form and meaning as we might hope, we will benefit from considering additional means of communicating even concepts that we deem universally relevant, but that might be represented in different ways on different worlds. The primers on chemistry offered by the Arecibo message and the Voyager interstellar recording assume that extraterrestrial chemists will readily recognize common chemical elements by either numerical descriptions (atomic numbers) or pictorial representations (Bohr models). Both the Arecibo and Voyager messages rely on the recipients first reconstructing the format of our messages, and then inferring which objects in the real world we are talking about when we introduce the numbers 1, 6, 7, 8, and 15, or when we show a diagram of a series of concentric circles. Given the varied ways that the same entities can be described, we would do well to look for additional message formats that attempt to communicate concepts using electromagnetic signals whose form mimics the concepts we wish to convey. For example, if we wish to explain how a hydrogen atom (H) and a hydroxyl radical (OH) combine to form water (H_2O), we might transmit signals at frequencies associated with the emission spectra of hydrogen, hyperfine transition (1.42 GHz), one of the main hydroxyl radical lines (1.665 or 1.667 GHz), and water (22 GHz)—illustrating a chemical reaction through the form of electromagnetic signals themselves [68].

D. What Is New?

Often those pondering interstellar messages have acted as if the messages are representing humankind for all ages and times. Such a task is daunting, and perhaps a bit presumptuous. We would do better to conceive of our missives to the stars as snapshots of current concerns and fashions, akin to new stories [69].

If in fact it is difficult for extraterrestrials to understand what we are trying to say, the most informative aspect of our transmissions may be their persistence—or transience. To receive an intentional signal from Earth each year, each decade, or even each century would say much about the commitment of humans to keep on attempting contact. Indeed, it is exactly the sort of strategy that takes into account the differing times in the history of our galaxy at which civilizations may arise. Humankind has had the technology to transmit evidence of its existence at interstellar distances for less than a century. The chance that a similarly young extraterrestrial civilization would coexist with ours at the same point in the more than ten billion year history of our galaxy would be unlikely in purely statistical terms. If we wish to be detected by such short-lived civilizations, it requires that we become long-lived ourselves, where longevity is measured not just in terms of the survival of terrestrial culture, but in our willingness to make ourselves known to other intelligence in the cosmos.

E. Should We Transmit?

There has long been consensus within the international SETI community that no individual or small group should take it upon themselves to reply to the detection of a signal from ETI. Any such decision should be made by humankind as a whole, it is argued, with consultation through international organizations such as the United Nations (UN) enabling input from across the globe.

To date, SETI scientists have had little success in getting the UN to make interstellar diplomacy a top priority. The greatest success came in 2000, when the Secretary General of the International Academy of Astronautics (IAA), Jean-Michel Contant, and Chair of that organization's SETI Committee, Jill Tarter, briefed the UN Committee on the Peaceful Uses of Outer Space (COPUOS). After providing background on the plausibility of detecting extraterrestrial intelligence, they drew attention to protocols developed by the IAA and International Institute of Space Law, and endorsed by several other international space and astronomical associations, recommending a process for deciding whether to send communications to another world. Their contributions were duly noted and archived: no further action ensued.

In the following years, the IAA SETI Committee considered the issue several times, ultimately drawing a distinction between two scenarios of transmitting from Earth: 1) in response to the detection of ETI, and 2) *de novo*, prior to the detection of ETI. In the first case, parties of the discussion were agreed that no transmissions should be made without broad-based, international consultation (although they still gave no indication of what that consultation would need to be). But in the second case, there was considerable debate and little agreement, and the SETI Committee never made a formal recommendation one way or the other.

F. Active SETI

Why would we transmit to other possible civilizations, before we know of their existence? Throughout most of the half-century history of SETI, its practitioners have often argued that we should not. Indeed, the contemporary name for this field, *Search* for Extraterrestrial Intelligence, was not proposed until the 1970s, when its proponents within NASA sought to emphasize that their discipline involved only listening, and not transmitting. Prior to that, the broader term Communication with Extraterrestrial Intelligence (CETI) was used to refer to interstellar communication from either direction, although in practice, the only sustained projects in interstellar communication were efforts to detect ETI, and not to signal evidence of our existence to them.

One argument against sending transmissions from Earth is that a serious effort requires greater resources—of time and energy—to succeed, than does listening alone, or passive SETI. Whereas a passive SETI project could detect a signal tomorrow, if we send a signal to another star system and await a reply, we must wait for success for a minimum of several years—or perhaps more realistically, for centuries or millennia, given the time for a roundtrip exchange at the speed of light. Why not let the other (arguably older) civilizations take the burden of transmitting, while we take the easier task of listening?

