



A cloaking device for transiting planets

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ABSTRACT

The transit method is presently the most successful planet discovery and characterization tool at our disposal. Other advanced civilizations would surely be aware of this technique and appreciate that their home planet's existence and habitability is essentially broadcast to all stars lying along their ecliptic plane. We suggest that advanced civilizations could cloak their presence, or deliberately broadcast it, through controlled laser emission. Such emission could distort the apparent shape of their transit light curves with relatively little energy, due to the collimated beam and relatively infrequent nature of transits. We estimate that humanity could cloak the Earth from *Kepler*-like broad-band surveys using an optical monochromatic laser array emitting a peak power of ~ 30 MW for ~ 10 hours per year. A chromatic cloak, effective at all wavelengths, is more challenging requiring a large array of tunable lasers with a total power of ~ 250 MW. Alternatively, a civilization could cloak only the atmospheric signatures associated with biological activity on their world, such as oxygen, which is achievable with a peak laser power of just ~ 160 kW per transit. Finally, we suggest that the time of transit for optical Search for Extraterrestrial Intelligence (SETI) is analogous to the water-hole in radio SETI, providing a clear window in which observers may expect to communicate. Accordingly, we propose that a civilization may deliberately broadcast their technological capabilities by distorting their transit to an artificial shape, which serves as both a SETI beacon and a medium for data transmission. Such signatures could be readily searched in the archival data of transit surveys.

Key words: extraterrestrial intelligence – planetary systems.

1 INTRODUCTION

In the last two decades, a new era of astronomical discovery has blossomed through the detection of planets orbiting other stars, exoplanets. In the first decade, this wave of discovery was largely enabled by precise measurements of the reflex radial velocity of stars, apparent via the spectroscopic shifts of atomic absorption lines (Mayor & Queloz 1995; Marcy & Butler 1996). From 1995 to 2005, 95 per cent of exoplanet discoveries were achieved using radial velocities (Exoplanet Orbit Database; Wright et al. 2011). During this time, only a handful of planets were found via the photometric brightness decrease of a star caused by a transiting planet (Charbonneau et al. 2000; Henry et al. 2000). However, once demonstrated, the relative technical ease, potential sensitivity and wide scope for surveying led to the transit method to become the dominant method of finding other planets. From 2005 to 2015, 75 per cent of exoplanet discoveries were made using transits, of which over 80 per cent were from the *Kepler Mission* (Borucki et al. 2003). With multiple transit surveys planned over the next decade,

such as NGTS (Wheatley et al. 2013), TESS (Ricker et al. 2014) and PLATO (Rauer et al. 2014), this pattern of discovery seems likely to continue.

One of the major goals of these exoplanet surveys is to improve our understanding regarding our uniqueness in the Universe to resolve whether the Copernican Principle (Bondi 1952) extends to self-aware, technological civilizations. Whilst this is usually framed as measuring the occurrence rate of Earth-like planets (see e.g. Petigura, Howard & Marcy 2013), a key term in the Drake Equation, transits can go further and more directly answer this most fundamental of questions. For example, transit spectroscopy (Seager & Sasselov 2000) searches for the chromatic transit variations due to absorbing molecules. So-called ‘biosignatures’, such as molecular oxygen (Des Marais et al. 2002; Kaltenegger, Fridlund & Kasting 2002), could be revealed this way, although abiotic activity could be ultimately responsible too (Wordsworth & Pierrehumbert 2014). Lin, Abad & Loeb (2014) proposed that advanced civilizations could be identified by detecting the atmospheric pollutants produced by industrial activity, although it is doubtful that present anthropogenic activity is sustainable (Field et al. 2014). These ambiguities would be eliminated if an advanced civilization chose to deliberately signal their presence or undertake mega-engineering in their system. Here

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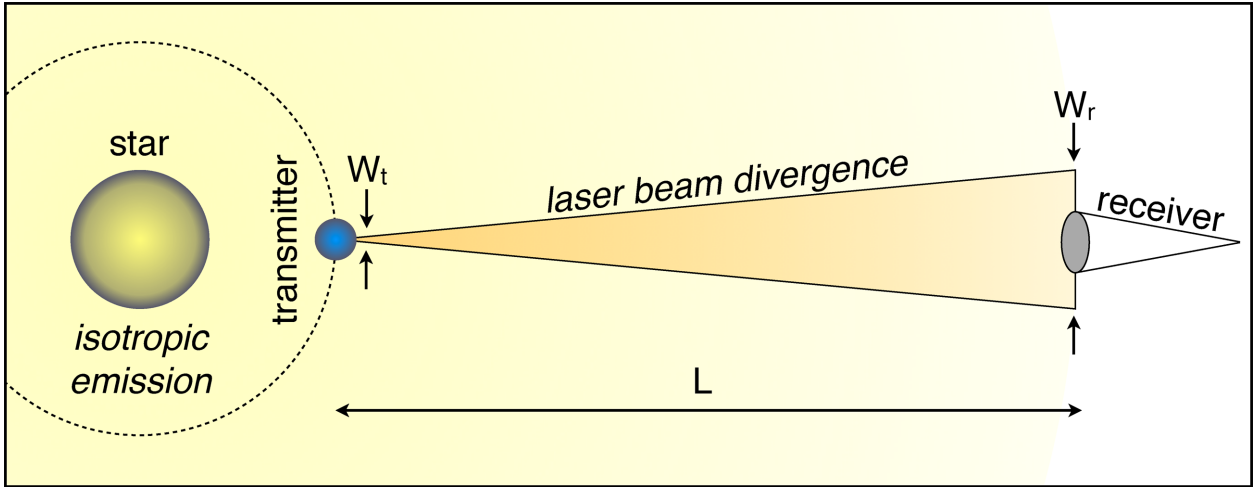


Figure 1. Illustration (not to scale) of the transit cloaking/broadcasting device. A laser beam (orange) is fired from the night side of inhabited planet (blue) towards a target star whilst the planet appears to transit the star, as seen from the receiver. In the case of the Earth, the planet could be cloaked by generating an inverse transit-like signal of peak power $\lesssim 60$ MW.

also, the success of recent transit surveys has motivated thinking as to whether transits could serve such a function too.

