Optical Detection of Lasers with Near-term Technology at Interstellar Distances

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Abstract

This paper examines the ability to produce a laser beam detectable to a cursory survey (SNR 0.1% with a 1 m receive telescope) by an extraterrestrial intelligence using proven or near-term technology (megawatt-class lasers, telescopes tens of meters in size). We find that such lasers can produce a signal at ranges of less than 20,000 lt-yr, with a broad enough beam to overcome uncertainties in nearby exoplanet orbits (e.g., Prox Cen b) or encompass entire habitable zones of more distant systems (e.g., TRAPPIST-1). While the probability of closing a handshake with even a nearby extraterrestrial intelligence is low with current survey methodologies, advances in full-sky surveys for SETI and other purposes may reduce the mean-time-to-handshake to decades or centuries, after which these laser systems may close links at data rates of kbps–Mpbs. The next major gap to address for searching for extraterrestrial lasers is in expanding spectral searches into the infrared, where most terrestrial communication and high-power lasers are manufactured.

Key words: extraterrestrial intelligence – instrumentation: photometers – instrumentation: spectrographs

1. Introduction

There is interest in building gargantuan lasers to accelerate small spacecraft at other stars. A 100 GW “DE-STAR 4” laser operating at a wavelength of 1064 nm, as proposed by Lubin (2016a), could be detectable at interstellar and even intergalactic distances by a civilization with our technology (Lubin 2016b). However, no continuous-wave laser has ever been built to that scale. This leaves the open question: could lasers and telescopes that exist today or in the next decade be used to signal a nearby (hypothetical) extraterrestrial intelligence? Could we produce a detectable laser beam and direct it toward a nearby system, with a beamwidth that is larger than our uncertainty in the positions of those planets? What data rates are achievable once contact is made?

2. Background

A glossary of key terms can be found in Table 1.

2.1. Breakthrough Starshot

Breakthrough Starshot is a project to develop and eventually construct a massive laser terminal to launch laser sail spacecraft to Alpha Centauri (and other “nearby” cosmic targets) at relativistic speeds. Lubin (2016a) proposes a 100 GW “DE-STAR 4” phased array laser, which could accelerate a 1 gram “starchip” to 20% of the speed of light and reach Alpha Centauri within 20 years.

2.2. SETI

SETI is the Search for Extraterrestrial Intelligence. Historically, SETI was centered around listening for alien radio transmissions, but programs such as the Search for Extraterrestrial Visible Emissions from Nearby Developed Populations (SEVENDIP; Werthimer et al. 2001) have “piggybacked” on astronomical databases to look for anomalies in recorded spectra. Breakthrough Listen is a parallel effort to Breakthrough Starshot with the goal of improving radio coverage from dozens to thousands of hours per year, as well as processing the spectral data from the 2.4 m Automated Planet Finder to look for signs of incident laser light. However, the APF’s spectrometer only extends out to 980 nm (Vogt et al. 2014), which encompasses one of the bands used in commercial fiber amplifiers, but not the wavelengths conventionally chosen for free-space optical communication (1064 nm and 1550 nm). More recently, Tellis & Marcy (2017) searched spectra obtained by the Keck 10 m telescope, but likewise those spectra only extended from 364 to 789 nm.

Lubin notes that the proposed DE-STAR 4 laser would be visible at intergalactic distances (Lubin 2016b). The implications of such a laser for SETI are studied more thoroughly in Lubin (2016c). Lubin defines a measure of a civilization’s “class” in terms of the directed energy it is capable of producing, with CW output power $P \approx 1 \text{ kW} \times 10^{2S}$ for class $S$. Humanity’s 1 MW lasers are thus identified as “class 1.5,” while the 100 GW DE-STAR 4 marks a civilization as “class 4.” Lubin’s calculations show that if a class 4 civilization is intelligent in splitting its DE-STAR’s output beam to target habitable zones of stars or galaxies, and we filter aggressively for short-linewidth emissions at integration times of approximately 1000 s, even with a modest 1 m telescope, we can be confident that a 30 year survey will detect any class 4 civilization within a range $\approx 1\text{ Mpc}$. This includes the Local Group of galaxies, including the Andromeda and Triangulum galaxies. At such extreme distances, communication as we typically understand it is not feasible, but simply establishing that extraterrestrial intelligence exists would be a rewarding “message” in itself.

This work differs by focusing on telescope and laser technology that exists currently and by considering broadband photometric surveys with higher cadences. The focus on class 1.5 technology is certainly a case of “presentism.” Laser technology is less than 60 years old (which is less than 0.01% of human history) and if the observed power-doubling time of 20 months (Lubin 2016c) holds, then humanity will reach class 4 in another 60 years. However, for the purposes of communication, one party will have to adapt to the other, and if a class 4 civilization is going to take the leap of reaching out to its neighbors, it costs nothing to be polite and moderate their laser output.