That is all well and good, assuming the other civilizations agree. But what if extraterrestrial civilizations are also waiting for someone else to take the initiative, while they too listen for intentionally broadcast signals? Might other civilizations too argue that they are too young to be expected to transmit—even if they have had the technology for interstellar communication for thousands or millions of years? Even if they do view themselves as likely being the more advanced partner in the dialogue, will they necessarily feel an obligation to transmit for our benefit? Or might they reason that the civilization with the most to gain—the one that has not yet made contact—should be expected to make a greater investment, and thus await our signals? Ronald Bracewell has evoked the image of a "Galactic Club" to suggest the confederation of civilizations to which we might gain access through a successful SETI project [70]. But to join the club, might we not be expected to pay our dues, or at least submit an application?

Even if we decide that a large-scale active signaling project is not feasible given humankind's current level of technological development, there are several benefits to small-scale transmission projects. By designing, building, and operating our own transmitting project, we will inevitably learn lessons that can inform terrestrial listening projects. In one such exercise [71], the Benfords have made a strong case that transmitter physics and economics will favor interstellar communications at frequencies higher than those included in most searches today. As SETI researchers develop new signal detection algorithms to search for broadband signals, one way to focus their work is to consider the modulation and encoding schemes that we might use on messages of our own that we deem appropriate for first contact.

Small-scale transmission projects would also help overcome a Catch-22 facing those grappling with how humankind should be represented in interstellar messages. Those who have been most serious about gaining broad-based representation in the decision-making process have tended to avoid any transmissions. But because there are no sustained transmission projects, even of a modest scope, there is little incentive for international organizations with other pressing issues to place SETI on their agendas. One modest first step to overcome this impasse would be for an international, multidisciplinary team to design and transmit a series of messages—but to limit these transmissions to stars that have already been targeted by past, privately organized transmission projects. While this might not increase the chances of a reply, neither does it involve making ourselves known to civilizations that do not, or could not, already know of our existence, alleviating the concerns of those who worry that intentional transmissions expose Earth to new dangers from ETI.

VI. LOOKING FORWARD AND CONCLUDING COMMENTS

It is difficult to predict the future character of this area of research and whether, or when, it might morph into a more balanced methodology of transmission and reception. The detection of another technological civilization could literally change everything, all at once. Number two is the all-important number for SETI, just as the detection of a second, independent genesis of life elsewhere in our solar system or in another planetary system would validate Nobel Laureate Christian DeDuve's claim that "Life is a cosmic imperative" [72]. The detection of evidence of another technological civilization will inform us that we are one among many. The immediate tasks of trying to decipher and interpret any encoded information will be tackled in parallel with deciding whether to respond, and expanding the search to find the other technologies we can now be confident are there. Having succeeded with the discovery of one particular type of technosignature, we are probably entitled to assume that this is the standard for communication among all of our cosmic neighbors. A successful detection would mean a reliable source of funding for future explorations and the ability to optimize the demonstrated, successful strategy so that additional detections will take place more rapidly than the first. Embedded information, if any, could also shape continuing searches.

In the absence of a detection, we can project more of the same things that we have already been doing—aided and improved by exponentially improving processing power, increased collecting areas and receivers that are asymptotically approaching perfect. A search of all the sky, all the time will finally be achievable and transient phenomena will come within our detection threshold. Any unpredictable new technologies that are invented and that end up having utility for the transmission of information over interstellar distances will become the basis for new search strategies that are pursued in parallel with the older explorations. Whenever it becomes economically feasible to do so, some individual group may begin transmitting, and it is likely that its message may be more self-serving than the universal messages discussed in the previous section.

By the time the second Centennial Issue of this journal is published, continued negative findings would be accumulating into a significant null result. Fermi's paradox will indeed have to be taken seriously as the space in which "everyone" can remain undetectable will have diminished considerably. If a lack of funding had not already terminated SETI explorations, a willingness to embrace the astonishing conclusion that we are in fact alone could finally put an end to this enterprise a century into the future. In order to survive to this second centennial, terrestrial technologies will have to have been harnessed to innovate around the challenges of our growing population, energy consumption, bioterrorism, and extreme weather due to global warming and perhaps we will even be postbiological. The internalization of the knowledge that we are in fact the first technological civilization in the Milky Way galaxy may provide additional motivation for us to properly husband our planet and all its resources for many centuries into the future, and undertake a transmission program to leave a record of who we were, should we get it wrong. ■

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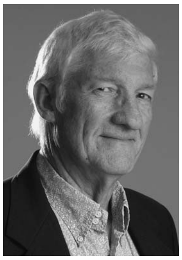

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