Transiting mega-structures, such as Dyson spheres (Dyson 1960), would present irregular transit profiles which may be difficult to distinguish from natural phenomena, such as cometary clouds (Boyajian et al. 2016; Wright et al. 2016). Deliberate signalling (or broadcasting) would be presumably easier to interpret, which motivated the original radio-based ‘Search for Extraterrestrial Intelligence’ (SETI) project (Morrison, Billingham & Wolfe 1977). Arnold (2005) proposed that advanced civilizations could broadcast their presence through transits by constructing large, thin artificial structures, such as a triangular mask, in a tight orbit around their host star. The transit profiles of such objects would display residuals to the assumed spherical planet model, of the order of 10^{-4} . A related concept using mirrors was recently proposed by Korpela, Sallmen & Leystra (2015), but both ideas require the construction of Earth-sized masks, which is far beyond our current capabilities.

In this work, we argue that artificial transit profiles can be feasibly generated using laser emission. Whilst typical optical SETI efforts focus on detecting brief pulse-like lasers at specific wavelengths (see e.g. Tellis & Marcy 2015), we propose that deliberate distortion of one’s own transit profile can be an effective means of signalling too. Moreover, an advanced civilization could plausibly cloak their planet (or moon) from *Kepler*-like transit surveys at relatively low energetic cost. Indeed, it is technologically feasible that we could soon begin cloaking the Earth from nearby Earth-analogues lying near the ecliptic plane (such that they see us transit) with this technique.

Starting with the cloaking case, which is conceptually simpler, we derive the energy requirements to cloak a transiting planet in Section 2, both in terms of individual events and the continuous power required averaged over the planet’s orbital period. We build upon this idea in Section 3, introducing the more energetically favourable case of a ‘biocloak’, a cloak of biosignatures alone. In Section 4, we propose a possible method for broadcasting via lasers to create an unambiguously artificial transit revealing our presence. We conclude in Section 5 by discussing the possibilities to actively search for artificial transits in archival and upcoming photometric mission data.

2 CLOAKING A PLANET

2.1 Concept

Consider an advanced civilization residing on a planet,¹ which would presumably have similar insolation to that of the Earth, S_{\oplus} . Let us imagine that the inhabitants have discovered all the nearby habitable planets along their ecliptic plane. Since the inhabitants presumably know the orbit of their own planet precisely and the positions of the stars hosting habitable planets, they are easily able to evaluate which habitable worlds would be able to observe transits of their home planet and when.

Given humanity’s own experience of highly successful transit surveys as a means of discovering exoplanets, it is not unreasonable that many extraterrestrial civilizations may have adopted this method as part of their planet hunting arsenal. With this realization, the hypothetical advanced civilization may wish to avoid other civilizations discovering their presence. Since this civilization knows precisely when other nearby habitable planets could see them transit, their objective would be to generate a brightness change, as viewed by a distant observer, which would cancel out the transit light curve caused by their home planet eclipsing their parent star.

One method to achieve this requirement would be with a fleet of finely controlled mirrors, analogous to the mega-engineering project discussed by Korpela et al. (2015). The dimensions, number and geometry of these mirrors would require carefully tuning for each target, at considerable expense to build and launch these structures. Whilst this elaborate method could work, it is arguably technologically more feasible, given our present state of development, to use a directed laser beam to achieve the same effect.

In our scheme, as depicted in Fig. 1, the advanced civilization emits a laser directed towards the other planetary system at precisely the instant when the other system would be able to observe a transit. The power profile of the laser would need to be the inverse of the expected transit profile, leading to a nullified flat line eliminating the transit signature.

¹ Whilst we use the term ‘planet’ throughout, this could equally apply for moons or trojans too.

2.2 Broadband cloak

In what follows, we consider the power and energy requirements needed to produce an inverted transit signal. For simplicity, we will first assume that the observer we wish to cloak from is using a *Kepler*-like survey, defined as an optical, broad-band photometer, and thus we refer to this as a ‘broad-band’ cloaking device. The issue of cloaking transits from spectroscopic transit measurements is discussed later in Section 2.4.

In the described scenario, one can utilize a monochromatic optical laser, which would emit at a wavelength around the broad high-efficiency plateau of an optical survey (e.g. for *Kepler* the response function plateaus for 450–800 nm). For simplicity, we will assume a bolometric bandpass, collecting photons of all wavelengths, in what follows. Modifying the final result for narrower bandpasses is easily achieved, as demonstrated towards the end of our calculation.

Consider a laser with a beam width at the transmitter and receiver of W_t and W_r , respectively, where the separation between them is given by L , as depicted in Fig. 1. The beam divergence angle, Θ , is defined by

$$\Theta = 2 \tan^{-1} \left(\frac{W_r - W_t}{2L} \right). \quad (1)$$

One may re-arrange this to express that

$$W_r = W_t + 2L \tan(\Theta/2). \quad (2)$$

Consider the case of L being very large, such that significant divergence will occur, causing $W_t \ll W_r$ and thus the above can be reasonably approximated to

$$W_r = 2L \tan(\Theta/2). \quad (3)$$

For a diffraction-limited beam, the divergence angle is given by

$$\Theta = \frac{\sqrt{2}\lambda}{D_t}, \quad (4)$$

which may be substituted into equation (3) to yield

$$W_r = \frac{\sqrt{2}L\lambda}{D_t}, \quad (5)$$

where we have used the small-angle approximation for Θ . The receiver has a finite diameter, D_r , which we assume to be less than the diameter of the beam width at the receiving end (i.e. $D_r \leq W_r$). In canonicalized units, the beam width at the receiver is

$$W_r \simeq 0.1 \text{ au} \left(\frac{L}{10 \text{ pc}} \right) \left(\frac{\lambda}{600 \text{ nm}} \right) \left(\frac{10 \text{ m}}{D_t} \right). \quad (6)$$

This suggests that for systems closer than 100 pc, the beam width will not exceed an au and some information about the target planet’s orbit would be required. The pointing precision is expected to be given by $\alpha = \frac{1}{2} W_r/L$, or

$$\alpha \simeq 10 \text{ mas} \left(\frac{\lambda}{600 \text{ nm}} \right) \left(\frac{10 \text{ m}}{D_t} \right). \quad (7)$$

By placing the receiver within the beam cone, the fraction of transmitted power collected by the receiver will be equal to the ratio-of-areas between the receiver and the beam width,² such that

$$\mathcal{P}_r = \left(\frac{D_r}{W_r} \right)^2 \mathcal{P}_t, \quad (8)$$

² In practice, the intensity of a standard laser would be non-uniform across the beam, but this may be correctable using beam shaping, as discussed later in Section 2.3.