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3. Approach

3.1. Detection

Before communication can occur, an extraterrestrial civilization must be detected (or must detect us). The mean variation in the Sun’s brightness during the solar cycle is approximately 0.01% \(^{1}\) (Fröhlich 2012); for the purpose of this analysis, we assume that a 10 times larger signal-to-noise ratio of 0.1% in a 1 m receive aperture (a dedicated but not “flagship” observatory) is the threshold for detection. Astronomers would probably not immediately associate an anomalously high solar output with intelligent activity, but it would be anomalous enough to merit the investment of resources from larger observatories. Additionally, the width of the beam should be wider than the uncertainty in the orbit of the target planet, or ideally wider than the habitable zone of the target star.

Note that, because SNR is a ratio of received laser power to star power, it is independent of range. The range limit could be set by requiring that the laser should be brighter than a limiting magnitude, but for lasers with EIRP comparable to stellar output, that limiting range can be very long. For example, a diffraction-limited 1 MW laser from a 40 m aperture would reach magnitude 26 \(^{1}\) at approximately 20,000 lt-yr, and thus is visible for the entire length of the Orion Arm or most of the way to the galactic center. Meanwhile, the DE-STAR 4 would be visible out to 100 Mly \(^{2}\), which is the diameter of the local supercluster. Range is therefore not the limiting factor in detecting lasers, but for interstellar communication between two civilizations not aware of the existence of the other, there are also practical considerations, such as the probability that a survey by one civilization happens to observe the emissions of the other, if they are not transmitting and/or observing in all directions. These are discussed in Section 4.8: Logistics.

\(^{1}\) For comparison, Saturn’s moon Fenrir, discovered in 2005, has apparent magnitude 25, making it one of the darkest moons in the solar system. It was detected by the Subaru, Gemini, and Keck telescopes, with diameters between 8 and 10 m.

\(^{2}\) The Astrophysical Journal, 867:97 (10pp), 2018 November 10
The SNR calculations will be laid out in Sections 3.1.1 and 3.1.2, but a schematic block diagram illustrating the flow of information through the model is shown in Figure 1. Essentially, the amount of power from the star and laser incident in the detector is computed by propagating through free space and summing over the bandwidth of the spectrometer or photometer. The beamwidth of the laser can then be optimized to produce the broadest possible beam that retains a detectable SNR.

### 3.1.1. Laser Link Budget

The primary equation for communication is the Friis link budget equation, Equation (1):

\[ P_{tx} = P_{tx} G_{tx} L_{fs} G_{rx} \]

Where \( P_{tx} \) is received power at the detector (which can be converted to photon flux by dividing by photon energy, \( E = \frac{hc}{\lambda} \), \( P_{tx} \) is power transmitted, \( G_{tx} \) and \( G_{rx} \) are transmit and receive gain, and \( L_{fs} \) is free-space loss for a range \( R \) and wavelength \( \lambda \), laid out in Equation (2):

\[ L_{fs} = \left( \frac{\lambda}{4\pi R} \right)^2 \]  

Other losses can be modeled in this way, such as atmospheric and pointing losses. Pointing losses are discussed in Section 3.1.3: Detectable Zone Width, and atmospheric loss is neglected, as the metric of concern is the ratio of laser power to star power in the same wavelength or photometric band (which are affected more or less equally by the atmosphere).

The width of a conventional (Gaussian) continuous-wave laser beam has its minimum value limited by diffraction. Given a wavelength \( \lambda \) and transmit or receive diameter \( D_{tx/rx} \), the beam cannot be any narrower than \( 4\lambda/(\pi D_{tx/rx}) \), and so the maximum possible gain (4\( \pi \) sradians divided by the angular area of the beam) is laid out in Equation (3):

\[ G_{tx/rx} = \left( \frac{\pi D_{tx/rx}}{\lambda} \right)^2 \]  

It is possible to make a beam wider (with lower gain) by using a lens, deformable mirror, or detuning a phased array, so the term “effective diameter” is used as the governing parameter when varying beamwidth. A DE-STAR 4 with a 1 m effective diameter is not literally transmitting 100 GW through a 1 m aperture (which would be over 1,500 times more flux than is emitted at the surface of the Sun); rather, it is detuned so that the beamwidth is the equivalent of a 1 m aperture transmitting at the 1064 nm wavelength.

