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POWER BEAMING LEAKAGE RADIATION AS A SETI OBSERVABLE

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ABSTRACT

The most observable leakage radiation from an advanced civilization may well be from the use of power beaming to transfer energy and accelerate spacecraft. Applications suggested for power beaming involve launching spacecraft to orbit, raising satellites to a higher orbit, and interplanetary concepts involving space-to-space transfers of cargo or passengers. We also quantify beam-driven launch to the outer solar system, interstellar precursors, and ultimately starships. We estimate the principal observable parameters of power beaming leakage. Extraterrestrial civilizations would know their power beams could be observed, and so could put a message on the power beam and broadcast it for our receipt at little additional energy or cost. By observing leakage from power beams we may find a message embedded on the beam. Recent observations of the anomalous star KIC 8462852 by the Allen Telescope Array (ATA) set some limits on extraterrestrial power beaming in that system. We show that most power beaming applications commensurate with those suggested for our solar system would be detectable if using the frequency range monitored by the ATA, and so the lack of detection is a meaningful, if modest, constraint on extraterrestrial power beaming in that system. Until more extensive observations are made, the limited observation time and frequency coverage are not sufficiently broad in frequency and duration to produce firm conclusions. Such beams would be visible over large interstellar distances. This implies a new approach to the SETI search: instead of focusing on narrowband beacon transmissions generated by another civilization, look for more powerful beams with much wider bandwidth. This requires a new approach for their discovery by telescopes on Earth. Further studies of power beaming applications should be performed, potentially broadening the parameter space of the observable features that we have discussed here.

Key words: extraterrestrial intelligence – space vehicles – stars: individual (KIC 8462852)

1. OBSERVABLE POWER BEAMING

The most observable leakage from an advanced civilization may well be from the use of power beaming to transfer energy and accelerate spacecraft, both within and beyond the star system where the civilization is located. In the future, such applications may make the Earth's radiation in the microwave, millimeter, and visible/near-IR parts of the electromagnetic spectrum be very intense. Beaming of power for a variety of space applications has been a frequent topic of study because it has many advantages. Beaming power for space transportation can involve Earth-to-space, space-to-Earth, and space-to-space transfers using high-power microwave (HPM) beams, millimeter wave beams or visible/near-IR lasers. Applications include launching spacecraft to orbit or raising satellites to a higher orbit. Several investigators have studied interplanetary cargo transfers by beam-driven sail craft using radiation pressure, principally space-to-space commerce, launch into the outer solar system, and interstellar precursor probes starships. Reviews of power beaming applications (Benford 2008, 2013; Benford et al. 2016, Ch. 3) provide details on these applications, which would be superfluous to repeat here. Other means of reaching high speeds are rockets: fusion rockets, anti-matter rockets, and Bussard ramjets. Alternative methods of propulsion are compared to power beaming in Moeckel (1972), Cassenti (1982), Dyson (1982), and Matloff (2005). There is increasing agreement that power beaming is the most likely way forward.

The power levels are high, focused, and transient and could easily dwarf any of our previous leakage to space. These are not SETI *signals* so much as *leakage*, a detectable aspect of advanced civilizations. Studies have shown that leakage of TV and radio broadcast signals are essentially undetectable from one star to another due to faintness and incoherence (Sullivan et al. 1978). Planetary radars are stronger, but very transient in time and solid angle (Billingham & Benford 2014). However, the driving of spacecraft by intense beams of radiation is far more focused than communication signals, more likely to repeat, and of course far more powerful. Therefore, they could be far more easily detected.

It has previously been noted that such leakage from other civilizations could be observable (Benford 2008). Guillochon & Loeb (2015) have quantified leakage from beaming for interplanetary space propulsion, its observables, and implications for SETI. Extraterrestrial intelligence (ETI), having done the same thinking, could realize that they could be observed. Hence, there may be a message on the power beam, delivered by modulating it in frequency, amplitude, polarization, phase, etc., and broadcast it for our receipt at little additional energy or cost. By observing leakage from power beams, we may well find a message embedded on the beam.

We quantify the various classes of power beaming applications/missions, estimate the principal observable parameters, and discuss the implications of observability of ETI power beaming leakage and our own future emissions.