where \mathcal{P}_t and \mathcal{P}_r is the power transmitted/received by the transmitter/receiver, respectively. Substituting in equation (5) for W_r yields

$$\mathcal{P}_r = \left(\frac{D_r D_t}{\sqrt{2} L \lambda} \right)^2 \mathcal{P}_t. \quad (9)$$

The parent star of this planetary system is also a power source, producing a power of $\mathcal{P}_{*,t}$. In the case of a bolometric receiver, the power seen to be emitted from the source equals the stellar luminosity, $\mathcal{P}_{*,t} = L_*$. If the star and laser are unresolved sources on the sky, then the receiver will collect photons from both sources, with the component coming from the star being equal to

$$\mathcal{P}_{*,r} = \mathcal{P}_{*,t} \left(\frac{\pi D_r^2}{4\pi L^2} \right). \quad (10)$$

In order to cloak a transiting planet, we require the power received from the laser to nullify that of the transit signal. The maximal laser power required would occur at the time of transit minimum (defined as the instant when the sky-projected planet-star separation is minimized), at which point the power balance would need to satisfy $\mathcal{P}_r \simeq (R_p/R_*)^2 \mathcal{P}_{*,r}$, where (R_p/R_*) is the ratio-of-radii between the planet selected for cloaking and the parent star. Substituting equation (9) for \mathcal{P}_r and equation (10) for $\mathcal{P}_{*,r}$, this condition implies

$$\mathcal{P}_t = \left(\frac{R_p^2 \lambda^2}{2 D_t^2 R_*^2} \right) \mathcal{P}_{*,t}. \quad (11)$$

Using the Stefan–Boltzmann Law for the stellar luminosity allows us to simplify the above to

$$\mathcal{P}_t = \frac{2\pi\sigma_B R_p^2 \lambda^2 T_*^4}{D_t^2}. \quad (12)$$

Assuming that most of the power is produced near $\lambda = 600 \text{ nm}$, the peak wavelength of Sun-like stars, the approximate laser power requirement is

$$\mathcal{P}_t = 58 \text{ MW} \left(\frac{R_p}{R_\oplus} \right)^2 \left(\frac{\lambda}{600 \text{ nm}} \right)^2 \left(\frac{D_t}{10 \text{ m}} \right)^{-2} \left(\frac{T_*}{5777 \text{ K}} \right)^4. \quad (13)$$

The actual peak power would depend on the degree to which limb darkening affects the light curve, leading to a modest increase in the power requirement near the centre of the transit and a decrease near the limb. For solar-like limb darkening in the *Kepler* bandpass, for example, this equates to an ~ 20 per cent increase in peak power.

Equation (13) reveals that the peak power required is $\sim 60 \text{ MW}$, although cloaking a planet from an observer using a narrower bandpass than bolometric would require less power. As an example, for the *Kepler* response function, a monochromatic laser at $\lambda \sim 600 \text{ nm}$ could cloak the Earth from *Kepler*-like surveys by reaching a peak power of $\sim 30 \text{ MW}$. In Fig. 2, we show the expected transit of the Earth as viewed by a civilization lying along the ecliptic ($b = 0$) using a *Kepler*-like bandpass, including the effects of limb darkening.

The implications of having to assume a bandpass for the observer are discussed further in Section 2.3 and a ‘chromatic cloak’ effective at all wavelengths is introduced in Section 2.4.

The effective time that the transmitter needs to be activated at the peak power level (accounting for the trapezoidal shape of the transit light curve) is given by \tilde{T} . Here, \tilde{T} is the time it takes for a transit to occur, starting from the planet’s centre overlapping with the stellar limb, to exiting the stellar disc under the same condition. A reasonable approximation of this duration is given by

$$\tilde{T} = \frac{3^{1/3} P^{1/3} (1 - b^2)^{1/2}}{\pi^{2/3} G^{1/3} \rho_*^{1/3}}, \quad (14)$$

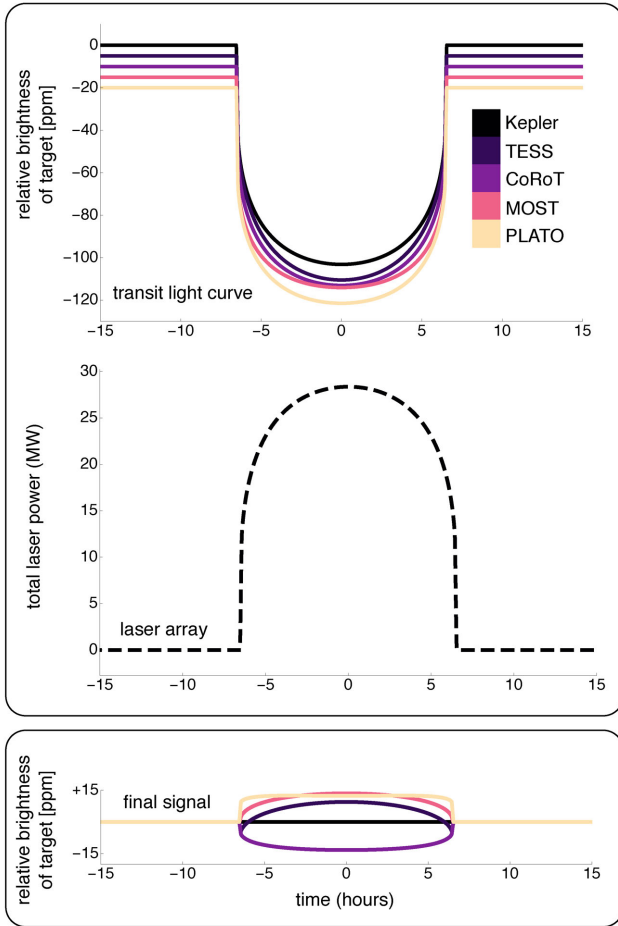


Figure 2. Top: the unaltered light curve of the Earth transiting the Sun, as viewed by different broad-band optical photometers (offset by 5 ppm). Middle: the power profile of a 600 nm laser array designed to cloak the Earth. An array of lasers producing a peak power of ~ 30 MW over 13 hours nullifies the transit. Bottom: residual light curve, as seen by the different photometers.