The three transmitter case studies considered in this paper are described in Table 2. The ABL was selected to represent proven high-power infrared lasers. The DS-1MW was “designed” to examine the effect of wavelength, independent of the effect of power. Finally, the DE-STAR 4 was selected to include Starshot as a point of comparison.

In all cases, the receiver is considered to have \( D_{rx} = 1 \text{ m} \). This represents a good-quality but common astronomical telescope.

### 3.1.2. Stellar Background

A star’s spectrum and power output is approximated by the Planck blackbody curve. Given a mean temperature \( T \), the spectral intensity \( B_\lambda \) (W m\(^{-3}\) sr\(^{-1}\)) is calculated per Equation (4) (where \( h \) is Planck’s constant, \( c \) is the speed of light in vacuum, and \( k_B \) is the Boltzman constant). It can then be converted to photon flux \( \Phi_\lambda \) by dividing by the energy per photon, \( E = \frac{hc}{\lambda} \).

\[ B_\lambda = \frac{2hc^2}{\lambda^5}(e^{hc/(\lambda k_B T)} - 1)^{-1} \]

\[ \Phi_\lambda = \frac{2c}{\lambda^2}(e^{hc/(\lambda k_B T)} - 1)^{-1} \]  

Given a star with this intensity and with radius \( R_* \), a telescope at a distance \( R \) looking at the star with area \( A_{rx} \) (with an instrument with some bandwidth) will receive the amount of flux calculated in Equation (5).

\[ \Phi_{rx} = \int_A \Phi_{tx} A_{tx} \left( \frac{R}{R_*} \right)^2 \]  

Three star/planet case studies are considered in this paper, laid out in Table 3 (and with their spectra depicted in Figure 2). Proxima Centauri is considered because it is the closest star (with the closest confirmed exoplanet) to our Sun, and because it is the target of Breakthrough Starshot. TRAPPIST-1 is considered because it is approximately 10 times more distant (but still communicable within a human lifetime), with a confirmed multitude of Earth-sized planets, including several in TRAPPIST-1’s projected habitable zone. The Sun is included because it is the noise source when communicating to those stars, and the Earth is considered to be the target for the “reverse” communication case. The forward and reverse cases are illustrated in Figure 3. In the forward case, Earth is transmitting to Proxima Centauri (or TRAPPIST-1), and is attempting to stand out against the Sun, and in the reverse case it is the hypothetical Proxima Centurians who are communicating with us. That figure shows the essential trade studied.
in this work: a narrower beam is more intense, and stands out from the solar spectrum better, but must be pointed directly at a planet (whose location may not be precisely known). If the beam is widened, it can cover more of the solar system, including regions where planets cannot be detected directly, but eventually, it becomes so broad that it is too weak to be detected, even directly at the center. Between these extremes, there is an optimal beamwidth that maximizes the detectable zone width, which is discussed in more detail in Section 3.1.3: Detectable Zone Width.

Absorption and emission by exozodiacal and interstellar dust is not modeled in this analysis. Exozodiacal dust absorption is estimated by Stark (2011) to be no greater than 1 part in $10^{4}$ for dust clouds in a 100 zodi dust disk excited by a Jupiter-mass planet at 1 au (a worst-case analysis to determine what, if any, dust cloud activity could be detected by the Kepler mission). Even that extreme case is below the threshold desired here for a positive anomaly detection (with a single, brief observation). Because dust temperatures are approximately 250 K (and interstellar dust and cosmic backgrounds are even cooler still, at 18 and 2.7 K, respectively), their peak emission lies beyond 10 microns, which is outside the band of sensitivity of near-infrared photometry (and even if its emission in the near-infrared was equal to its peak in the midinfrared, the flux would be about six orders of magnitude below the target star; May 2008).

\[
D(R) = D_{\text{tx}} \sqrt{1 + \left( \frac{R}{z_{R}} \right)^{2}}, \quad (7)
\]

\[
DZW = D(R) \sqrt{\ln(M)/2}. \quad (8)
\]

### 3.1.3. Detectable Zone Width

The signal-to-noise ratio of the laser is the received flux at its beam center (Equation (1)) divided by the star’s background flux that shares the detector bandwidth with the laser’s wavelength (Equation (5)). The detector bandwidth for spectrometry is assumed to be 1 nm (although there are better spectrometers in use, such as the EXPRES instrument in the Discovery Channel Telescope; Jurgenson et al. 2016), centered on the wavelength of the laser, and the photometry noise is the star spectrum integrated over the corresponding UBVRI band, illustrated in Figure 4.

