Fast Radio Bursts from Extragalactic Light Sails

Manasvi Lingam[1,2] and Abraham Loeb[2]

[1] John A. Paulson School of Engineering and Applied Sciences, Harvard University, 29 Oxford Street, Cambridge, MA 02138, USA; manasvi@seas.harvard.edu
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Abstract

We examine the possibility that fast radio bursts (FRBs) originate from the activity of extragalactic civilizations. Our analysis shows that beams used for powering large light sails could yield parameters that are consistent with FRBs. The characteristic diameter of the beam emitter is estimated through a combination of energetic and engineering constraints, and both approaches intriguingly yield a similar result that is on the scale of a large rocky planet. Moreover, the optimal frequency for powering the light sail is shown to be similar to the detected FRB frequencies. These "coincidences" lend some credence to the possibility that FRBs might be artificial in origin. Other relevant quantities, such as the characteristic mass of the light sail, and the angular velocity of the beam, are also derived. By using the FRB occurrence rate, we infer upper bounds on the rate of FRBs from extragalactic civilizations in a typical galaxy. The possibility of detecting fainter signals is briefly discussed, and the wait time for an exceptionally bright FRB event in the Milky Way is estimated.

Key words: astrobiology – extraterrestrial intelligence – intergalactic medium – radio continuum: general

1. Introduction

Ever since the first discovery of fast radio bursts (FRBs) over a decade ago (Lorimer et al. 2007), there has been a great deal of interest in uncovering their origin. Currently, only 17 FRBs have been recorded, and a summary of their properties can be found in Petroff et al. (2016).[3] Hypotheses put forward for FRBs range from supramassive neutron stars (Falcke & Rezzolla 2014) to gamma-ray bursts (Zhang 2014) and stellar flares (Loeb et al. 2014). Regardless of their actual origin, it is now widely accepted that most FRBs are at cosmological distances (Thornton et al. 2013), particularly owing to the recent localization of the repeating FRB 121102 to a dwarf galaxy at a redshift of $z \sim 0.2$ (Chatterjee et al. 2017; Tendulkar et al. 2017).

The unusually high brightness temperature of FRB sources at cosmological distances (Katz 2016a) implies that their radio emission mechanism must be coherent as known to exist in pulsars or human-made radio transmitters. Despite the diversity of explanations advanced for FRBs, the possibility that they may be of artificial origin has not been specifically investigated, apart from Section V of Luan & Goldreich (2014).

In this Letter, we examine the possibility that FRBs are artificial beams[4] that have been set up as beacons, or for driving light sails. The idea that extraterrestrial civilizations may be using radio beams (manifested as dispersed pulses) is certainly not a new one, as it dates back to the pioneering paper by Cocconi & Morrison (1959). This idea was extended by researchers engaged in the Search for Extraterrestrial Intelligence (SETI), accounts of which can be found in Drake & Sobel (1992) and Tarter (2001); also Siemion et al. (2012). In addition to traditional, radio-based SETI, many other approaches have been advanced for detecting alien civilizations (e.g., Dyson 1960; Schwartz & Townes 1961; Howard et al. 2004; Benford et al. 2010; Wright et al. 2014; Lingam & Loeb 2017).

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[3] http://www.astronomy.swin.edu.au/pulsar/frbcat/
[4] Alternatively, FRBs could also be pulsar beams (Katz 2016b).

In Section 2, we show that the parameters required for generating artificial beams (to possibly power light sails) are compatible with FRB constraints. We discuss the implications and predictions in Section 3 and summarize our conclusions in Section 4.

2. Compatibility of FRBs and Beams

We start by examining whether some of the major FRB constraints are consistent with the assumption of artificial beams, and then explore the possibility that these beams may be used to power light sails.