where b is the impact parameter of the transit (related to the orbital inclination of the planet’s orbit relative to the target star), ρ_* is the mean density of the parent star and P is the orbital period of the planet to be cloaked. For a planet receiving comparable insolation to the Earth, the orbital period of this world would be

$$P = \frac{2\pi(L_*/L_\odot)^{3/4}}{G^{1/2}M_*^{1/2}} \text{ au}^{3/2}, \quad (15)$$

which, with some manipulation, allows us to write that the effective duration of Earth-like planets would be

$$\tilde{T} = 13 \text{ h} \sqrt{1 - b^2} \left(\frac{T_*}{5777 \text{ K}} \right) \left(\frac{\rho_*}{\rho_\odot} \right)^{-1/2}. \quad (16)$$

Accordingly, the energy usage to cloak each transit is given by

$$\begin{aligned} \mathcal{E}_t &= 760 \text{ MW h} \sqrt{1 - b^2} \left(\frac{R_p}{R_\oplus} \right)^2 \left(\frac{\lambda}{600 \text{ nm}} \right)^2 \left(\frac{D_t}{10 \text{ m}} \right)^{-2} \\ &\times \left(\frac{T_*}{5777 \text{ K}} \right)^5 \left(\frac{\rho_*}{\rho_\odot} \right)^{-1/2}. \end{aligned} \quad (17)$$

The total energy required can be collected over the span of the planet’s orbital period, P , assuming it can be stored. This provides

the time averaged power as

$$\bar{P}_t = \left(\frac{\mathcal{E}_t}{P} \right). \quad (18)$$

Substituting in the expression for P , equation (15), gives

$$\begin{aligned} \bar{P}_t &= 87 \text{ kW} \sqrt{1 - b^2} \left(\frac{R_p}{R_\oplus} \right)^2 \left(\frac{\lambda}{600 \text{ nm}} \right)^2 \left(\frac{D_t}{10 \text{ m}} \right)^{-2} \\ &\times \left(\frac{T_*}{5777 \text{ K}} \right)^2. \end{aligned} \quad (19)$$

In the picture described, the advanced civilization would continuously generate 87 kW of power over the course of its orbit, storing up the energy and then releasing it with a peak power of 58 MW during the relatively brief transit event. For comparison, the solar cells on the International Space Station generate 84–120 kW. However, we point out cloaking from N targets would of course require $(87N)$ kW average power production. These power requirements are small compared to the GW–TW power requirements of laser-driven light sailing (Guillochon & Loeb 2015), meaning that cloaking could be a secondary function of laser arrays designed primarily for propulsion.

2.3 Laser requirements

A detailed discussion of the engineering requirements is beyond the scope of this work, which merely aims to investigate the first-order feasibility of a cloak. Nevertheless, here we briefly discuss some obvious technical concerns and suggest they are tractable.

The monochromatic nature of lasers at first seems problematic, but even with a single beam, the cloak would remain effective at masking planets from *Kepler*-like surveys. Most transit surveys are optimized for Sun-like stars, which peak at $\lambda \sim 600$ nm, for reasons largely motivated by the Copernican Principle. Rather than use a narrow bandpass filter on *Kepler*, the instrument is designed to collect as many photons as possible surrounding this key wavelength, in order to maximize signal-to-noise ratio. For this reason, a monochromatic laser at an optical wavelength would be still effective at cloaking a planet from *Kepler*-like surveys. Whilst the cloak would be imperfect since the exact power requirement would depend upon the sensitivity curve of the transit survey, the transit would be sufficiently attenuated that the world would either be undetectable or apparently too small to be habitable. Examples of this are shown in Fig. 2, where we show how for TESS, CoRoT, MOST and PLATO the residuals would still be below 15 ppm, suppressing the transit amplitude by a factor of 6.

For our calculations a continuous beam is assumed during the transit event, but the same effect could be achieved using short pulses, provided that the interval between the pulses is less than the integration time of the transit survey against which one wishes to cloak. Alternatively, an array of pulsed lasers could be used where the relative phasing between them produces near-continuous emission.

For targets closer than 200 pc, the arriving beam width is less than 2 au. For nearby systems, this leads the requirement of some knowledge of the position of a planet. If the inclination of the target planet is unknown, then the positional uncertainty is essentially the semi-major axis, making effective cloaking only possible through deliberate beam dispersion, increasing the energy requirements. Otherwise, if the inclination is known, the uncertainty in position is approximately the error in the semi-major axis, Δa , indicating that we require $\lesssim 1$ per cent uncertainty for all systems beyond 1 pc

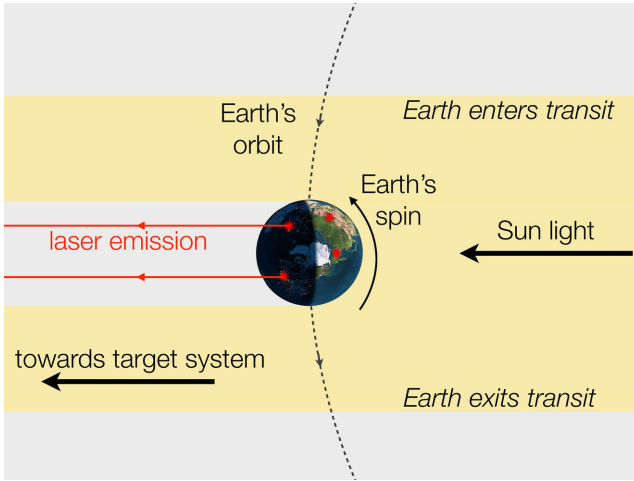


Figure 3. Illustration (not to scale) depicting the Earth's revolution and rotation as it passes through the transit cone of a distant target system. For ground-based emission, numerous sites would be required to compensate for the Earth's rotation, as shown.

(using equation 6). If the advanced civilization were to use a Lagrange point for their transit survey, then this would displace the detector from the assumed target by up to $\frac{\sqrt{3}}{2}a$, which using equation (6) suggests that cloaking the Earth from advanced civilizations closer than 100 pc would require us to deliberately disperse the beam, somewhat increasing the energy demands.

In equation (8), it was assumed that the laser beam has a constant intensity across the beam profile. In reality, the intensity would follow an Airy function in the far-field limit considered here (Guilochon & Loeb 2015), meaning that small pointing errors much less than that of equation (7) would lead to imperfect cancellation of the transit light curve. Beam shaping using a large number of beams could potentially solve this problem, which has the extra advantage of relieving the peak power demand of each laser. Whilst the engineering requirements for such beam shaping are beyond the scope of this work, we highlight that this problem appears tractable.