Once the SNR is calculated, the margin $M$ is the center SNR divided by the threshold, which is 0.1% in this analysis. Recall that, in Section 3.1.1: Detection, this threshold was established because it is 10 times larger than the typical variation in solar output due to the solar cycle. Assuming that the beam is Gaussian in profile, then the “$1/M$ beamwidth” is the detectable zone width. The $1/e^{2}$ beam diameter $D(R)$ is calculated in Equation (7) (using the Rayleigh length, the distance for the beam to double in cross-sectional area, calculated in Equation (6)), and then the $1/M$ beamwidth (the detectable zone width) is calculated in Equation (8).

\[
z_{R} = \frac{\pi D_{\text{tx}}^{2}}{4\lambda}, \quad (6)
\]

### 3.1.4. Pulse Detection

Another method used for optical SETI is pulse detection. The pulse detector consists of a triplet of photodetectors that are connected together. When all three are triggered within a nanosecond, a pulse is registered. In practice, this requires that slightly more than three photons arrive together to guarantee that a pulse is registered (5.5 on average), but nevertheless it is highly sensitive to very small numbers of photons. This instrument is intended to be sensitive to high-power pulsed lasers from distant extraterrestrial intelligence (Wright et al. 2001). However, the background count of photons received from nearby stars themselves is comparable to or greater than 1 billion photons s$^{-1}$, so the pulse count will be swamped by background noise. Or, if the detector is imaging a distant, fainter object, then the laser would have to be transmitting much higher EIRP to be detectable. Because this research is focused on near-term lasers (that are not substantially brighter than the Sun) and nearby targets of observation, pulse detection will not be considered in this study.

### 3.1.5. Inadvertent Detection

This research is focused on deliberate illumination of exoplanets (or likely exoplanet-bearing systems), but it is worth comparing the possibility of inadvertent detection of lasers not intended for interstellar communication. Guilllochon & Loeb (2015) estimate that a microwave beamed-propulsion system for interplanetary travel would produce detectable “leakage” of approximately 0.01% stellar luminosity for several hours; this would not be enough of a deviation to trip the “direct” survey approach considered here, but it could be detected by a SETI survey. Their propulsion system had a nominal frequency of 10s of GHz, or wavelengths of approximately a centimeter, and a diameter of 1.5 km, for a far-field beamwidth of approximately 7 $\mu$rad, and (at a transmission power of 1.5 TW) an EIRP of $5 \times 10^{23}$ W (or about 0.0017 $L_{\odot}$). For comparison, NASA’s Deep Space Optical Communication system (Glavich 2015) will have a 1 m aperture and operate at 1064 nm, for a narrower beamwidth (1 $\mu$rad), but with 5 kW average power, its EIRP will only be $8 \times 10^{16}$ W, or less than $3 \times 10^{-10} L_{\odot}$—far below the threshold of the survey conceptualized here, but above the threshold of $10^{-10}$ established by Ford et al. (2003) as necessary for direct imaging with a coronagraph. The laser would be especially notable because of its spectral purity. This suggests that SETI researchers should support imaging campaigns of

| Name       | $T_{\text{star}}$ (K) | $D_{\text{star}}$ ($D_{\odot}$) | $R$ (ly) | Notes                                                                 |
|------------|-----------------------|----------------------------------|----------|----------------------------------------------------------------------|
| Sol        | 5800                  | 1                                | N/A      | One planet with confirmed presence of intelligent life at 1 au.       |
| Prox Cen   | 3042                  | 0.141                            | 4.25     | Closest star to our Sun, 1 confirmed planet at 0.0485 ± 0.005 au.    |
| TRAPPIST-1 | 2550                  | 0.114                            | 39.5     | Seven confirmed planets, 3 (e, f, g) in habitable zone (0.028–0.045 au). |
exoplanet systems when multiple planets are in conjunction from Earth’s perspective, and should review spectral data from exoplanet imaging campaigns to search for laser-like spectra.

3.2. Communication

Once detection is achieved, laser communication can occur. For laser communication, the limiting factor on data rate is the rate at which photons are received. Coherent receivers are capable of closing laser communication links with multiple bits per photon (Boroson et al. 2004), with suitable coding, but while this may be feasible for communication between two stellar systems inhabited by the same species, it may not be achievable between two different species (who may not necessarily have developed identical encoding schemes). More conventional direct detection (using photodiodes rather than photon counting) is generally feasible with 100 photons per bit (Kingsbury 2015).