2.1. FRB Constraints and Requirements

We begin by denoting the distance of the beam source from the Earth by r. One of the primary *observable* parameters for FRBs is the dispersion measure (DM), defined through a line-of-sight integral,

$$\mathrm{DM} = \int_0^r n_\mathrm{e}(s)\,ds = \bar{n}_\mathrm{e} r, \qquad (1)$$

of the mean number density of free electrons $\bar{n}_\mathrm{e}$. Ignoring contributions from the source, its host galaxy, and the Milky Way, one may adopt the mean comoving electron density for the intergalactic medium, $\bar{n}_\mathrm{e} \approx 2 \times 10^{-7}\,\mathrm{cm}^{-3}$ (Fialkov & Loeb 2016; Planck Collaboration et al. 2016). For simplicity, we assume that the FRB redshifts are <1 and drop the redshift factors in the context of our order-of-magnitude estimations.

Most sources in the FRB catalog (Petroff et al. 2016) have DM values of order hundreds of $\mathrm{cm}^{-3}\,\mathrm{pc}$. Using Equation (1), the distance can be estimated as

$$r \sim 1\,\mathrm{Gpc} \left(\frac{\mathrm{DM}}{200\,\mathrm{cm}^{-3}\,\mathrm{pc}} \right) \left(\frac{\bar{n}_\mathrm{e}}{2 \times 10^{-7}\,\mathrm{cm}^{-3}} \right)^{-1}. \qquad (2)$$

This distance is also consistent with more accurate estimates (Petroff et al. 2015, 2016).

Next, we suppose that the beam has an angular width θ and a radiated (peak) power P. The beam angle is expressible as

some factor η times the minimum value set by the diffraction limit,

$$\theta = \eta\left(\frac{c}{\nu D}\right), \qquad (3)$$

where ν is the frequency of the radiation, D is the diameter of the beam emitter, and $\eta \geqslant 1$. The spectral flux density is given by

$$S_\nu = \eta^{-2}\left(\frac{D}{cr}\right)^2 \alpha \varepsilon \nu P, \qquad (4)$$

where $\alpha = d\ln S/d\ln\nu$ is the spectral index needed for the relation $\alpha P/\nu = P_\nu$, and ε is the fraction of P that is emitted as FRB radiation (radiative efficiency). We have assumed that $\Delta\nu/\nu \sim 1$ and will use $\varepsilon\alpha \sim 1$ henceforth (Luan & Goldreich 2014; Katz 2016a), which implies that the artificial beams are *broadband*. This unorthodox assumption, which is contrary to current terrestrial engineering design, will be central to our analysis, and does represent a significant conceptual challenge as to why civilizations would opt for broadband emission.[5] The mean spectrum of FRBs is observed to be Gaussian-shaped, centered on a frequency of a few GHz (C. Law et al. 2017, in preparation). While being consistent with an artificial origin, this spectral shape is puzzling for pulsar or magnetar-like sources that are expected to show power-law spectra. Inverting Equation (4) yields[6]

$$P \sim 10^{25}\,\mathrm{erg\,s^{-1}}\left(\frac{r}{1\,\mathrm{Gpc}}\right)^2\left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-1}\left(\frac{S_\nu}{1\,\mathrm{Jy}}\right)$$
$$\times\,\eta^2\left(\frac{D}{3\times10^9\,\mathrm{cm}}\right)^{-2}, \qquad (5)$$

where the value of D was normalized to the size of a large rocky planet (Winn & Fabrycky 2015) for reasons explained below.

First, let us suppose that extraterrestrial civilizations adopt the strategy of harnessing stellar energy (Lubin 2016) to power the beams, thereby leading to

$$P \sim \mathcal{S}D^2 \sim 10^{25}\,\mathrm{erg\,s^{-1}}\left(\frac{\mathcal{S}}{\mathcal{S}_\odot}\right)\left(\frac{D}{3\times10^9\,\mathrm{cm}}\right)^2, \qquad (6)$$

where $\mathcal{S}$ is the stellar irradiance, which should be close to the solar value $\mathcal{S}_\odot$ in the habitable zone. The characteristic value of D is found from (4) and (6) by substituting the typical values for all other parameters.

