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# The Case for Technosignatures: Why They May Be Abundant, Long-lived, Highly Detectable, and Unambiguous

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## Abstract

The intuition suggested by the Drake equation implies that technology should be less prevalent than biology in the galaxy. However, it has been appreciated for decades in the SETI community that technosignatures could be more abundant, longer-lived, more detectable, and less ambiguous than biosignatures. We collect the arguments for and against technosignatures' ubiquity and discuss the implications of some properties of technological life that fundamentally differ from nontechnological life in the context of modern astrobiology: It can spread among the stars to many sites, it can be more easily detected at large distances, and it can produce signs that are unambiguously technological. As an illustration in terms of the Drake equation, we consider two Drake-like equations, for technosignatures (calculating $N$(tech)) and biosignatures (calculating $N$(bio)). We argue that Earth and humanity may be poor guides to the longevity term $L$ and that its maximum value could be very large, in that technology can outlive its creators and even its host star. We conclude that while the Drake equation implies that $N$(bio) $\gg N$(tech), it is also plausible that $N$(tech) $\gg N$(bio). As a consequence, as we seek possible indicators of extraterrestrial life, for instance, via characterization of the atmospheres of habitable exoplanets, we should search for both biosignatures and technosignatures. This exercise also illustrates ways in which biosignature and technosignature searches can complement and supplement each other and how methods of technosignature search, including old ideas from SETI, can inform the search for biosignatures and life generally.

*Unified Astronomy Thesaurus concepts:* Technosignatures (2128); Astrobiology (74); Biosignatures (2018); Search for extraterrestrial intelligence (2127)

## 1. Introduction

The search for life elsewhere in the universe focuses on identifying biosignatures that would indicate the presence of extraterrestrial life. An extension of the search for biosignatures is the search for "technosignatures" (Tarter 2007), which specifically focuses on identifying remotely observable signatures of extraterrestrial technology.

The search for remotely detectable biosignatures has developed greatly since the discovery of exoplanets (Wolszczan & Frail 1992; Mayor & Queloz 1995). Since that event, the field has tackled a number of scientific questions and challenges including the coupling of climate models to atmospheric chemistry networks for the production of synthetic observations (Seager et al. 2012; Grenfell 2017; Kaltenegger 2017; Catling et al. 2018; Fujii et al. 2018; Meadows et al. 2018; Schwieterman et al. 2018; Walker et al. 2018; Lammer et al. 2019), the exploration of alternative pathways for biological processes such as photosynthesis (Wolstencroft & Raven 2002; Kiang et al. 2007; Schwieterman et al. 2018; Lingam & Loeb 2020a), and the ongoing development of agnostic biosignatures such as markers of chemical complexity (Johnson et al. 2018; Walker et al. 2018; Marshall et al. 2021).

Searches for remotely detectable technology have benefited from renewed energy in recent years due to a confluence of several events, including the discovery that habitable-zone rocky planets are ubiquitous in the universe (Burke et al. 2015; Dressing & Charbonneau 2015; Hsu et al. 2018; Kopparapu et al. 2018; Mulders et al. 2018; Bryson et al. 2021), the resulting development of a robust astrobiology program focused on biosignatures, the Breakthrough Listen Initiative —which has pledged $100 million over 10 yr toward the search for technosignatures (Worden et al. 2017)—and a renewed interest from the US Congress and NASA in funding technosignature research. This renewed investment has cultivated a much broader range of avenues for the detection of extraterrestrial life.

Both fields (technosignature and biosignature searches) have developed expectations and theoretical frameworks for the abundance of signs of life in the universe. Our goal here is to perform a comparison of these expectations. Of course, an objective, quantitative comparison of the actual relative abundances of technosignatures and biosignatures is difficult because it depends on details of extraterrestrial life that we cannot know for certain until we have some examples to learn from.