Lubin et al. (2018) study the case of wafersats communicating with a photon-counting receiver station that uses highly selective optical bandpass filters to reduce background noise to negligible levels (SBR > 100). Their analysis finds that the number of bits per photon is in principle unlimited, so long as the ratio of peak to average transmitted power (which they label “PAR”) can be increased. However, wafersats are principally limited by available average power, while beams studied in this work are limited by peak power, and so increasing PAR can only come at the expense of the average received photon rate. In particular, the average photon rate \( \Lambda_A = \Lambda_P / PAR \). With this limitation taken into account, the total channel capacity per Lubin et al. (2018) Equations (2) and (5) is:

\[
\mathcal{R} = \text{BPP} \cdot \Lambda_A = \frac{\Lambda_P}{\text{PAR}} \cdot \frac{\text{PAR} \cdot \log_2 e}{e} = \frac{\Lambda_P}{e \ln 2} \approx 0.53 \Lambda_P \text{ (for } 1 \leq \text{PAR} \leq e) \\
= \Lambda_P \cdot \frac{\log_2 \text{PAR}}{\text{PAR}} \text{ (for } \text{PAR} > e).
\]

Clearly, the maximum possible bit rate occurs for \( 1 \leq \text{PAR} \leq e \), as with, e.g., on–off keying (OOK, \( \text{PAR} = 2 \)). It may still be desirable to use a higher \( \text{PAR} \) to make the signal easier to distinguish against low-frequency background noise. Doing so comes at the cost of decreasing the maximum possible bit rate, but up to \( \text{PAR} \) of approximately 900, the theoretical maximum bit rate is still greater than that achievable with direct detection.

4. Results

In general, it is not difficult for a laser to get EIRPs comparable to or greater than the Sun’s, but there is a trade between EIRP and detection zone width. An extremely narrow beam (such as that planned for DE-STAR) may only be as wide as a planet, even after traveling interstellar distances. This would require orders of magnitude improvement in our knowledge of an exoplanet’s orbit or an hours-long scanning operation (which will in turn levy requirements on telescope pointing and make large-scale “surveys” infeasible) to reliably score a “hit” on the planet. On the other hand, a beam can easily be made as wide as a solar system, but at some point the beam is so diffuse that it is not detectable, even at its center.

When detection zone width is plotted against effective telescope diameter, as in, e.g., Figure 5, we see that there is an optimum diameter between these two extremes that produces the maximum detection width for an extraterrestrial astronomer using a particular technology. From this figure, we can observe that a beam is detectable with spectrometry over approximately 10 times greater beamwidth (with 1/10 the optimum effective transmit diameter) than photometry. This is driven by the narrower noise bandwidth—in spectrometry, the laser is only compared against approximately 1 nm of bandwidth from its host star, while photometry bands are approximately 100 nm wide.

4.1. DE-STAR 4 to Proxima Centauri

Plotting the detection zone width versus effective transmit diameter in Figure 5, we can see that the detectable beam (even with photometry) can be nearly 2 au wide at the optimum
design point \((D_{\text{in}} = 15 \text{ cm})\). In that case, the photon flux in a 1 m aperture at the center of the beam is 4 million photons s\(^{-1}\), corresponding to a data rate of 40 kbps for a conservative, direct-detection receiver and up to 2 Mbps for a photon-counting detector. If the beam is narrowed to point directly at Prox Cen b (DZW of 0.005 au—the size of our uncertainty in Prox Cen b’s orbit; \(D_{\text{fl}} = 200 \text{ m}\)), then the photon flux is (up to) \(7 \times 10^{12}\) photons s\(^{-1}\), for a data rate of 70 Gbps (or 3.5 Tbps with a sufficiently fast photon-counting detector). The nominal DE-STAR 4 is planned to have a 1 km effective diameter, which would produce a detectable beam of only 0.001 au wide (or 23 Earth radii) at Prox Cen, and would have a photon flux of \(1.8 \times 10^{14}\) photons s\(^{-1}\) (over 16,000 times as many photons as would be received from the Sun itself), corresponding to a data rate of 1.8 Tbps for direct detection and 90 Tbps for photon counting (assuming that the telescope has a sufficiently fast detector array).

It is said that one should “never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway” (Andrew 1989); the equivalent in interstellar terms would be the maximum data storage that could be compressed into 1 gram, which DE-STAR 4 could launch to Proxima Centauri in 20 years (assuming that the extraterrestrials have an identical laser to slow and capture it when it arrives). Hippke et al. (2017) estimate that an interstellar probe optimized for information carriage would have a negligible fraction of mass devoted to shielding, so we can assume that nearly the entire mass is devoted to data storage. DNA storage densities of 215 PB per gram have been demonstrated (encoding and decoding) in laboratory settings (Erlich & Zielinski 2017), corresponding to a bandwidth of 2.7 Gbps (less than DE-STAR), while Hippke’s recommended fluoropolymer-based data encoding scheme encodes approximately \(10^{23}\) bits (12.5 ZB) per gram, for a bandwidth of approximately 160 Tbps (substantially greater than DE-STAR). However, “inscribed matter probes” fail less gracefully than laser beam (a laser transmission may be partially decoded if part of it is missed; a gram of DNA or fluoropolymers hurtling through space at relativistic speeds cannot be “partially captured”), and so it may be better reserved for communication after using lasers to establish contact.