2. POWER BEAMING MISSIONS AND SPECIFICATIONS

2.1. Launch to Orbit

Beamed power can be used to launch spacecraft into orbit. *Microwave thermal thrusters* operate on an analogous principle to nuclear thermal thrusters and have been experimentally demonstrated (Parkin et al. 2004). In this concept, HPM beam radiates power to a thermal propulsion system in a single stage rocket. The spacecraft has a flat aeroshell underside covered by a thin microwave absorbing heat exchanger made of, for example, silicon carbide. The exchanger consists of ∼1000 small channels carrying fuel, such as hydrogen, to the motor. To be specific, a system with, for example, a beam power of 300 MW radiates from an aperture spanning 300 m impinging on a 7 m^2 converter on the underside, heating the hydrogen fuel, which exits the nozzle. Such rockets are much more efficient than conventional fuel burning rockets. By using HPM, the energy source and all the complexity that entails remains on the ground, and a beamed power transmission system carries the energy to the craft. It has a high acceleration ascent trajectory, which provides most of the transfer of energy at short range, in order to minimize the size of the radiating aperture. For such a system, the launch cost could potentially fall to as low as a few times the *energy* cost of launch (as opposed to capital cost of a throwaway rocket and fuel), so low-cost and reusable launchers are possible.

Frequencies used for power beaming depend on the location of the transmitter. For launch to orbit in an Earth-like atmosphere, the microwave frequency window at about 1–10 GHz would be appropriate because atmospheric losses are low. For an Earth-like atmosphere with some oxygen and low water vapor, high-altitude sites, further windows are at 35 GHz, 70–115 GHz, 130–170 GHz, and 200–320 GHz. With a different planetary atmosphere and weather patterns, different frequencies could make better economic sense and the absorption and breakdown thresholds would be different.

The launch rate on Earth could be as quick as one every three minutes per facility, based on the time required to accelerate a payload to low-Earth orbit. Launches could be bunched together to propel many craft in the space of a few hours to save on range operating costs. Additionally, a night launch is preferred for better beam propagation due to lower wind speeds and fewer clouds. Thus, there could be a correlation of microwave intensity with the day–night cycle of the planet with pulse lengths that are 1–10 minutes in duration. There could be a correlation between the carrier frequency and planetary atmosphere type as well. Perhaps there may also be clues as to the type of microwave-generating technology used in the linewidth and its frequency stability once Doppler shift is accounted for.

2.2. Orbit Raising

A lower power application of power beaming is orbit raising, where microwave energy from the ground is used to lift a satellite gradually into a higher orbit. An orbital transfer vehicle shuttles cargo from low-Earth orbit (in the example above, taking the cargo from the thermal rocket, which could then be returned to the surface) to geosynchronous or cislunar orbits. The Brown (1992) concept for this has a 60 ton mass, with a payload mass fraction of about 40%. The microwave beam of 10 MW provides electric power directly via a rectifying antenna to drive ion thrusters on the platform at a steady acceleration of 10^{-2} m s^{-2}. Such orbit raising takes about half a year. It is a good example of the strengths of power beaming: it is efficient, reusable, and inexpensive, and can operate around the clock, although any given target can receive power and accelerate only when it is above the horizon of the transmitter. Efficiency improves by using a higher frequency, such as 94 GHz, a water window for low-loss transmission.

A ground-based or orbiting transmitter can impart energy to a satellite if they have resonant paths (Benford & Nissenson 2006); that is, the power beam source and satellite come near each other, either by waiting for the satellite to be overhead of the ground transmitter, or for both to be nearby while in orbit in space). When resonance occurs, an amount of energy specific to that particular conjunction is radiated to the satellite. Resonant orbit boosting, accelerating lower down in the gravity well and therefore closer to the beam director, is also more efficient due to the Oberth effect (a powered flyby in which a spacecraft falls into a gravitational well, and then accelerates when its fall reaches maximum speed, producing a greater gain in kinetic energy as compared to using the same impulse outside of a gravitational well). Such resonant orbits can use several transmitter locations. The total time to escape Earth's gravity well can be as little as 10 days. Such transmitters will require powers up to 100 MW, but will use a fraction of each satellites' orbital period, which will gradually lengthen.