To make our comparison, we will draw on many arguments that are familiar to veterans of SETI programs but have not, in

our experience, had much purchase in the broader astrobiology landscape. This is likely because many of these arguments have appeared in journals rarely read by astrobiologists, in conference proceedings, in books, and in the gray literature—that is, where they have been formally published at all. Our goal is to compile these arguments into a single coherent argument for the plausibility of the abundance of technosignatures and to do so in the context of modern astrobiology (especially since many of these arguments were first made before that field even existed in its modern form).

The essence of our argument is that technology—and its attendant technosignatures—differs in fundamental ways from biology—and its biosignatures—in that it can spread far beyond its origin in space, time, and scope (e.g., Walters et al. 1980; Papagiannis 1982; Freitas 1983). In this work, we explore how this difference gives technosignatures almost unlimited potential for key metrics associated with exolife searches: abundance, longevity, detectability, and ambiguity.[9]

This is important because the most commonly used heuristics for describing biosignatures—such as the Drake equation—can lead one to the erroneous conclusion that technosignatures must be poorer search targets than biosignatures. As we will see, there is no incontrovertible reason that technology could not be more abundant, longer-lived, more detectable, and less ambiguous than biosignatures.

### 1.1. The Role of the Drake Equation

For the first two of our four points, abundance and longevity, we can turn to the heuristic of the Drake equation (Drake 1965; Vakoch et al. 2015), which has for decades been a powerful guide to how to think about the prevalence of life, biosignatures, and technosignatures. Usually expressed in its canonical form:

$$N = R_* f_p n_p f_l f_i f_c L, \tag{1}$$

it seeks to express an estimate of the number of planets with communicative species in the Milky Way.

Broadly speaking, the first three terms on the right-hand side of the equation, capturing the rate of star formation in the galaxy ($R_*$), the fraction of stars with planets ($f_p$), and the number of habitable planets per star ($n_p$), can be determined by astronomers without having to rely on much interdisciplinary input and have reasonably well-known values. The next term, $f_l$, the fraction of those habitable planets that develop life, helps determine how likely it is that searches for biosignatures succeed. The next two, $f_i f_c$, capture the fraction of those planets that give rise to intelligence and communicative species, respectively, and so narrow things down further to the fraction we could detect via communicative signals, such as radio waves. $L$ is the average length of time a species spends sending a detectable communicative signal, yielding an expectation value for the number of communicative species at any moment.

If we think of technosignatures more broadly and do not just focus on communication, we can write a pair of Drake-like equations for biosignatures and technosignatures generally. The first,

$$N(\text{bio}) = R_* f_p n_p f_l L_b, \tag{2}$$

captures the number of planets with detectable biosignatures, where $f_l$ here is interpreted as the fraction of planets that develop sizable biospheres of the sort that give rise to remotely detectable biosignatures (and, potentially, technological life) and $L_b$ is the average length of time that the biosphere remains detectable.

Similarly, we write

$$N(\text{tech}) = R_* f_p n_p f_l f_t L_t, \tag{3}$$

which captures the number of planets with detectable technosignatures, where here $f_t$ is the fraction of planets with life with detectable technosignatures of any sort and corresponds to $f_i f_c$ in the equation's canonical form, and $L_t$ is the length of time that such technosignatures remain detectable.

### 1.2. The Case for N(*bio*) ≫ N(*tech*) and the Flaw in that Argument

A naïve conclusion from the Drake equation is that $N(\text{bio}) \gg N(\text{tech})$, based on at least two seemingly sound assumptions. The first assumption is that $f_t \ll 1$ because the development of technology is presumably a rare event (e.g., Simpson 1964; Mayr 1985, 2004). The second assumption is that any technological life that does arise will exist for only a small fraction of the time that life of any kind exists on the planet (e.g., von Hoerner 1961; Sturrock 1980). Both of these assumptions are based on the sole example of the evolutionary history of Earth.

In other words, these two assumptions would lead to the expectation that

$$\frac{N(\text{tech})}{N(\text{bio})} = f_t \frac{L_t}{L_b} \ll 1. \tag{4}$$

The primary flaw in the reasoning from the Drake equation is that it restricts technology to a small subset of biospheres in time and space and that it does so tacitly and by assumption. In truth, while technology may originate from biology, it may also exist independently of it in many ways that the Drake equation does not capture.