If another star system happens to lie behind the target and within the beam, it would also be subject to the cloaking effect. Eliminating the transit signal requires careful timing but the transit parallax effect (Scharf 2007) could introduce errors of $\gtrsim 1$ s for targets closer than 50 pc and thus the background target could experience imperfect cloaking. However, such a situation is unlikely given that the angular area of the beam on the sky is $\pi(\theta/2)^2$, which is 2.4×10^{-4} arcsec² for $D_t = 10$ m and $\lambda = 600$ nm. For comparison, the URAT1 survey (Zacharias et al. 2015) reveals that even the highest density regions of the sky (near the galactic plane) have $\lesssim 8 \times 10^{-3}$ stars per arcsec² down to $R < 18.5$, suggesting the maximum number of stars within a beam is ~ 30 . The fraction of stars which have inhabited world's harbouring technological civilizations is less than 1 in 30 for even the most optimistic estimates and thus we consider this to be a highly unlikely situation.

The selection of a suitable location for the laser array bears mentioning. Clearly, to cloak a transit the lasers must be beamed at the antisolar point, but the rotation of the planet complicates the selection of any geographic location for the array. More than one site would be needed, as a single location would be in daylight for a significant fraction of the time and would therefore be unable to shine at the antisolar point (see Fig. 3). The arrays would need to pivot to adjust for azimuthal and altitudinal changes continuously like any tracking telescope, and the lasers would suffer from ab-

sorption in Earth's atmosphere. The absorption would also change continuously as a function of atmospheric path length.

One way to eliminate these difficulties would be to place the laser array in space at the third or fourth Lagrange point (L_4/L_5). Of course, locating the array in space would have its own challenges: it would require a dedicated mission for installation, sufficient power would have to be generated by solar panels alone, and maintenance would be non-trivial if possible at all. We omit here a discussion on the relative merits of a terrestrial versus a space-based solution. It is worth pointing out, however, that placing the laser array at L_4/L_5 means that any planet, not just the inhabited world, could be cloaked or used for broadcasting (see Section 4). An extraterrestrial civilization might therefore opt to utilize the transit of the inner most planet in their system for this purpose (e.g. a hot-Jupiter), as it would be particularly efficient for signalling given the short orbital period.

2.4 Chromatic cloak

A chromatic cloak (a cloak effective at all wavelengths) could be achieved using a large number of beams, rather than one. This would have the additional advantage of relieving the peak power requirement per beam. Since the actual origin of the lasers is unresolved from the parent star, using multiple lasers at different wavelengths is indistinguishable from a single source at multiple wavelengths. Each of these beams would emit at a different wavelength, with the power tuned to the spectral radiance function of the parent star.

To calculate the total chromatic power required to cloak a planet, we modify equation (11) to define the spectral power, $\tilde{\mathcal{P}}$, of the transmitter as

$$\tilde{\mathcal{P}}_t(\lambda) d\lambda = \left(\frac{R_p^2 \lambda^2}{2D_t^2 R_*^2} \right) \tilde{\mathcal{P}}_{*,t}(\lambda) d\lambda, \quad (20)$$

where for blackbody-like stellar radiation, we have

$$\tilde{\mathcal{P}}_{*,t}(\lambda) d\lambda = \left(4\pi R_*^2 \right) \left(\frac{2hc^2}{\lambda^5} \frac{\pi}{e^{\frac{hc}{\lambda k_B T_*}} - 1} \right) d\lambda. \quad (21)$$

Here, $\tilde{\mathcal{P}}_t(\lambda)$ and $\tilde{\mathcal{P}}_{*,t}(\lambda)$ are the wavelength-specific transmission power and fractional stellar luminosities, respectively, such that the spectrally integrated power is

$$\mathcal{P} = \int_{\lambda=0}^{\infty} \tilde{\mathcal{P}}(\lambda) d\lambda. \quad (22)$$

Accordingly, the total power required to the transmitter array of a chromatic cloak is

$$\mathcal{P}_t = \left(\frac{4\pi^2 hc^2 R_p^2}{D_t^2} \right) \int_{\lambda=0}^{\infty} \frac{1}{\lambda^3} \frac{1}{e^{\frac{hc}{\lambda k_B T_*}} - 1} d\lambda, \quad (23)$$

for which a closed-form expression is obtainable as

$$\mathcal{P}_t = \sigma_C \left(\frac{R_p^2 T_*^2}{D^2} \right), \quad (24)$$

where we define $\sigma_C = \frac{2}{3}\pi^4 k_B^2 h^{-1} = 1.86818 \times 10^{-11} \text{ J s K}^{-2}$. Evaluating equation (24) in canonicalized units, one may write

$$\mathcal{P}_t(\lambda) = 254 \text{ MW} \left(\frac{R_p}{R_{\oplus}} \right)^2 \left(\frac{T_*}{5777 \text{ K}} \right)^2 \left(\frac{D}{10 \text{ m}} \right)^{-2}. \quad (25)$$

Clearly, an infinite series of monochromatic lasers spaced at infinitesimal wavelength intervals is not practical and thus the effectiveness of any chromatic cloak will depend upon the wavelength resolution. If the observer is taking spectroscopic transit observations with a spectral resolution power of R , then in the wavelength

range of $\lambda_1 = \lambda_{\min}$ to $\lambda_N = \lambda_{\max}$, one would require N monochromatic lasers, where each laser would operate at a wavelength of

$$\lambda_i = \lambda_{\min} \left(\frac{1 + R^{-1}/2}{1 - R^{-1}/2} \right)^{i-1}, \quad (26)$$

and requiring a total number of lasers equal to

$$N = 1 + \frac{\log(\lambda_{\max}/\lambda_{\min})}{\log\left(1 + \frac{2}{2R-1}\right)}. \quad (27)$$