### 4.2. ABL to Proxima Centauri

Running the simulation for the more modest\(^2\) ABL shows that, while the detectability zone is much smaller, it can still be larger than our uncertainty in the orbit of Proxima Centauri b, even if ETs are only using photometry. Connecting the ABL directly to the ELT would produce a photometric detectable zone that is slightly smaller than our uncertainty in Prox Cen b’s orbit (which can be remedied by sweeping the beam, though it would extend the time required to guarantee illumination), but a 60 m aperture would produce a detectable zone that is just larger than the uncertainty, and a photon flux of 5.3 million photons s\(^{-1}\), or a data rate of 53 kbps with a direct-detection receiver and 2.7 Mbps with a photon-counting receiver. Alternatively, the ELT (or a slightly smaller aperture, such as the Thirty Meter Telescope) could be used unmodified if the laser power is increased from 1 to 2 MW, and the Giant Magellan Telescope could be used if the laser power is increased to 4 MW.

### 4.3. DS-1MW to Proxima Centauri

The final simulation was performed for the hypothetical DS-1MW laser, with the same power as the ABL but with a shorter wavelength. Because the DS-1MW produces higher-energy

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\(^2\) Technologically speaking, anyway; the challenge of convincing the United States Air Force to commission a megawatt laser and deliver it to the European Southern Observatory, and then convincing the ESO to build an Overwhelmingly Large Telescope and install the ABL into its primary optics (and then convincing them to devote the billion-Euro telescope to attempting to contact extraterrestrial intelligence instead of “real astronomy”), is an exercise left for future work.
photons than the ABL, the total photon count is lower, but the shorter wavelength also produces a narrower diffraction-limited beam, so the photon flux at the beam’s center is the same (and thus the theoretical maximum data rate, although the pointing losses will be worse). However, the Sun is much brighter at 785 nm than it is at 1315 nm (see Figure 2), so the detectable zone is slightly smaller, as shown by comparing the dotted and dashed–dotted curves in Figure 5.

4.4. DE-STAR 4 to TRAPPIST-1

The same lasers, transmitting to TRAPPIST-1, produce the detectable zone width curves shown in Figure 6. From this figure, we observe the independence of SNR (and thus the shape of the detectability zone width curve) with respect to range. Only the laser system and the host star affect the shape of the curve.

Because TRAPPIST-1 is approximately 10 times farther away than Proxima Centauri, data rates by beam transmission are reduced by approximately a factor of 100, but the “data rate” of the “station wagon” approach is only reduced by a factor of 10. At $D_{\text{rs}} = 200$ m, the detectable beam is almost exactly as wide as TRAPPIST-1’s habitable zone (0.045 au), and the photon flux (in a 1 m aperture at the beam center) is $8.9 \times 10^{10}$ photons s$^{-1}$, corresponding to a data rate of 89 Mbps (4.5 Gbps with photon counting), while the data rate of the DNA chip is 270 Mbps (16 Tbps with fluoropolymer chemistry). However, if the receive aperture is 1 km wide (i.e., a DE-STAR configured as a telescope rather than a laser for capturing the data chip), then the received photon rate is 1 million times greater (89 Tbps/4.5 Pbps) and laser communication is more advantageous again. The $1/R^2$ versus $1/R$ scaling argument still holds, with the “crossover point” at a range of over 200 ly with fluoropolymers, or 12 million lt-yr if the medium is DNA. Twelve million light-years corresponds to intergalactic distances, and many of the assumptions in this link budget (not to mention our usual understanding of communication) break down. At that range, it is almost certainly impossible to hold a two-way conversation, so there can be no exchange of protocols, and therefore it is unlikely that the maximum photon-limited data rate can be achieved. It is likewise vanishingly unlikely that a civilization in another galaxy could track the motion of a 1-gram “starchip,” never mind intercept it (although, if they could, it would certainly be more data delivered at once than could be transmitted and received via laser in the same amount of time).