To give some examples of what we mean:

1. Technology can long outlive the biology that created it (e.g., Holmes 1991; Ćirković et al. 2019). One can thus have technosignatures without technological life, and even without a biosphere.
2. Technological life can spread to other worlds, and thus create sites of technosignatures that outnumber biospheres (e.g., Walters et al. 1980; Papagiannis 1982, 1983; Freitas 1983).
3. Once created, technology could self-replicate and spread without any further association with life at all (e.g., Tipler 1980; Armstrong & Sandberg 2013; Gertz 2016).
4. Technosignatures can exist beyond planets, for instance arising from spacecraft (e.g., Viewing et al. 1977; Harris 1986; Garcia-Escartin & Chamorro-Posada 2013; Lingam & Loeb 2020b).

[9] The "Nine Axes of Merit for Technosignature Searches" (Sheikh 2020) provide a framework for a similar comparison within the technosignature field. "Abundance" here maps loosely to the "Inevitability" axis in that work, and "Longevity" here to the "Duration" axis, while "Detectability" and "Ambiguity" are more directly comparable.

## 2. Abundance

Consider the solar system, which at the moment hosts only a single planet with remotely observable biosignatures (at least, any obviously discernible ones) but has four major planets with potentially detectable technosignatures. In addition to Earth, Jupiter and Venus are both orbited by probes actively transmitting radio waves, and Mars hosts several orbiters, landers, and rovers.

Thus, in our solar system, we have $N(\mathrm{bio}) = 1$, $N(\mathrm{tech}) = 4$. The radio technosignatures of these other planets are obviously weak at the moment, but the strength of such technosignatures will increase if and when space exploration of these planets intensifies in the future. There are substantial plans to increase humanity's presence on Mars, and regardless of whether it takes decades or millennia to realize those visions, it may be reasonable to expect Mars at some point to have strong, remotely detectable radio and other technosignatures while still lacking a conspicuous indigenous biosphere and its attendant biosignatures.

Looking further, there is no reason that future humans or an alien species could not choose to use some uninhabitable worlds as sites for significant technology, whether for industry, energy generation, or even waste processing, creating entire "technospheres" spatially independent of the biosphere which spawned them. These "service worlds," described by M. Lingam et al. (2022, in preparation), might not host any biology at all and might outnumber sites of biology from their originating species.

There is also no reason to think that technological life in the galaxy cannot spread beyond its home planetary system (see Mamikunian & Briggs 1965; Drake 1980). While interstellar spaceflight of the sort needed to settle a nearby star system is beyond humanity's current capabilities, the problem is one being seriously considered now, and there are no real physical or engineering obstacles to such a thing happening (e.g., Mauldin 1992; Ashworth 2012; Lingam & Loeb 2021). Even if we cannot envision it happening for humans in the near future, it is not hard to imagine it transpiring in, say, 10,000 or 100,000 yr. Many (e.g., Purcell 1980) have argued that such travel is unlikely because, while not impossible, it certainly seems difficult, and so radio transmissions are a more likely and energy-efficient form of contact. But the two are not mutually exclusive activities, and energetics are not as daunting as might seem at first glance: Hansen & Zuckerman (2021) show that there are episodes of close encounters between stars that can lower launch costs by an order of magnitude below their mean values, and Carroll-Nellenback et al. (2019) show that such close encounters can drive an efficient settlement of the galaxy even for slow ships with short range.

Therefore, the idea that such spreading would happen is not outrageous—indeed, it lies at the very heart of the Fermi paradox, which assumes that technological life will spread throughout the galaxy (Hart 1975; Tipler 1980; Gray 2015).[10] Because the time it would take even slow ships to cross the galaxy is small compared to its age, a settling species has had ample time to settle every star in the galaxy. Carroll-Nellenback et al. (2019) and others cited therein have shown that there is a wide range of rather conservative settlement parameters (e.g., very infrequent launches of ships only capable of reaching the nearest stars) that lead to the exponential growth of the number of settlements, limited only by the number of suitable stars.