As the aperture efficiency is ε, a fraction $(1-\varepsilon)$ would be dissipated, amounting to a power per unit area of $(1-\varepsilon)P/D^2$ at the base of the emitter. If we assume that this excess heat is

radiated away thermally, we get

$$\frac{(1-\varepsilon)P}{D^2} = \sigma T^4, \qquad (7)$$

where T is the surface temperature of the beamer. If the value of T is too high, structural damage may follow. Hence, an upper bound on T translates to a lower bound on D. This leads us to

$$P = 10^{25}\,\mathrm{erg\,s^{-1}}\left(\frac{1}{1-\varepsilon}\right)\left(\frac{D}{3\times10^9\,\mathrm{cm}}\right)^2\left(\frac{T}{373\,\mathrm{K}}\right)^4, \qquad (8)$$

and a comparison with (5) and (6) reveals that the same power estimate follows for $D \sim 3 \times 10^9$ cm. This represents the *minimum* aperture diameter that is required to keep the system running. Note that the value of T has been normalized to the boiling temperature of water, since it is widely used as a coolant in many beamer designs (Weber et al. 1998).

Thus, we have shown that the characteristic value of $D \sim 3 \times 10^9$ cm is obtained in two very different ways, from energetic and engineering requirements. This already constitutes a remarkable coincidence. It is rendered more unique because of a third coincidence—the value is about twice the diameter of the Earth. In other words, the beam emitter is an object akin to a planet; more precisely, it lies fairly close to the boundary between super-Earths and mini-Neptunes (Rogers 2015). Another possibility worth considering is that the emitter could have been fashioned along the lines of the Stapledon–Dyson sphere (Stapledon 1937; Dyson 1960).

To summarize, we assumed that: (i) the emission was broadband, (ii) stellar energy was used to power the beams, and (iii) water was used as a coolant. A subtle distinction is that (i) relies on advanced technological choices (and underpinnings), while (ii) and (iii) are tantamount to statements about the availability and usefulness of raw materials.

2.2. What is the Purpose of These Beams?

The preceding discussion concluded that some of the major observables for FRBs are consistent with the idea that they may be manifestations of extragalactic beams. However, this still fails to answer the important question of why they would be extant.

The first, and most immediate, possibility is that they serve the purpose of "beacons," and are thus meant to broadcast the presence of alien civilizations. However, why would a civilization want to broadcast its presence? In Benford et al. (2010), a variety of motives were considered, many of them of a sociological origin, such as a call for help, a desire to proclaim their technological achievements, etc. Although these possibilities cannot (and ought not) be ruled out, there are some inherent difficulties. They rely on complex (anthropocentric) reasons to some degree, and are thus not easily testable. Moreover, Equation (5) demonstrates that a power of 10^{25} erg s^{-1} is required, representing a fairly high expenditure. Hence, it seems rather implausible that this power would be expended on merely broadcasting a civilization's existence.

Instead, we consider the idea discussed in Benford et al. (2010), further elaborated in Guillochon & Loeb (2015) and Benford & Benford (2016), that these beams may power light sails. Suppose that a civilization wishes to construct a light sail capable of attaining relativistic speeds. In Guillochon & Loeb (2015), it was argued that an efficient strategy for achieving the largest possible velocity for a limited acceleration value leads

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[5]　Potential reasons include: (i) photon recycling for multiple passes between the spacecraft and the planet. Each cycle yields the standard kick but one gains by the number of cycles relative to the case where the beam is dispersed after one reflection. The frequency will be Doppler shifted in each pass, and once the spacecraft reaches relativistic speeds, the beam could be broadband because it will include a mix of photons with different number of passes. (ii) Optimization of engineering and economic costs and functionality (Benford et al. 2010; Messerschmitt 2012).