2.3. Interplanetary Logistics

A number of higher velocity power beaming applications have been quantified for fast transit of the solar system—Mars, Jupiter, the Kuiper Belt, Plutinos, Pluto, and the Heliopause. An attractive interplanetary mission could be the rapid delivery of critical payloads within the solar system. For example, such emergencies as crucial equipment failures and disease outbreaks can make prompt delivery of small mass payloads to, e.g., Mars colonies, an imperative. Lasers or microwaves accelerate such urgent cargo with sail spacecraft at fast boost for a few hours of propulsion to speeds of 100–200 km s^{-1}. The craft then coasts at constant high speed until decelerating for a few hours into Mars' orbit (probably by a decelerating beam system like the one which launched it), giving a 10 day transit time (Meyer et al. 1985). This method has been extended to missions with 5 gee acceleration near Earth (Benford & Benford 2006). Using a ground station, acceleration occurs for a couple of hours for a 100 kg payload. Guillochon & Loeb (2015) have quantified a strategy for detecting leakage transients from such ETI interstellar logistics. They estimate that if we monitor continuously, the probability of detection would be on the order of 1% per planetary conjunction event. They state that "for a five-year survey with ∼10 conjunctions per system, about 10 multiply transiting, inhabited systems would need to be tracked to guarantee a detection" with our existing radio telescopes.

2.4. Interstellar Probes

Interstellar probes are solar/interstellar boundary missions out to ∼1000 au. The penultimate is the interstellar precursor mission. For this mission class, operating at high acceleration, the sail size can be reduced to less than 100 m and accelerating power ∼100 MW focused on the sail. At 1 GW, sail size extends to 1 km and super light probes reach velocities of 300 km s^{-1} (63 au yr^{-1}) for very fast missions of about 10 year duration (Benford & Benford 2006).

2.5. Starships: The Biggest and Grandest Missions

Concepts of this sort require very large transmitter antenna/lens and sail (e.g., 1000 km diameters for missions to 40 ly). A Space Solar Power (SSP; see below) station radiates a

Table 1
Representative Parameters for Applications of Power Beaming

Application	Frequency f (GHz)	Power P	Duration T	Repeat Time (s)	Beamwidth $\Delta\theta = 2.44\lambda/D$ (radians (arcsec))
Launch to Orbit	94	300 MW	minutes	Immediate	2×10^{-5} (4.″1)
Orbit Raising	94	300 MW	hour	hour	2×10^{-4} (41″)
Interplanetary	68	0.3 TW	hours	Immediate	4×10^{-6} (0.″8)
0.1c Starship	100	1 TW	10 hours	days	2×10^{-8} (0.″004)
0.5c Starship	3×10^{14} Hz (1 μm)	100 TW	years	years	2×10^{-11} (4.1 μas)

microwave beam to a perforated sail made of carbon nanotubes with lattice scale less than the microwave wavelength. The sizes of the first mission concepts were enormous, with sails on 1000 km scales (Forward 1984, 1985). Landis (1999) and Frisbee (2004) found ways to reduce it dramatically to 1–10 km. Systems were further optimized, with a higher peak power of ~10 TW and a smaller vehicle size of ~0.1–1 km for the sail, requiring a ~100 km antenna array aperture (Dickinson 2001; Long 2011). Later concepts developed cost-optimized systems (Benford 2013).

2.6. SSP Stations

SSP stations, using microwave beams to efficiently transport power from solar cells in space to a planet's surface, are not likely to be observable. (Concepts for SSP vary from the microwave bands to lasers in the optical.) The beam must be carefully controlled to deliver power to the receiving rectifying antennas on the ground (Mankins 2014). Any side emissions are economic losses, therefore substantial measures would be taken to reduce side lobes to a minimum. Furthermore, the first several side lobes are absorbed in the ground. The remaining side lobes are dispersed in angle so that the power density in the far field will be very low. For the worked example in Mankins (Mankins 2014; R. M. Dickinson 2016, private communication), the back lobe is down 40 dB relative to the ~1 GW main beam. This is in contrast to power beaming transportation applications, in which the varying solid angle of the receiving spacecraft results in the main beam increasingly leaking around the edges of the vehicle being accelerated.

3. PARAMETER SPACE OF POWER BEAMING OBSERVABLES

We have surveyed 20 concepts, referenced in the above remarks, for power beaming systems which have sufficient detail to determine whether they could be observed. Tables 1 and 2 summarize parameters of the power beaming applications discussed here, the power radiated, duration, and likely time for the radiation to repeat. The beamwidth is given by diffraction, $\Delta\theta = 2.44\lambda/D$, where λ is the wavelength at the operating frequency and D is the effective diameter of the radiating aperture, likely a phased array of either antennas or optics.

Table 1 gives rough average powers and durations averaged over a given application. The power required by the applications varies by many orders of magnitude, with the launch to orbit and orbit raising application at levels below ~1 GW and the interplanetary and interstellar applications at far higher powers, into the TW and PW range. The increasingly energetic missions all require higher power and longer durations. This corresponds to the velocities needed varying by four orders of magnitude. The repeat times also increase steadily as the energy requirement rises. Figure 1 shows the power duration parameter space.