If such spreading is common, then the Drake equation must underestimate $N(\mathrm{tech})$ by a very large factor, potentially even up to order $10^{10}$ in some extreme scenarios. Indeed, the idea of including a spreading factor in the Drake equation has been suggested by many authors (see, e.g., Walters et al. 1980; Prantzos 2013).

Does the same logic apply to $N(\mathrm{bio})$? If the question is posed purely in terms of nontechnological life, then the answer would appear to be "no" unless interstellar transport of life is highly effective (e.g., Crick & Orgel 1973; Napier 2004; Grimaldi et al. 2021; Lingam et al. 2022). In addition, however, $N(\mathrm{bio})$ should include biosignatures stemming from biospheres that have been purposely engineered for habitation, for example, planets that have been "terraformed."

Such spreading of biosignatures is plausibly a much rarer event than the spreading of technosignatures; the problem of how to have robots and self-replicating machines settle a nearby star system would likely be easier to solve than the problem of how to send a crewed ship because one need not worry about safety and life support for the crew during the trip (Freitas 1980; Tipler 1980; Borgue & Hein 2021). This case may, however, be overstated in actuality. The spread of life need not invoke enormous "generation ships" (Hein et al. 2012) or warp drives: One can imagine many solutions to the difficulties of the very long journey between stars. For instance, one might imagine cryostasis or even the regeneration of life "from scratch" by using artificial ova and DNA sequences stored in computer memory (e.g., Freitas 1983; Crowl et al. 2012; Hippke et al. 2018; Edwards 2021), and Hansen & Zuckerman (2021) discuss how stellar motions mean that occasionally such trips can be quite short. Regardless, once it arrives at a new home, such life will almost certainly create technosignatures (because it used technology to get there), and some fraction of them may also eventually give rise to a new biosphere, as well.

Finally, and perhaps most important for the issue of abundance, one can have many more sites of technology than technospheres, because one technosphere can produce myriad technosignatures that spread across space. A simple example already raised is the launching of interstellar vessels for any purpose, whether for settlement, scientific studies, simply trade, or something else. On a related note, self-replicating probes are already not far removed from the technological capabilities of humans (Borgue & Hein 2021). One can, therefore, imagine a single example of technological life producing a single example of a technosphere, which would, nonetheless, produce an arbitrary number of technosignatures distributed across interstellar space. In terms of the Drake equation, we might write that as $f_t \gg 1$.

Thus, while the Drake equation may underestimate $N(\mathrm{bio})$ to some degree, there are reasons inherent to technology that permit us to argue that the attendant degree of underestimation will be much larger for $N(\mathrm{tech})$, by potentially enormous factors.

## 3. Longevity

The next place the Drake equation implies low values of $N(\mathrm{tech})/N(\mathrm{bio})$ is in $L_t$, which one might think must be much

[10] Indeed, Hart and Tipler took the opposite extreme, arguing that the spreading would be so extensive that it would be too obvious to ignore, and so therefore has never happened. See references in Carroll-Nellenback et al. (2019) for many examples of rebuttals to this reasoning.

smaller than $L_b$. In particular, $L_b$ for Earth is of order 4 Gyr, and $L_t$ seems to be of order decades to millennia, based on human technosignatures. Much ink has also been spilled tying the $L_t$ in the Drake equation to fears of human catastrophes, for instance from nuclear or biological warfare or climate change, and arguing it would be optimistic to think it could be orders of magnitude larger than a thousand years or so; indeed, such arguments are as old as the Drake equation itself (e.g., Drake 1965; Mamikunian & Briggs 1965; Shklovskiĭ & Sagan 1966; Gott 1993; Charbonneau 2001).

But there are at least five strong reasons to think $L_t$ might be greater than $L_b$.

### 3.1. Humanity May Be a Poor Guide for $L_t$

Even if we choose to focus just on technological life and the technospheres they create, we must be careful of anthropocentrism, which is one of the trickiest traps to escape in the theory of technosignature searches. Humanity is the only example we have of the sort of species we seek to detect via technosignatures, and so it is both an essential and misleading data point.