4.5. ABL to TRAPPIST-1

Even though the ABL’s detectability zone is much smaller than that of the DE-STAR 4, because TRAPPIST-1 is 10 times farther away from Earth than Proxima Centauri, the detectability zone is once again comparable in size to the solar system (over 0.045 au, the radius of the habitable zone). The data rate to a direct-detection receiver is just over 600 bps—just enough to literally “phone home” with dial-up, or to flash the Arecibo message in 3 s. If the receiver uses photon counting, then the link can reach a bandwidth of 30 kbps, and can transmit a 1200-by-1000 pixel image of the Pioneer plaque in 40 s.

4.6. ABL from Proxima Centauri

“Reverse” cases, examining beam transmission from Proxima Centauri to the Earth, were also calculated. In general, their detection zones are much wider than beams from Earth (corresponding to much smaller effective $D_{\text{rs}}$ and reduced photon fluxes and data rates), because Proxima Centauri is dimmer than the Sun (see Figure 2). The Sun and the solar system is larger, but even so, even the ABL could produce a detectable zone comparable in size to Earth’s orbit (directing the beam out of a 22 cm effective aperture would produce a detectable zone 1.4 au wide at the solar system, as shown in Figure 7) provided we use a spectrometer to look for it. Like the Sun, Proxima Centauri is brighter at 785 nm than at

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5 That is still quite small as a fraction of the size of our solar system, so perhaps it would be more neighborly of us to make the initial transmission ourselves, rather than force the Proxima Centaurians to scan our solar system to find us. If the ETs are phoning from TRAPPIST-1, 10 times farther away, the beam will be 10 times broader, 14 au in diameter, and fully encompass the inner solar system, so this is not an issue.
1315 nm, and so the ABL produces wider detection zones than the DS-1MW.

4.7. Safety

When transmitting powerful lasers in narrow beams, we should ask what the safety impact on an exposed human or vehicle might be. The Rayleigh length of the “ABL-ELT” configuration (Equation (6)), the design with the least power and broadest beam, is over 900,000 km, so the beam can be approximated as a straight column even well past the Moon’s orbit (atmospheric turbulence effects notwithstanding). Therefore, the safety calculation might as well be done on the face of the primary mirror. Projecting 1 MW through a 39.3 m circle produces a flux of 824 W m$^{-2}$, which is slightly less than the solar constant (1360 W m$^{-2}$). A person or vehicle exposed to the beam would experience some heating, but not to an immediately threatening degree. However, a human who looked down the beam (with a 9 mm pupil) would receive an exposure of 50 mW of power in each eye, which exceeds the safety limit of exposure of 50 mW of power in each eye, which exceeds the Class 1 lasers, especially as infrared radiation does not provoke a blink response. Cameras not intended to receive direct sunlight (such as star trackers, space telescopes, and Earth observation imagers) would also be at risk of damage. If the ABL-ELT were to use a 4 MW laser, then the beam would be substantially more hazardous, and in all cases, the narrower beams within the telescope itself are even more so.

4.8. Logistics

A 1 m telescope making 1 s exposures has a limiting magnitude of approximately 15 (corresponding to a Sun-like star at a distance of 3 million lt-yr), and there are approximately 40 million such objects in the night sky (Louis Strous 1997). With a 50% duty cycle imposed by the Sun, those 40 million objects could be cataloged in 2.5 years. Such surveys are regularly performed, and have even been searched for signs of alien laser transmissions (Werthimer et al. 2001), but they have largely focused on visible wavelengths. While of course there are more mainstream scientific interests in infrared spectra of stars (to seek transmission spectra of greenhouse and life-supporting gases in exoplanetary atmospheres, for example), it is also true that high-power, large-volume commercial laser technology has evolved in the infrared more so than the visible. Infrared spectral surveys (which could be named “SEIREN-DIP,” “Search for Extraterrestrial Infrare-red Emissions from Nearby Developed Populations”) would benefit exoplanet astronomy and optical SETI alike.

Much as an observational survey can be completed in 2.5 years, a 1 s laser pulse could be sent to all of those stars in the same amount of time. If a pulse should be detected by extraterrestrials, they could answer by constructing a beacon of their own and pointing it at Earth, which would be detected within another 2.5 year survey. The “handshake” would be extended into a “conversation” by shining a modulated beacon from Earth back to the extraterrestrials, and so on.