Table 2
Representative Observable Parameters for Applications of Power Beaming

Application	Slew Rate $d\phi/dt$ (rad s^{-1})	EIRP $W = 4\pi P/(\Delta\theta)^2$ (W)	Time $\Delta\theta/(d\phi/dt)$ (s)
Launch to Orbit	5×10^{-3}	10^{19}	0.04
Orbit Raising	10^{-4}–10^{-5}	10^{16}	3
Interplanetary	7×10^{-8}	10^{25}	0.04–0.4
0.1c Starship	0	10^{32}	long
0.5c Starship	0	10^{38}	long

Aperture gain is set by the angular width of the beam $\Delta\theta$, $G = \frac{4\pi}{(\Delta\theta)^2}$. The power density S at range R is determined by W, the effective isotropic radiated power (EIRP), which is the product of radiated peak power P and aperture gain G

$$W = PG \qquad \text{and} \qquad S = \frac{W}{4\pi R^2}. \tag{1}$$

Spectral flux density, typically denoted in Janskys, is the power density divided by the bandwidth. While this is commonly used as the observed quantity in radio astronomy, we cannot know the bandwidth of an ETI transmitter. Consequently, in thinking about ETI power beaming emission, we must deal with EIRP, not spectral flux density. Beaming power does not require or even necessarily benefit from narrow bandwidth; energy transference is what matters. To highlight this point, we have drawn diagonal lines of constant energy; there is a trend for applications of a certain type to follow these lines. For scale, the kinetic energy of a 5 ton vehicle moving at interplanetary speeds (~20 km s^{-1}) is 1 TJ.

Beam widths and beam slew rates, the rate at which the beam moves to follow the spacecraft and therefore sweeps past the observer, decline with power. The *observation time* is the duration when the beam leakage could be detected. It is the beamwidth divided by the slew rate, $T = \Delta\theta/(d\phi/dt)$, is short and increases with higher power applications.

Table 2 shows observables of power beaming at long range: slew rate, the EIRP, and the observation time. Observers must be able to record transients over periods of the order of at least days.

The beam slew rate, $d\phi/dt$, is given by mission requirements. Slew rates are slow relative to planetary and stellar rotation rates. Observation times tend to be short, ranging from a few seconds to about 10 ms, a span of a couple of orders of magnitude. The reason for that broad span is that sailship concepts proposed have velocities that vary by similar amounts. With a launch driven by an intense beam to arrive years later at a neighboring stellar system, the starship would