[6]　We obtain Equation (20) in Luan & Goldreich (2014), although the factor of b^{-1} should be corrected to b^{-2} in that paper.

to

$$v_{\max} = \sqrt{2a_{\max}d_F}, \qquad (9)$$

where $v_{\max}$ and $a_{\max}$ are the maximum velocity and acceleration respectively, while $d_F = \nu D^2/c$ is the Fresnel distance. The above expression takes advantage of the constant beam diameter in the near-field Fresnel region (with the sail size matching D) out to d_F, where the beam enters the Fraunhofer (far-field) regime and starts to diverge with an opening angle θ. In Section 2.1, we argued that D should be normalized in units of 3×10^9 cm for a multitude of reasons; this amounts to $d_F \sim 0.1$ pc. Using this value along with the characteristic values for $v_{\max}$ and $a_{\max}$, we arrive at

$$\nu = 1.5 \text{ GHz} \left(\frac{v_{\max}}{c}\right)^2 \left(\frac{a_{\max}}{1 \text{ gee}}\right)^{-1} \left(\frac{D}{3 \times 10^9 \text{ cm}}\right)^{-2}, \qquad (10)$$

having normalized the acceleration in the anthropic units of 1 gee. Remarkably, the above frequency coincides with characteristic value of 1 GHz considered thus far, which implies that the beam frequency that is optimal for powering the light sail falls within the range of FRB frequencies. Thus, it seems somewhat reasonable to hypothesize that the beams can be used to power light sails, and the ensuing implications are explored next.

3. Discussion

Next, we delve into some of the other consequences arising from our prior analysis.

3.1. The Angular Velocity of the Beam

Hitherto, we have not discussed any of the temporal aspects of the beam. We begin by noting that FRBs are detected as pulses with a duration Δt that is typically milliseconds. Suppose that the beam sweeps across the sky with an angular velocity Ω that is related to Δt (Benford & Benford 2016) via

$$\frac{\eta c}{\nu D} = \theta = \Omega \Delta t. \qquad (11)$$

Alternatively, we can introduce the time period $\tau = 2\pi/\Omega$, which can be determined from the above formula, and is given by

$$\tau = \frac{7.3 \text{ days}}{\eta} \left(\frac{\nu}{1 \text{ GHz}}\right)\left(\frac{D}{3 \times 10^9 \text{ cm}}\right)\left(\frac{\Delta t}{1 \text{ ms}}\right). \qquad (12)$$

Thus, the beam has a characteristic angular velocity of 10^{-5} rad s^{-1}, namely, a time period around one week. The derived sweep time of the beam direction reflects the spin or orbital motion of the beamer footprint relative to the receding sail (which cause the direction of the beam to change relative to the observer). Sweeping is likely to be operational during the relatively short acceleration and deceleration stages.

3.2. On the Dimensions of the Potential Light Sail

The total beam power required for driving a sail of total mass m_s and maximum acceleration $a_{\max}$ can be easily computed, assuming that the reflectivity is perfect (Benford 2013;

Guillochon & Loeb 2015):

$$P = 3 \times 10^{25} \text{ erg s}^{-1} \left(\frac{m_s}{2 \times 10^6 \text{ tons}}\right)\left(\frac{a_{\max}}{1 \text{ gee}}\right), \qquad (13)$$

and the same characteristic value of $a_{\max}$ from (10) has been utilized. Note that m_s has been normalized by that particular amount to ensure that Equation (13) matches the other estimates, namely, Equations (5), (6), and (8).

This implies that the mass of the sail is approximately 10^6 tons. In deriving this estimate, we have assumed a rough equipartition of the total mass between the sail and the payload, implying that the latter is also $\sim 10^6$ tons. If the payload's density is akin to that of the International Space Station, the dimensions must be of the order of 100 m.

The mass is rather high by human standards; most estimates for light sail propulsion are two orders of magnitude lower (Crawford 1990; Vulpetti et al. 2015). This estimate is approximately equal to the early fission-based rockets considered in the literature, which posited a total weight of up to 10^7 tons (Dyson 1968). Thus, if the beam was indeed used to power a spaceship, the latter would possibly have to be very large—an "interstellar ark" or "world ship" of sorts, although their typical masses ($\sim 10^{11}$ tons) are much higher (Hein et al. 2012).