For $R \gg 1$, this is well approximated by

$$N \simeq R \log(\lambda_{\max}/\lambda_{\min}). \quad (28)$$

For example, a chromatic cloak able to defeat the $R = 2700$ integral field NIRSpec instrument planned for JWST from 0.6–5 μm would require approximately 6000 monochromatic lasers in the array. The power of each laser, $p_{t,i}$ may be estimated by taking the limit of equation (23) with infinitesimal integral limits, giving

$$p_{t,i} = \left(\frac{4\pi^2 hc^2 R_p^2}{R D_t^2} \right) \left(\frac{1}{\lambda_i^2} \frac{1}{e^{\frac{hc}{\lambda_i k_B T_*}} - 1} \right), \quad (29)$$

where the total power fed to the transmitter array, \mathcal{P}_t , is equal to the sum of these lasers such that $\mathcal{P}_t = \sum_{i=1}^N p_{t,i}$. Equation (29) can be shown to be maximized at a wavelength of

$$\lambda_{p,\max} = 1.563 \mu\text{m} \left(\frac{T_*}{5777 \text{ K}} \right)^{-1}. \quad (30)$$

Evaluating the power per wavelength bin function at this maximum for a Sun-like T_* allows us to write

$$p_{t,i} \leq 100 \text{ kW} \left(\frac{R}{1000} \right)^{-1}. \quad (31)$$

In summary then, a chromatic cloak may be achieved by an array of lasers emitting at controlled and regularly spaced wavelength intervals each with a unique peak power given by equation (29). Emerging technologies, such as tunable lasers which can be swept across the spectrum at high speed, so-called supercontinuum lasers (e.g. see Cumberland et al. 2008), may allow for direct simulation of any spectrum desired, thereby negating some of the technical issues discussed above. Whilst a detailed technology feasibility study is beyond the scope of this paper, we see no reason why advanced civilizations could not build such devices given that we are on the cusp of such abilities ourselves.

3 CLOAKING BIOSIGNATURES

3.1 Concept

As a more energy-efficient alternative to cloaking the presence of the planet, it may be desirable to cloak only certain atmospheric signatures (see Fig. 4), in particular, atmospheric constituents that may indicate the presence of life (so-called ‘biosignatures’ or industrial pollutants; Kaltenegger et al. 2002; Lin et al. 2014) or otherwise favourable conditions for life (such as the presence of water vapour). We refer to this as a ‘biocloak’ in what follows.

It is straightforward to use a chromatic laser array to cancel out the absorption features in the planet’s transmission spectrum, assuming laser emission can be produced at any desired wavelength. Indeed, the presence of an atmosphere could be cloaked altogether if the effective height changes of the planet as a function of wavelength are cancelled out by lasers. The planet might then resemble a dead

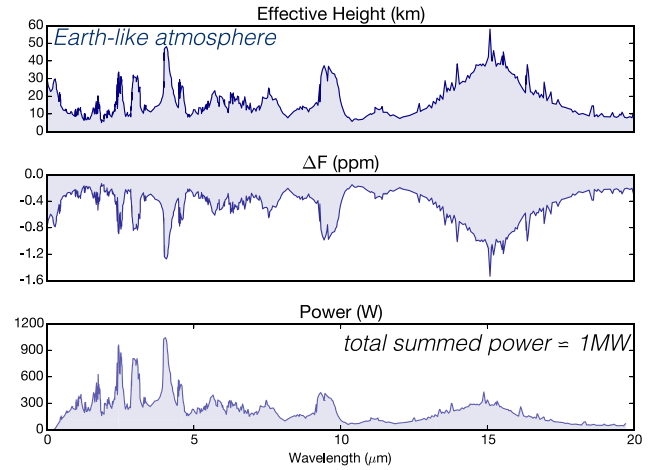


Figure 4. Top: effective height of the Earth’s atmosphere in km, taken from Kaltenegger & Traub (2009). Middle: the reduction in flux associated with these absorption features in parts per million. Bottom: power requirement $\mathcal{P}_t(\lambda)$ in W, assuming a solar blackbody with $T_{\text{eff}} = 5777 \text{ K}$ and chromatic lasers spaced dynamically according to equation (26) and setting $R = 1000$.

world totally devoid of any atmosphere and appear almost certainly hostile to life. Not only would this approach require a significantly smaller power output, it would also have the benefit of producing self-consistent observations inasmuch as the presence of the planet might still be inferred by other means (i.e. through radial velocity analysis). Since we do not here present a means for disguising a radial velocity signature, the presence of such a signature without a corresponding transit could raise suspicions that the planet’s transit was deliberately cloaked, thus inadvertently indicating the presence of a technologically advanced civilization.

3.2 A biocloak for the earth

Since the atmospheres of inhabited exoplanets may be diverse and quite exotic (e.g. see Seager, Bains & Hu 2013) we consider here the case of cloaking the Earth’s atmosphere as a concrete example. To estimate the power output required, we employ the Kaltenegger & Traub (2009) model of terrestrial effective height as a function of wavelength in the 0–20 μm range. This region shows a number of important absorption features in the Earth’s atmosphere, including water and several molecules typically considered biomarkers when found in extreme thermodynamic disequilibrium (e.g. O_2 , O_3 , and CH_4). From here, we can calculate the change in flux associated with these absorption features by

$$\frac{\Delta F(\lambda)}{F(\lambda)} = \left(\frac{R_p + h(\lambda)}{R_*} \right)^2 - \left(\frac{R_p}{R_*} \right)^2, \quad (32)$$

where h is the effective height. To calculate the total chromatic power required to cloak the atmosphere, we modify equation (20) such that

$$\tilde{\mathcal{P}}_t(\lambda) d\lambda = \left(\frac{\lambda^2 [(R_p + h(\lambda))^2 - R_p^2]}{2 D_t^2 R_*^2} \right) \tilde{\mathcal{P}}_{*,t}(\lambda) d\lambda. \quad (33)$$

Taking $D_t = 10 \text{ m}$ and using a dynamic spacing between laser wavelengths as determined by equation (26), the total power required for atmospheric cloaking over the 20 μm range is then just the sum across all wavelengths. Clearly lasers spaced at larger wavelength intervals will have to compensate with more power, and will

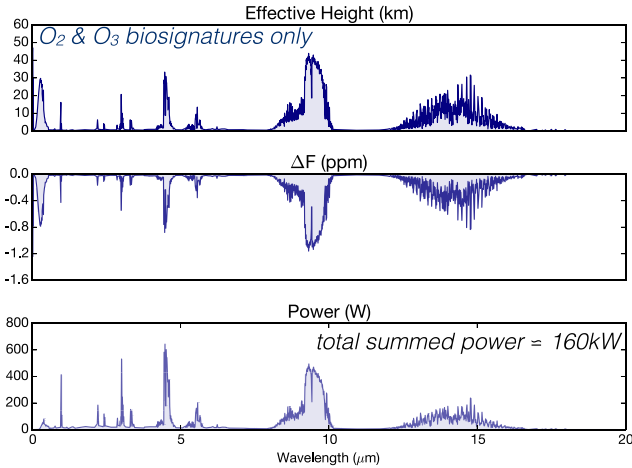


Figure 5. Top: effective height of the Earth’s atmosphere in km due solely to molecular oxygen and ozone, derived from Kaltenegger & Traub (2009). Middle: the reduction in flux associated with these absorption features in parts per million. Bottom: power requirement $P_t(\lambda)$ in W, assuming a solar blackbody with $T_{\text{eff}} = 5777$ K and chromatic lasers spaced dynamically according to equation (26) and setting $R = 1000$.

result in a more unnatural spectral appearance if the observing instrument has sufficiently high resolution. It is therefore desirable to minimize the spacing of the laser wavelengths as much as is feasible.