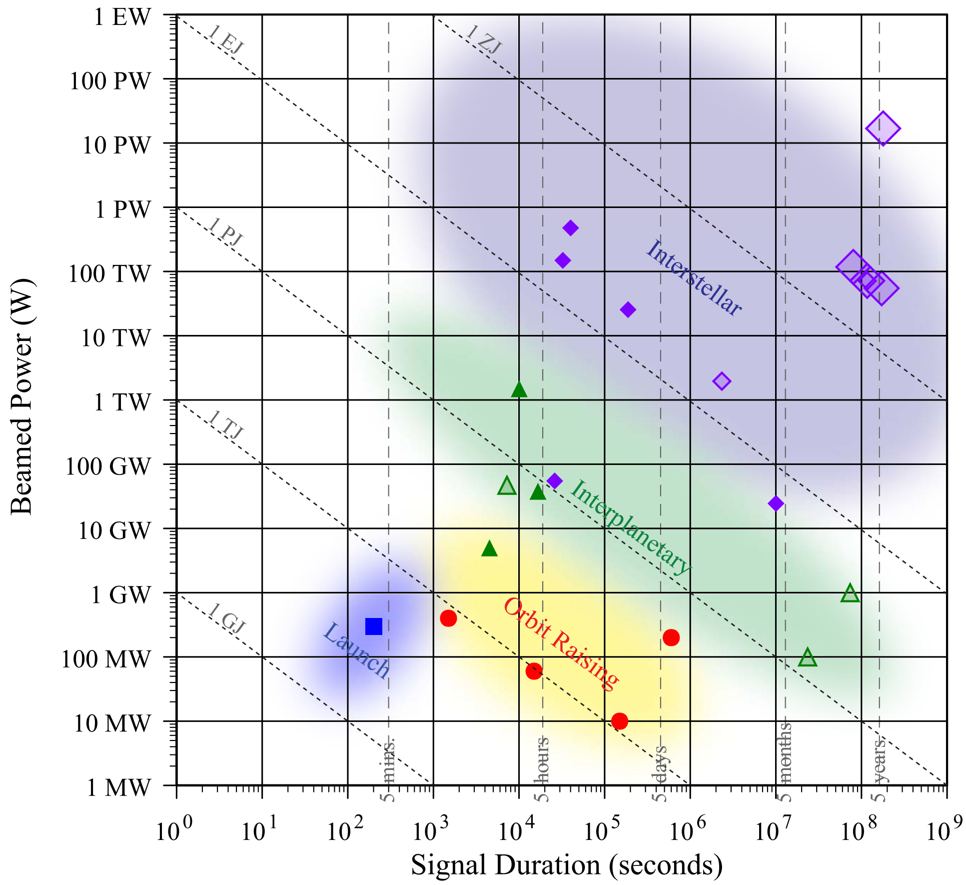

Figure 1. Domains of beam power and duration of power beaming applications. Symbols indicate launch to orbit (■), orbit raising (•), interplanetary (▲), interstellar $0.1c$ (◊), and interstellar $0.5c$ (◊). Data for the concepts are from the references. Solid symbols are for microwave and millimeter beaming, and hollow symbols indicate visible/near-IR laser beams.

be launched toward where the stellar system will be when the starship arrives. The ratio of the distance the star would move to the beam spot size is given by $v_s/(v_{ss}\Delta\theta)$, where v_s is the average velocity of the star relative to stars on our stellar neighborhood, typically $20\,\mathrm{km\,s^{-1}}$, and v_{ss} is the starship velocity. For the starship concepts proposed, that ratio varies from 10^4 to 10^7. The angle of the radiated beam with respect to the light path between the two stars is larger than the width of the beam. Thus, the beam is generally not observable from the target planetary system.

Very high-power devices might be located in space, so that atmospheric windows would not matter and frequency would depend upon the availability of efficient microwave, millimeter wave, or laser sources. At present on Earth the most developed sources with high efficiencies and fairly low cost are in the microwave and millimeter wave regime. ETI may well have far more advanced technology and be able to generate high-power beams at any frequency.

4. POWER BEAMING FROM KIC 8462852?

Based on the above quantities, the recent report from the SETI Institute of radio observations of the anomalous star KIC 8462852 has immediate implications (Harp et al. 2016). That report concluded that, using the Allen Telescope Array, in the 1–10 GHz microwave range, (1) no "narrowband" signals (1 Hz channels) were found above an EIRP of 4–7 $\times$ 10^{15} W, and (2) no "moderate band" signals (100 kHz channels) were seen in above an EIRP of 10^{19} W. The observations spanned two weeks, observing half the time.

Comparing the reported thresholds set by the ATA observations to the power beaming applications summarized in Tables 1 and 2, the non-detection of leakage signals at their stated thresholds implies the following.

1. The 1 Hz channels could see all the applications, but they are not seen.
2. Launch from a planetary surface into orbits is marginally detectable, at the threshold of the Allen Array for the 100 kHz observations, if at the frequencies observed. Orbit raising, which requires lower power, is not detectable.
3. Interplanetary transfers by beam-driven sails should be detectable in their observations, but are not seen. This is for both the 1 Hz and for the 100 kHz observations.
4. Starships launched by power beams with beam widths that we happen to fall within (to other solar systems, not our own) would be detectable, but are not seen.

In addition to radio measurements, an optical SETI measurement has been conducted toward KIC 8462852 using the Boquete observatory (Schuetz et al. 2016). Its photomultiplier detector has a detection threshold of 67 photons $\mathrm{m^{-2}}$ using a 25 ns gate time. Assuming that the signal to noise improves as the square root of bandwidth, for the times shown in the first three rows of Table 2, the detection limit in EIRP would be around 5×10^{26} W. The longer times for starships would be implausible to detect with this technique, which does not support measurements of photon fluxes that are constant for more than a few seconds. Hence, none of the power beaming applications would be likely to have been detected if using visible photons.

These results must be qualified by noting the following.