3.3. Implications for the Number of Advanced Civilizations

Equation (2) and the DMs listed in the FRB catalog imply that the characteristic distance to FRBs is of order a few comoving Gpc (Petroff et al. 2016) and the survey volume is of the order of $\sim \frac{4\pi}{3}(3 \text{ Gpc})^3 \sim 100 \text{ Gpc}^3$. Since we know that there are $\sim 10^{10}$ habitable Earth-size planets in our Galaxy (Burke et al. 2015; Dressing & Charbonneau 2015; Winn & Fabrycky 2015), and $\sim 10^{20}$ in the entire Hubble volume (Behroozi & Peeples 2015), it is fair to assume that there are $N_E \sim 10^{19}$ habitable Earth-size planets within a volume $\sim 100 \text{ Gpc}^3$. Of these, suppose that a fraction f of these planets are broadcasting beams, manifested as FRBs.

Next, note that the characteristic beam solid angle is $\theta^2 = \eta^2 10^{-16}$ steradians, based on the characteristic parameters from the previous sections and Equation (3). Since the sky is comprised of 4π steradians, and there are $f \cdot N_E$ broadcasting planets, at any given point in time $\sim (10^{-16}/4\pi)f\eta^2 N_E$ beams are visible. Each beam is visible for $\Delta t \sim 1$ ms, which implies that approximately $10^{10} f\eta^2$ beams should be visible in a day. The latest estimates suggest that there are $\sim 10^4$ FRBs per day (Scholz et al. 2016). If we posit that not every FRB arises from extragalactic civilizations, then we find

$$f\eta^2 \lesssim 10^{-6}. \qquad (14)$$

Since we know, by definition, that $\eta \geqslant 1$, we arrive at the conclusion that $f \leqslant 10^{-6}$. If each civilization broadcasts only a single beam, this allows us to place a bound on the number of technologically sophisticated civilizations. Using this value of f in conjunction with the fact that there are $\sim 10^{10}$ habitable Earth-size planets in our Galaxy leads us to the conclusion that there are less than 10^4 FRB-producing civilizations in a galaxy similar to our own. These civilizations must belong to the Kardashev I class (Kardashev 1964) at the minimum,[7]

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[7] Recently, extensive studies have been undertaken that place stringent constraints on the number of Kardashev III civilizations (Wright et al. 2014; Zackrisson et al. 2015).

as seen from the characteristic power required in Equation (5). Although this number is undoubtedly on the higher side, it is consistent with the earlier, more optimistic studies involving the famous Drake equation (Drake & Sobel 1992); some of the current theories have also yielded similar values (Forgan 2009; Lingam 2016).

We reiterate that the above value is an *upper bound*. There exist at least three factors which can lower it:

1. It is possible that the beam angle is not diffraction limited. Even a fairly modest choice of $\eta \approx 3$ can lower the value of f_{max} by an order of magnitude, as is evident from (14).
2. Not all FRBs have an artificial origin—only a fraction of them could correspond to alien activity. As an example, one may need to single out only those FRBs that repeat, such as FRB 121102 (Maoz et al. 2015; Spitler et al. 2016; Chatterjee et al. 2017; Tendulkar et al. 2017).
3. A civilization can set up more than one beam emitter. Although it may seem unlikely, this could very well happen if a civilization has progressed to the Kardashev II or III stages.

An interesting corollary also follows: since we have assumed that FRBs are of planetary origin, the rate of FRBs is therefore set by the number of planets with advanced civilizations. This is in contrast to other models of FRBs, such as gamma-ray bursts (Zhang 2014; DeLaunay et al. 2016), whose occurrence rate is determined by the formation rate of massive stars.