For the Earth and in this wavelength range, we find that the integrated sum of the peak powers across all wavelengths is ~ 1 MW. In fact, if we subtract the minimum effective height (~ 6 km) from the atmospheric thickness and add it to the planet’s radius this number can be reduced to ~ 607 kW. Chromatic atmospheric cloaking in the $0\text{--}20$ μm range then requires only ~ 2 per cent the power required for broad-band transit cloaking (up to 30 MW at 600 nm), as shown in Fig. 5.

Selective cloaking of certain atmospheric features will reduce power requirements further still. In principle, it could be possible to mimic a wide range of atmospheric compositions by artificially adjusting absorption features to any desired depth. We consider here the case of cloaking the absorption features of molecular oxygen and ozone in the $0\text{--}20$ μm range, which we label as a ‘biocloak’. For this calculation we derive the effective height due to these molecules from the relative transmission spectrum published in Kaltenegger & Traub (2009). With values for $h(\lambda)$ in hand we repeat the process from before to derive the power requirements. We find a total power requirement ~ 160 kW to mask O_2 and O_3 . In this case we cannot subtract any baseline as there are some wavelengths for which h is zero.

4 BROADCASTING A PLANET

4.1 Concept

Finally, we introduce a third type of laser emission which performs the opposite function of cloaking, namely deliberate broadcasting. Indeed, as outlined in Section 1, this formed the original inspiration behind our idea – to find a more practical approach to creating artificial transits versus the Arnold (2005) mega-structure concept.

Whilst any number of artificial transit profiles can be created with lasers, one ideally seeks a profile which is both energy efficient and

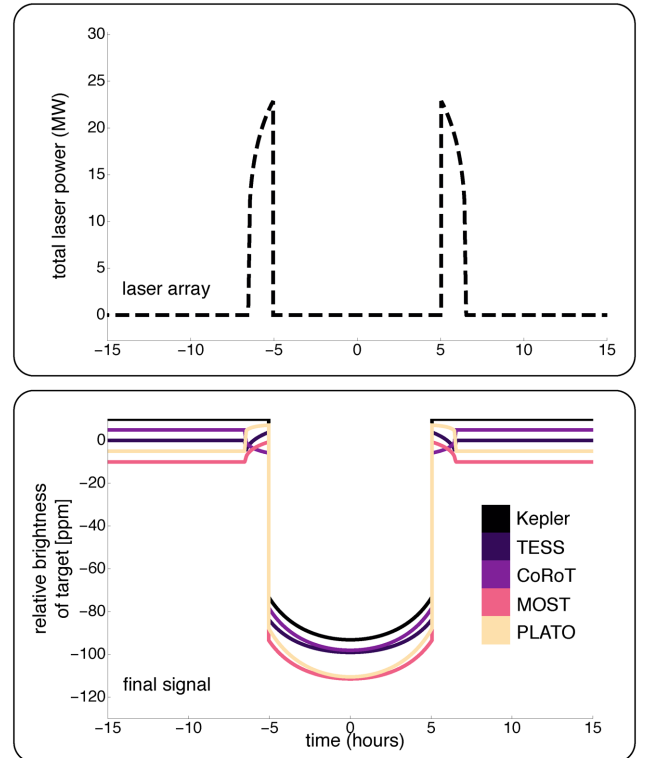


Figure 6. Same as Fig. 2, except for the case of broadcasting rather than cloaking. Top: the power profile of a laser array designed to broadcast the Earth. An array of lasers producing a peak power of ~ 20 MW for approximately 15 minutes nullifies the transit ingress and egress. Bottom: the resulting light curves as viewed by different broad-band optical photometers. The observed impact parameter would be complex infinity, for which a normal light curve fit would be unable to explain and thus indicating the presence of artificial transit manipulation.

unambiguously artificial. Producing upward spikes in-transit might seem like an obvious suggestion, but star spot crossings produce these forms with complex and information-rich signatures (e.g. see Beky et al. 2014). Here, we argue that cloaking the ingress/egress of a transit, but leaving the main transit undistorted, would be a highly effective strategy since no known natural phenomenon is likely to produce such an effect.

The duration of the ingress/egress (T_{12}) is a proxy for the impact parameter, b , of the transit. The shortest ingress/egress time possible occurs for equatorial transits, when $b = 0$. By measuring both the first-to-fourth and second-to-third contact durations of a transit, one may solve uniquely for both b and the mean stellar density, ρ_* (Seager & Mallén-Ornelas 2003).

For any transiting planet, one should always expect $T_{12} \geq \lim_{b \rightarrow 0} T_{12}$ and certainly an instantaneous ingress/egress cannot be produced by any physical phenomenon presently known to us. This geometric boundary condition provides an avenue to broadcast a clear artificial signature. Instead of cloaking the full transit then, cloaking just the ingress/egress components would create an artificial transit, as shown in Fig. 6.

The depth of the transit is unaltered, meaning that the observer is still able to accurately infer (R_p/R_*) . Assuming the observer is able to independently measure a near-zero eccentricity and the mean stellar density, the inferred impact parameter is given by equation (7)

of Seager & Mallén-Ornelas (2003)

$$b = \sqrt{\frac{(1-p)^2 - f^2(1+p)^2}{1-f^2}}, \quad (34)$$

where f is approximately the ratio T_{23}/T_{14} . Accordingly, by cloaking the ingress/egress the observer finds $f \rightarrow 1$ leading to an imaginary impact parameter for all $f > (1-p)/(1+p)$, which is 0.98 for the Earth–Sun transit. Therefore, artificial transits should be revealed by their imaginary impact parameters.