1. Power beaming is not an isotropic endeavor, and so the geometry of the transmitter and the intended recipient will produce a conjunction from our point of view only episodically. The observations were conducted for only a limited time and further observations would provide more stringent constraints. In general, the beam widths in Table 1 give an idea of the likelihood of intercepting power beaming leakage radiation.
2. The examples presented in Figure 1 that guide the estimates for observable parameters represent a broad summary of available studies; they are not, however, a coherent set of conceptual designs. They sample a range of assumptions and purposes, and were not necessarily optimized in any similar fashion. The shaded regions in the figure would improve from a more comprehensive exploration of the design space of beam-driven craft.
3. The powers and timescales presume launches for purposes similar to those studied, and for our planet and solar system. Substantially different applications, crafts, or payloads may yield different results, as would launches in a substantially different gravitational environment (for instance, if used commonly for transport around an asteroidal zone). It is possible to use a high powered laser to move solar system objects, such as diverting asteroids for planetary protection (Lubin et al. 2014) or evaporation and desorption of an comet's icy surface could produce a thrust to guide it into a planet (such as Mars, to produce lakes).
4. For the radio measurements, even the "moderate band" observation is actually quite narrow compared with the kinds of sources that would be used in power beams, based on our current understanding of microwave physics. For the applications discussed here, the 100 kHz bandwidth observed would be about 10–100 millionths of the center frequency of the transmitter. High-power devices using presently understood physics are not designed for such narrow bandwidths. In microwave and millimeter wave devices on Earth, bandwidth is seldom a key parameter; other factors such as power are more important. Some examples: high-power gyrotrons are very narrowband devices. They are highly overmoded, so have to be narrowband to avoid competition between modes, which reduces power. One 2 MW gyrotron operating at 140 GHz has a bandwidth of 70 MHz, which is 0.05% bandwidth (M. Thumm 2015, private communication). However, 100 kW class pulsed gyro-backward wave oscillators have up to 17% bandwidth. Klystrons have bandwidth fractions of ~0.1%. Consequently, future SETI observations should take such bandwidths into account.
5. The optimal radio frequencies we would presently use for power beaming are in the millimeter band, so are outside the microwave range the Allen Telescope Array observed. Similarly, power beaming using near-IR frequencies would be undetectable by the Boquete observatory.

Therefore, the Harp et al. (2016) and Schuetz et al. (2016) limited observation times and wavelength coverage are not sufficient to produce firm conclusions on power beaming from KIC 8462852. Most applications would be seen in the radio—if transmissions were oriented in our direction at the proper time and at the frequencies observed—but are not. More extensive observations should be made in more systematic studies of power beaming leakage, including observing at higher radio frequencies and for longer times at visible wavelengths.

5. CONCLUSIONS AND IMPLICATIONS

We have listed several classes of power beaming applications/missions, quantifying the principal observable parameters. Applying this reasoning to the recent observations of KIC 8462852, we conclude that if power beaming were in use at the time observed, generally pointed in our direction, and at frequencies between 1 and 10 GHz, that most power beaming applications would have been detectable. The non-detection provides a weak (owing to the caveat of the probabilities listed) rejection of the popular hypothesis that the system is inhabited by an advanced spacefaring extraterrestrial civilization.

As discussed above, the beaming power levels are high and transient and easily dwarf any ETI civilization's diffuse leakage to space (Sullivan et al. 1978). Power beaming described here is larger than that necessary for beaming systems for communication: EIRP = 10^{18} W for a 1000 ly range beacon (Benford et al. 2010).

SETI programs could explore a different part of parameter space by observations suitable to finding leakage from power beams. Such beams would be visible over large interstellar distances. This implies a new approach to the SETI search: instead of focusing on narrowband beacon transmissions generated by another civilization, look for more powerful beams with much wider bandwidth. This requires a new approach for their discovery by telescopes on Earth. Past SETI observations have been in the 1–10 GHz microwave band. For our atmosphere, future observations should look in bands where with lower oxygen and water vapor allow transmission: windows at 35 GHz, 70–115 GHz, 130–170 GHz, and 200–320 GHz. And, of course, such transient sources require longer observing times. A promising avenue is to revisit past observations of transient events, of which there are many, to look for patterns and identify as possible regions of the sky to emphasize.

ETIs would know their power beams could be observed. They could put a message on the power beam and broadcast it for our receipt at little additional energy or cost. By observing leakage from power beams, we may well find a message embedded on the beam. That message may use optimized power-efficient designs such as spread spectrum and energy minimization (Messerschmitt 2012, 2015).

If we build large power beaming systems in the future, we should be mindful of the possibilities of increased detectable leakage from Earth due to them. Such radiation may be a message, whether intentional or not.

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Facility: Allen Telescope Array.

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