One critique of this approach to technosignature searches is that it seeks technosignatures of the sort that humanity happens to create now, ignoring that other societies might develop radically different technologies and behaviors from what we have (see Denning 2011), especially if they have been doing so for far longer than humans have. And indeed, we should avoid projecting human values and tendencies (or what we imagine human values and tendencies to be) onto alien species (e.g., Rubin 2001). But this criticism is equally just as true when assigning small values to $L_t$ because one is pessimistic about humanity's future. In actuality, there is likely some wide distribution of values for $L_t$ for alien species, including very large values for some of them (Kipping et al. 2020; Balbi & Ćirković 2021).

In short, there is no reason to think that humanity's value for $L_t$ will be characteristic of alien societies, which anyway presumably occupy a wide range, and whose mean may be driven by a long tail out to large values (e.g., Shklovskiĭ & Sagan 1966).

### 3.2. We Cannot Use the Past to Predict $L_t$ for Earth's Future

Even if we do choose to base our expectations of $L_t$ on humanity—because it is, after all, the only example we have—we should still be skeptical that $L_t \ll L_b$ because this intuition is based only on Earth's past, which may be a poor guide for the future where technology is involved.

Humanity's impact on many of Earth's geological and biological processes has been profound, and some have suggested that the emergence of technology actually heralds a new state of Earth that will persist as long as Earth does (Baum et al. 2019); see, for instance, the Sapiezoic Era (Grinspoon 2019) or Earth as a Class V planet (Frank et al. 2018). Of course, such profound changes could be self-limiting, as humanity may face severe global catastrophic risks (Bostrom & Cirkovic 2008) or existential risks (Bostrom 2002) that could prevent a long-term sustainable future. Examples of such self-limiting threats include climate change, nuclear war, and pandemics.

But, as pointed out by Drake (1965), unless such a catastrophe is apocalyptic, it will not necessarily end our technosignatures. The collapse of civilizations and even widespread ecological devastation would certainly be deeply terrible, but unless they result in human extinction, humanity may be able to eventually recover, even though the ecological consequences might extend to millions of years (Myers & Knoll 2001). Catastrophic events conceivably lead to scenarios in which the loss of infrastructure, knowledge, and resources is so great that recovery of large-scale technology is impossible (Baum et al. 2013). But even then, what humans have developed once, they could potentially develop again, even from scratch.[11]

And even in the face of catastrophe, humanity may retain much of its knowledge and enough infrastructure to quickly be able to recover any lost technology, for example, by establishing refugia. In other words, the timescales for catastrophe and the resulting recovery might be short compared to the future of Earth's habitability, so while such catastrophes may lower the duty cycle during which our technosignatures are detectable, they do not necessarily present a hard upper limit to $L_t$.

Likewise, humanity is the first species on Earth that can prevent its own extinction with technology, for instance by diverting asteroids, stopping or mitigating pandemics, or building "lifeboat" settlements elsewhere in the solar system or beyond (Baum et al. 2015; Turchin & Green 2017; Turchin & Denkenberger 2018). This means that the upper limit on our technology's survival is essentially unlimited in theory, even in the face of inevitable natural catastrophes. Apart from these modern examples, Earth-analogs from human history teach us that a technological downshift—to temporarily become less technological until circumstances improve—is a common and healthy adaptation to catastrophe in human history and that technology and longevity are in this way inextricably linked (Denning 2011).

Further, $L_b$ in the past is of order a few gigayears, but Earth's future probably has $\lesssim$1 Gyr of habitability (Caldeira & Kasting 1992; Wolf & Toon 2015; Ozaki & Reinhard 2021), putting a hard limit on $L_b$. Earth's technosignatures, however, have no such limits except those set by geological processes on functionality, as even an uninhabitable Earth can still host technology (as Mars does). Indeed, considering the solar system as a whole, there is no reason technology could not exist for several gigayears, meaning that it is plausible that $L_t > L_b$ might be achievable for the solar system.