Broadcasting has the advantage that one does not need to be concerned with perfect cloaking across all wavelengths any longer. For example, the laser emission could be monochromatic here, which would be initially identified as an artificial transit by a *Kepler*-like survey and then follow-up spectroscopy would find clear evidence for laser emission, further supporting an artificial origin. Moreover, information could be beamed along the laser for the purposes of communication. In this sense, the transits provide both an initial way of signalling our presence, like a beacon, and also a suitable short-window in which to attempt active communication.

4.2 Energy requirements

For completion, we estimate the energy requirements to accomplish broadcasting, as was done earlier for cloaking. The peak power emission required will be of the same order as that needed for cloaking, with the only difference being that the emission time can be reduced from many hours to many minutes, thereby reducing the total energy requirement. Assuming a circular orbit for simplicity, the ingress/egress time can be approximated to

$$T_{12} = \frac{0.12 \text{ hours}}{\sqrt{1-b^2}} \left(\frac{R_p}{R_\oplus} \right) \left(\frac{L_\star}{L_\odot} \right)^{1/4} \left(\frac{M_\star}{M_\odot} \right)^{-1/6} \left(\frac{R_\star}{R_\odot} \right)^{-1} \times \left(\frac{\rho_\star}{\rho_\odot} \right)^{-1/3}, \quad (35)$$

which can be further simplified to

$$T_{12} = \frac{0.12 \text{ hours}}{\sqrt{1-b^2}} \left(\frac{R_p}{R_\oplus} \right) \left(\frac{L_\star}{L_\odot} \right)^{1/4} \left(\frac{M_\star}{M_\odot} \right)^{-1/2}. \quad (36)$$

Accordingly, we estimate that the total energy needed to cloak the ingress and egress for a single transit event would be

$$\mathcal{E}_t = \frac{6.9 \text{ MW hours}}{\sqrt{1-b^2}} \left(\frac{R_p}{R_\oplus} \right)^3 \left(\frac{\lambda}{600 \text{ nm}} \right)^2 \left(\frac{D_t}{10 \text{ m}} \right)^{-2} \times \left(\frac{R_\star}{R_\odot} \right)^{-2} \left(\frac{L_\star}{L_\odot} \right)^{5/4} \left(\frac{M_\star}{M_\odot} \right)^{-1/2}, \quad (37)$$

which per orbital period of an Earth-like insolation planet equates to an averaged power of

$$\bar{\mathcal{P}}_t = \frac{6.9 \text{ MW hours yr}^{-1}}{\sqrt{1-b^2}} \left(\frac{R_p}{R_\oplus} \right)^3 \left(\frac{\lambda}{600 \text{ nm}} \right)^2 \left(\frac{D_t}{10 \text{ m}} \right)^{-2} \times \left(\frac{R_\star}{R_\odot} \right)^{-2} \left(\frac{L_\star}{L_\odot} \right)^{1/2}. \quad (38)$$

To compare the requirements for different host stars, we may adopt $L_\star \propto M_\star^4$ and $M_\star \propto R_\star$ to re-write the above as

$$\bar{\mathcal{P}}_t = \frac{720 \text{ W}}{\sqrt{1-b^2}} \left(\frac{R_p}{R_\oplus} \right)^3 \left(\frac{\lambda}{600 \text{ nm}} \right)^2 \left(\frac{D_t}{10 \text{ m}} \right)^{-2} \left(\frac{M_\star}{M_\odot} \right)^2. \quad (39)$$

It therefore requires two orders of magnitude less energy (or orbit-averaged power) to broadcast a planet than cloak it, due to the fact the ingress/egress is two orders of magnitude shorter in duration.

5 DISCUSSION

In this work, we suggest that directed laser emission may be used to either broadcast or cloak the presence of the Earth to extraterrestrial transit surveys. Motivated by earlier proposals of searching for mega-structures designed to create artificial transits (Arnold 2005), we argue that artificial transits could be produced with presently available technology. On this basis, a search for artificial transit signatures, similar to those described in this work, may be a worthwhile search strategy for non-radio SETI.

We estimate that cloaking the Earth from a broad-band *Kepler*-like survey could be achieved with an array of monochromatic optical lasers emitting a peak power of ~ 30 MW. In this scheme, one would target a known Earth-analogue residing near the ecliptic (and thus can see the Earth transit) and emit for ~ 10 hours once per year. A $\mathcal{O}[10 \text{ m}^2]$ solar cell array would be sufficient to gather this energy over the course of a year, meaning that the laser array could be feasibly placed in space. We estimate that a chromatic cloak (effective at all wavelengths) would be an order-of-magnitude more costly energetically.

Deliberate broadcasting relaxes some of the technical challenges of chromatic cloaking and requires three orders of magnitude less energy. We argue that cloaking of the transit ingress/egress alone would present a clear artificial signature, one which we could begin surveying archival *Kepler* data for immediately. The time of transit provides a natural communication window, analogous to water hole in radio SETI (Oliver 1979). This argument can be extended to non-transiting systems, where the moment of inferior conjunction becomes the communication window. Moreover, our method allows one to simultaneously alert an observer to an artificial source (serving the same function as radio SETI beacons; Benford, Benford & Benford 2008) and transit large volumes of data along the beams.

Whilst it is possible to actively begin searching for broadcasted signals in, say, archival *Kepler* photometry, cloaked exoplanets obviously present a challenge by their very design. Transits are not the only method to discover planets and thus a truly xenophobic civilization may conclude that even a perfect and chromatic transit cloak would be ultimately defeated by observation of the planet using radial velocities. In this sense, the biocloak is perhaps the most effective strategy since certainly the transit and radial velocity measurements would appear compatible. However, even here, direct imaging would reveal a strong discrepancy in terms of the atmospheric interpretation and thus overcome the cloak.

For these reasons, perhaps the most effective use of laser enabled transit distortion would be for broadcasting rather than cloaking. In such a case, it may be more effective to construct the laser array not in the vicinity of L_4/L_5 for their own home planet, but at L_4/L_5 for the shortest period planet in their system. Therefore, in the Solar system we would distort the transit of Mercury. This provides a higher duty cycle of distorted events, facilitating their detection. We therefore suggest that any survey in archival data should not be limited to rocky planets in the habitable-zone of their host star.

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