However, the probability that our pulse is timed to arrive at an extraterrestrial astronomer (assuming they exist and are surveying in the same way that we are) at the moment they are looking at our Sun (which will be between 4 years and 3 million years after transmission) is $1/(40,000,000^2)$. That is the probability that the astronomer is surveying our star out of the 40 million targets in his survey at the same time that our laser pulse is arriving at the inhabited star out of the 40 million targets in our survey. We would have to perform over 1 quadrillion surveys with the laser to have a 50% probability of achieving an extraterrestrial detection, assuming that a single detection is enough to convince the ETs to focus a laser beacon at the Earth. All in all, the expected time to complete a handshake (given a survey of $M$ objects, with $T$ time spent on each object, and mean distance $d \propto \sqrt{M/\rho}$ for some spatial object density $\rho$) is laid out in Equation (9):

$$M^3T + 2d/c.$$  

The $M^3T$ term is from the required number of surveys to ensure that both transmitter and receiver are looking in the right place at the right time, and the time required per survey. The $2d/c$ term is the two-way round-trip delay time to close the handshake. It is clear that the number of targets should be reduced to bring the handshake time to a more reasonable span.
If we reduce the number of targets from all magnitude 15 stars to all stars within 50 lt-yr (of which there are approximately 2000), then the survey can be completed in under an hour and the handshake time is “only” 500 years, which is comparable to the longevity of major political and scientific institutions (for example, the Universities of Bologna and Oxford have been in operation since the late 11th century). If the search is limited to the 40 stars in that range confirmed to have planets (or multiple sites are used around the world, so that each only has to image or laser 40–400 stars), then the survey can be run practically continuously and the handshake time is only (up to) 100 years, dominated by the wait time for the message to travel. Extraterrestrial astronomers would see anomalous bright pulses in our Sun’s output at centi-Hertz rate, which would certainly attract attention. The assessment of how good or bad such attention would be is beyond the scope of this paper, but demonstrating the ability to produce EIRP on par with a star (and the ability to direct this energy toward planets) may serve as a deterrent against hostile behavior. In fact, DE-STAR was originally conceptualized in Kosmo et al. (2015; prior to the announcement of Breakthrough Starshot) as a laser for planetary defense against asteroid impacts.

The handshake time can be reduced from $O(M^3)$ to $O(\sqrt{M})$ by surveying the entire sky simultaneously. This might be regarded as the opposite approach of Lubin (2016c), in which the class 4 civilization can transmit to the entire “habitable” sky at once. By removing the requirement that a detecting intelligence must be looking in the right direction at the right time to receive a laser pulse from a transmitting intelligence, the problem of handshaking and communication is only
delayed by laser propagation. This means that we can return to
surveying the entire population of stars within a desired range,
without requiring the survey to run longer than the lifetime of
Earth. The SETI Institute has successfully crowdfunded a
prototype wide-angle spectroscopic survey camera intended to
look for alien lasers (SETI Institute 2017). The data recorded
will also be processed to look for other transient visible
phenomena that surveys with a narrow field of view are
unlikely to observe, such as stellar occultations (as Unistellar
has done with their eVscope developed in partnership with the
SETI Institute; Marchis 2018). As-built, the cameras use silicon
detectors and therefore cannot see the infrared spectrum where
communication lasers are mass-produced, but this gap may be
filled with future development in this class of instruments.

4.9. Future Work

In this work, instrument response curves and atmospheric
transmission curves were assumed to be unity, and star spectra
were assumed to be ideal blackbodies. Future refinements can
be made by introducing actual stellar spectra and transmission
curves. Additionally, the effect of atmospheric turbulence has
not been calculated, but it would broaden the beam beyond its
diffraction limit. For DE-STAR, this is not a concern, as the
optimum detectable zone width is much broader than its ideal
diffraction limit. However, for terminals using near-term laser
technology, and where the optimum detection zone width
requires an aperture close to diffraction-limited, the broadening
would have to be compensated. This would most easily be done
by increasing laser power, as adaptive optics technology would
be severely challenged by a multimegawatt incident beam.
Finally, a more thorough examination of interstellar communica-
 tion can be performed, including the impact of transmission
delay (which makes it impossible to close the loop between
transmission and reception) and stellar background noise,
rather than assuming a certain number of signal photons per bit.

5. Summary

With respect to interstellar optical detection and commu-
nication, we can definitively answer the question posed by
Tsoukalos (2010): “Is such a thing even possible? Yes it is.”
With technologies and facilities that exist now or will be
constructed within the next decade, humanity is capable of
producing signals detectable against the Sun to even cursory
photometric or spectrometric observations. However, the
logistics and probabilities of making contact with extraterres-
trial intelligence are daunting; even if extraterrestrial Intelli-
gence does exist “nearby” in galactic terms, it is vanishingly
unlikely that a conversation could be held within human
lifetimes. Even so, it is not inconceivable that a single
“handshake” could be closed within an institutional lifetime,
and as infrared spectral observations are made of nearby
systems for exoplanetary atmospheres, it is recommended that
SETI researchers support these surveys and investigate them
for anomalous emission lines.

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