In short, our expectations are that $L_t \ll L_b$ should not be based on Earth's past but on its future and that the probability distribution of $L_t/L_b$ in this future even for human technology has a long tail extending to large values.

### 3.3. Other Species and $L_t$ for Earth Life

Even if we accept that Earth life is a good guide to extraterrestrial life and that humanity's future is short, we can still argue that $L_t$ could be quite large because Earth has a plausible chance of giving rise to another technological species after humanity's extinction (Drake 1965, pg. 328); see, however, Timmis & Hallsworth (2022). After all, few of the most striking traits of our species are altogether unique in the animal world: Intelligence, tool use, communication, and social behavior are all common (as reviewed in Lingam & Loeb 2021,

[11] However, the subsequent development of widespread technology could be impaired by prior technological life depleting a planet's easily accessible resources, if the timescales of development and resource replenishment are comparable.

Chapter 3). Given that it has already happened (at least) once, there is no inexorable reason to think that as long as animal life exists at all, another species cannot develop an even longer-lived technological society. The actual probability of such a second evolution of technology would, of course, strongly depends on the extent of the particular extinction event and whether the evolution of technological intelligence is "favored" by evolution (see Powell 2020).

Pessimism about humanity's future is thus not sufficient to argue that $L_t$ for Earth is short, especially if one believes that our propensity for self-destruction or environmental degradation is a particularly human failure.

### 3.4. We Do Not Know $L_t$ for Earth's Past

In a similar vein, if we grant that other terrestrial species could be capable of technology, then we cannot even use Earth's past to precisely constrain $L_t$ empirically because we do not know it! Our assumption that $L_t \ll L_b$ is usually based on what we think we know about Earth, namely, that remotely detectable technosignatures on Earth have only existed for decades or, optimistically, perhaps in the millennia since humans developed agriculture—that is, $L_t/L_b \sim 10^{-7}$–$10^{-6}$.

This assumption seems well justified, but a little examination reveals that we actually have very little to base it on. Schmidt & Frank (2019) showed that, while humanity's impact on the geological record (marking the Anthropocene epoch) will be indelible, the fact that it is due to technology will be indiscernible on a timescale of millions of years. That is to say, the Anthropocene will be obvious over geological timescales as an important event in Earth's past, but there will be little to no evidence that it was the result of technology, as opposed to being a purely natural phenomenon. The implication is that if there have been prior episodes of technological life on Earth, we would not know it.

So while Earth's past certainly teaches that $L_t < L_b$, the magnitude of the difference could easily be much smaller than we might guess. If there have been tens of millions of years of prior technology, and if this technology could be conceivably detectable at interstellar distances, then $L_t/L_b \sim 10^{-2}$. We just do not know.

To summarize Section 3 so far, using Earth as a guide for our expectations for $L_t/L_b$ is probably unreliable because we do not know $L_t$ for Earth's past; even if we did we should not use it to predict $L_t$ for Earth's future, and even if we did, we should not expect Earth to be a good guide for alien life, and even if we did, we should expect a broad distribution of longevities across alien species.

### 3.5. Technologies and Technosignatures Can Outlast Technological Life

An additional feature of technology is that it can be robust enough to outlive its creators and even the conditions for biology on the planets that created it. Another important difference between technology and biology is that while we would not expect biosignatures to survive the end of their biosphere, we cannot say the same for technosignatures.

To give just one example, if a fraction of a planet were covered with solar collectors (Lingam & Loeb 2017), then the associated technosignature in the form of a reflectance spectral imprint could survive long after its creators or even the entire biosphere were to end. If the solar collectors were placed on an uninhabited world such as an airless moon or planet, the timescale associated with the persistence of these technosignatures may perhaps run into the hundreds of millions of years. In addition, automation and artificial intelligence imply that technologies associated with planetary technospheres or surviving in space can persist in a functioning state long after the technological life that created them ceases to exist. It is plausible, for instance, that technology in space (even if defunct) might survive over long timescales, and searches for such technosignatures have been proposed (Holmes 1991; Carrigan 2010).