3.4. Detecting FRBs of an Artificial Origin

The power "leakage" from the light sails would be high, comparable to the beam power, because of broadband emission, which implies that the diffraction limit is different for each frequency, unlike the idealized case of monochromatic emission studied in Guillochon & Loeb (2015).

It should be possible to distinguish between FRBs of natural and artificial (light sail) origin based on the expected shape of the pulse, as the beam sweeps by to power the light sail (Guillochon & Loeb 2015). More specifically, the sail would cast a moving shadow on the observed beam, thereby leading to a diffraction pattern and multiple peaks in the light curve based on the sail geometry (Manchester & Loeb 2017). A series of short symmetric bursts would be observed as the beam's path intersects with the observer's line of sight (Guillochon & Loeb 2015). Hence, looking for similar signatures in the signal could help determine whether FRBs are powered by extragalactic civilizations (although the use of a broad range of frequencies might smear these signals).

We suggest that initiatives such as Breakthrough Listen[8] could be first directed toward the repeating FRB 121102 (Scholz et al. 2016; Spitler et al. 2016; Chatterjee et al. 2017; Tendulkar et al. 2017). This proposition is reasonable since astrophysical explosions tend to produce single bursts, while artificial beacons can repeat.

3.5. Looking beyond FRBs

In our analysis thus far, we have explicitly worked with parameters that were characteristic of FRBs, such as $S_\nu \sim 1$ Jy. If all other quantities were held fixed in Equation (4), except for the power which is lowered significantly, S_ν would be much smaller.

If the beam is assumed to power a light sail, Equation (13) implies that the light sail's mass or its maximum acceleration should be reduced to lower the power. In turn, this implies that the spacecraft would not be capable of interstellar travel on short timescales; instead, it would be more likely to operate over *interplanetary* distances. Hence, there may be a large number of interplanetary spacecraft operating at extragalactic distances that are too faint to be detected. In contrast, such spacecraft (and beams) *within* our Galaxy are potentially detectable (Guillochon & Loeb 2015).

Finally, we end our discussion with an interesting observation. There are approximately $10^9 L_\star$ galaxies within 100 Gpc^3, and approximately 10^4 FRBs per day, as discussed in Section 3.3. Thus, each Galaxy has a probability of 10^{-5} FRBs/day. Hence, an FRB emanating from our own Galaxy can be detected every 10^5 days ≈ 300 years (Maoz & Loeb 2017). A Galactic FRB at a distance of 10–20 kpc would be truly spectacular since the expected value of S_ν would be 10^{10}–10^{11} Jy, and are detectable by low-cost radio receivers (Maoz & Loeb 2017). This striking event could reveal everything that can be known about the true origin of FRBs, and thereby settle this FRB origin debate once and for all.

4. Conclusions

In this Letter, we have posited that FRBs are beams set up by extragalactic civilizations to potentially power light sails.

In Section 2, we showed that the FRB parameters were consistent with the assumption that they are artificial beams. We also demonstrated that there existed a "natural" size for the emitter that was approximately twice the diameter of the Earth. This value was obtained by adopting two contrasting estimates—the first from energy considerations, while the second followed from engineering constraints. Subsequently, we illustrated that the frequency needed to power the light sail was consistent with those observed for FRBs, lending further credence to our hypothesis.

Our analysis gave rise to many interesting consequences. It was shown that the payload of the light sail and the beam's characteristic period should be approximately 10^6 tons and 7 days, respectively. Moreover, under certain simplifying assumptions, we derived an upper bound on the total number of intelligent civilizations in a galaxy (akin to the Milky Way). We also suggested that smaller light sails may be widely prevalent, which are presently undetectable as their spectral flux densities are too low. Using the all-sky cosmological rate of FRBs, we argued that an FRB might originate within the Milky Way once every several centuries.

Although the possibility that FRBs are produced by extragalactic civilizations is more speculative than an astrophysical origin, quantifying the requirements necessary for an artificial origin serves, at the very least, the important purpose of enabling astronomers to rule it out with future data.

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[8] https://breakthroughinitiatives.org/Initiative/1

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