## 4. Detectability

There is a maximum strength of any exoplanetary biosignature: Life on another planet cannot modify a space larger than its own biosphere—that is, barring unproven mechanisms that could move microbial life among planets. Life also generally does not appear to concentrate and radiate power or to tightly concentrate it temporally or spectrally (see Raup 1992), implying that it can only be detected passively on exoplanets, for instance via atmospheric gases or surface reflection spectra.

Technosignatures, by contrast, have essentially no upper limit to their detectability. Kardashev (1964) outlined a famous scale spanning over 20 orders of magnitude of potential amounts of power available for technological manipulation, from humanity's current energy supply today to the total stellar luminosity of a galaxy.

Indeed, humanity's technosignatures are already on par in strength with Earth's biosignatures and may even exceed them in detectability at interstellar distances. Humanity does not currently have the technology to detect most of Earth's biosignatures if seen from the distance of, say, $\alpha$ Centauri. It is even unclear if James Webb Space Telescope (JWST) will provide that capability, although it may be able to detect potential biosignatures on the TRAPPIST-1 planets (Lincowski et al. 2018; Fauchez et al. 2019; Lustig-Yaeger et al. 2019).

On the other hand, when completed, the full Square Kilometre Array(SKA) may be sensitive enough to detect the combined chatter of our aircraft and other radar at a few parsecs (see Loeb & Zaldarriaga 2007; Forgan & Nichol 2011). Kopparapu et al. (2021) showed that LUVOIR might be able to detect $NO_x$ in an Earth-like planet at 10 pc, in principle. Furthermore, Haqq-Misra et al. (2021, submitted) estimated that some chlorofluorocarbons might be detectable, if present, on TRAPPIST-1e with JWST, in principle.

So, while it is unclear which would be more detectable on a putative technological species' home planet, the lesson from Earth is that biosignatures and technosignatures may be of quite similar strengths.[12] It is also not unreasonable to argue that, for an older society with more time for its technology to have grown, technosignatures might be much stronger, and so have the upper hand. And on the previously adumbrated "service worlds" and other places technology has spread, we would expect technosignatures to be entirely dominant.

On balance, the lesson from Earth is that we expect technosignatures to be at least as detectable—and potentially

[12] Intentional technosignatures (like the Arecibo message), which we have not been outlined, are detectable by roughly Earth-level technology over much larger distances of order 1 kpc (Tarter 2001) but are extremely intermittent and narrow band, so perhaps less detectable than our biosignatures in that specific sense.

greatly more so—than biosignatures on any planet with a technological species.

## 5. Ambiguity

Ambiguity is a major problem with searches for both biosignatures and technosignatures. This comes in two forms: ambiguity in the nature of a detection (e.g., is this spectral signature really methane/phosphine/$NO_x$?) and ambiguity in the meaning of the detection (e.g., could those species be abiogenic?).

Technosignatures, however, offer at least the potential for complete unambiguity (e.g., Margot et al. 2019). A narrowband radio signal (of order ∼Hertz spectral width) can only be technological (e.g., Tarter 2001). Indeed, the only ambiguity comes from identifying the source of the technology because it could be human, as is often the case with detections in radio SETI (see the recent example of Sheikh et al. 2021). The case for an artificial gas might be slightly more ambiguous because exotic biology might create species we think of as purely artificial, but the primary confounders then are biogenic sources, which is still a "win" for astrobiology.

Other technosignatures, such as the waste heat of industry, have many astrophysical confounders and are thence strongly ambiguous, but such is also the case for many biosignatures. One possible solution in these cases is to look for other potential technosignatures (comprising "constellations") that could increase our confidence and build a contextual understanding of the detection, rather than relying on a single observed feature at a given wavelength. Similar strategies are adopted to remotely detect biosignatures on exoplanets, where multiple biologically produced gases (gas "fluxes") are used to obtain an understanding of the planetary environment under which such detections would be made (Catling et al. 2018; Schwieterman et al. 2018).

Finally, for both biosignatures and technosignatures, we may fail to recognize what we are seeing because it is so unexpected and therefore may mistake it for a strange, natural, and purely abiogenic phenomenon. So, on balance, it is unclear whether biosignatures or technosignatures would be more ambiguous because it will depend strongly on which signature or collection of signatures is being considered, but there exist at least some technosignatures for which ambiguity is simply not a problem.

## 6. Discussion and Conclusions

We have evaluated four ways to assess the relative prevalence and detectability characteristics of biosignatures and technosignatures in the search for life in the universe and find that in all cases it is unclear which of the duo would be stronger, and that technosignatures have a higher ceiling.

The primary reasons in the first two cases are related to the assumptions baked into the Drake equation, namely, that life stays put and lasts only as long as its biosphere. To put it differently, we can state that life and technology have related but potentially independent evolutionary trajectories. Alternatively, biology, which gives rise to biosignatures in a biosphere, has different spatial and temporal limitations than technology, which gives rise to technosignatures both within and beyond a technosphere.

This means that while the emergence of biosignatures and technosignatures on a planet can be seen as complementary aspects of the same problem, their evolutionary trajectories need not be coextensive for all time. Processes that produce biosignatures and those that produce technosignatures may begin sharing the same planet with a certain distribution and strength. But over time, their distribution and strengths may diverge by orders of magnitude. As the field of technosignature search matures, we develop new considerations of the forms such divergences can take (e.g., Bradbury et al. 2011; Wright 2017; Lingam & Loeb 2019; Balbi & Ćirković 2021; Wright 2021). These new theories offer insights into the possibilities for life in the universe, as well as an opportunity to reassess priors in terms of search strategies for biosignatures and technosignatures.

Because the Drake equation implicitly assumes technology follows a biology-like evolutionary trajectory, it may not accurately represent the prevalence of detectable technosignatures. In other words, it ignores the very real possibility that technological life can spread efficiently (Walters et al. 1980). In particular, while a naïve application of this formalism might argue for there being many more sites of biosignatures than technosignatures, the spread of technology could reasonably imply that the number of sites of technosignatures might be larger than that of biosignatures, potentially by a factor of as much as $>10^{10}$ if the galaxy were to be virtually filled with technology.

In the case of longevity, the history of technology on Earth (or, rather, our perception of that history) is not necessarily a good guide for the future of technology on Earth and may not even be pertinent for the longevity of technology elsewhere in the galaxy. In addition, there is no incontrovertible reason that technology could not far outlive its parent species or even its parent biosphere. Combined with our preceding abundance arguments, this increases the maximum value of the number of present-day sites of technosignatures to be many times larger than the number of sites of biosignatures, potentially by many orders of magnitude.

In the case of detection strength, we argue that the case is roughly a tie for biosignatures and technosignatures on the present-day Earth and solar system and that in the future, technosignatures may very well attain the more obvious presence. By this reasoning, we should expect a very long tail extending out to very strong technosignatures to be found, perhaps associated with long-lived technological species, for which the likelihood of contact is higher (Kipping et al. 2020; Balbi & Ćirković 2021). Lastly, in the case of ambiguity, we have argued that the case is again no worse than a tie, with certain technosignatures being significantly less ambiguous than any known biosignature.

It thus makes sense that the collective efforts of astrobiologists should strive to include vigorous searches for both technosignatures and biosignatures because neither is clearly the superior search target. Another conclusion is that the two communities have much to gain from cross-fertilization of the sort we have attempted here.

For instance, the biosignature search community is developing many mature frameworks for designing and interpreting the results of life detection experiments, including the development and selection of good biosignatures to search for, selection criteria and prioritization of target lists, and frameworks for determining the confidence of detection and dealing with ambiguity (Neveu et al. 2018; Stark et al. 2019; Truitt et al. 2020; Tuchow & Wright 2020; Green et al. 2021;

Tuchow & Wright 2021 to give a few recent examples in addition to the references in Section 1).

In many cases, such as the ones we have presented here, there is substantial prior art in the SETI community, and indeed both communities are engaged in similar problems and have often come to similar conclusions from different directions. Both communities would thus benefit from comparative analyses of the kind we have performed here, and from further collaborative efforts and integration of ideas.

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