**TRANSIT LIGHTCURVES AS TEMPLATES FOR INTELLIGENT SIGNALS.** D. Ragozzine[1], [1]Brigham Young University, Provo, UT, USA, darin_ragozzine@byu.edu.

**Overall Goal(s) and Objective(s):** Discuss the value of transit lightcurves as a template for intelligent beaconing with near-universal understandability. Emphasize the value of systems of multiple transiting planets.

**Main Body of Text:** It is hard to imagine establishing communication with a distant civilization without using light from some part of the electromagnetic spectrum. Without the ability to somehow detect the light of the stars, there is a slim chance that extra-terrestrial civilizations (ETCs) would postulate our existence and desire to communicate. The vast distances and limitations of physics make communication via particles, spacecraft, or gravitational waves impractical. It is not unreasonable to assume that ETCs would have some ability to understand varying intensities of light (though here I try to minimize their specific conception of light and its properties). This is why SETI has focused on communication via optical and radio wavelengths of light.

Here, I also focus on the time varying light intensity, known in the astrophysical community as lightcurves. Lightcurves are a raw template for communicating with other civilizations. Lightcurves are a strong candidate for universal markers and signals, particularly the lightcurve of a planet as it transits in front of its parent star.

Why focus on planets? Intelligence is scientifically understood to be an emergent phenomenon from sufficiently complex biochemical reactions. Such biochemical reactions require large numbers of atoms and molecules to be in the same place at the same time and with sufficient kinetic energy to induce reactions. These clearly indicate that dense warm media, e.g., liquid water, are ideal for intelligent life. Among all known astronomical objects, only planets can maintain such conditions for the geologic timescales necessary for complex life to evolve. SETI has, thus, focused on searching for life on terrestrial planets (as opposed to white dwarfs or neutron stars).

**I propose that the lightcurve of a transiting planet is a near-universal signal template that would be understandable by a wide range of alien civilizations.** Whether ETCs would also come to the conclusion of lightcurves as a universal marker is debatable, but it is convenient to structure this discussion from the perspective of the message sender. In this context, I discuss the signal I would transmit that would act as a beacon indicating the presence of intelligent life.

**Beaconing: Where and When**

As pointed out in [2], omnidirectional powerful beacons are expensive and it follows that signal transmission (and reception) should identify the most valuable and universally-recognizable "special" locations and times to focus their energies. Though not the first to introduce this idea, [4] point out that the small part of the sky where Earth is seen as a transiting planet is a way of localizing in direction. [5] identify the short time of transit ($1.5 \times 10^{-3}$ of our orbit) as a universally understandable time when a beacon or information transmission would be most obvious.

Here, I add additional perspective to these thoughts based on our understanding of systems of multiple transiting planets. These multi-transiting systems are the most information-rich planetary systems outside of our own solar system [7]. The arguments by [4] and [5] are made even stronger when considering our solar system as a multi-transiting system.

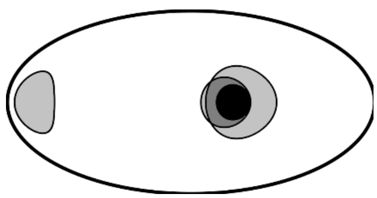
I propose that regions where the solar system is seen as a multi-transiting system are the highest priority for SETI searches. These regions form an even smaller slice of the sky than the Earth transiting zone of [4], which covers about $5 \times 10^{-3}$ of the sky. [3] show that only $2.1 \times 10^{-3}$ of the sky would see two solar system planets transiting, only $2.79 \times 10^{-4}$ of the sky sees three solar system planets transiting, and no observer could see more than three.[1] These numbers are even smaller ($\sim 6 \times 10^{-4}$ and $2.1 \times 10^{-4}$, respectively) if Earth must be one of the transiting planets, though [5] have good reasons for not overfocusing on the habitable planet.

Extending [5] to multi-transiting systems, transmitting a beacon would be even more powerful when multiple planets are transiting simultaneously. Depending on the planets chosen, this localizes the time down from $1.5 \times 10^{-3}$ to approximately $10^{-6}$. [7] point out that, most of the time, when multiple planets transit simultaneously, the result is simply an addition of the transit signals. Only in the rare case of exosyzygies, when planets align well enough in a mutual event, is there a unique signal. The easiest such signal to identify is an "overlapping double transit" in the nomenclature of [7], when the shadows of the planets on the star overlap, resulting in a brief (~10 min) brightening since a smaller area of starlight is being blocked. Although dozens of these likely occurred in the Kepler data, only ~1 exosyzygy had detectable SNR, despite Kepler's

[1] As [4] point out, these regions on the sky evolve over time, and [3] explicitly determines the evolution of the multi-transiting regions due to secular evolution of planetary orbits on $10^4$ year timescales.

search of 150,000 stars over 4 years of near-continuous observations. Restricting our transmission times to when Earth would participate in an exosyzygy can localize a special time down to $\sim10^{-8}$.[2]

The spatial and temporal special times I have identified are highly correlated. In the single-transiting case, there is only a small patch of sky that is currently seeing the Earth transit (about 0.25 square degrees directly antipodal to the Sun). Extending this to multi-transiting systems in space or exosyzygies in time restrict the location more strongly. [3] develop the framework to understand the geometric locations of these exosyzygies. Shown here is part of their Figure 7, showing the celestial sphere in an Aitoff projection with gray regions identifying locations where one planet is transiting, dark gray where two planets are transiting, and black where an exosyzygy would be seen. (Note that this illustration uses unrealistically large planets for illustration purposes; in our solar system, the regions would be much smaller.)



What is the implication for SETI? As [5] point out, we should more strongly search during "their" special times, i.e., when planets are transiting, with the strongest searches at the most special times. Extensive effort should be given to observing exosyzygies, which are scientifically valuable in their own right [7], but are widely recognizable as extremely special times. We should also search during *our* special locations/times, e.g., focusing efforts on the regions of the sky that are currently viewing, with increasing priority, a transit[3] [5], multiple transits, and/or an exosyzygy between Earth and another planet.

Arguably, localizing in space and time too much may be too restrictive. If there are only a handful of communicating civilizations in the galaxy, then an exclusive focus on exosyzygies may result in a false negative. Hence, these special times should be used to create prioritized lists. [5] mention that non-transiting systems have a special time too: planetary conjunctions. ETCs who detect our multi-planetary system astrometrically could likely recognize that periapse/apoapse passages, planetary conjunctions, near multiple-planet conjunctions, or combinations of these effects are "special" times. ETCs who study Earth through radial velocities would recognize quadratures, planetary conjunctions, multi-planet quadratures, as particularly important. Indeed, most of these are also scientifically valuable times to observe.

**Beaconing: What**

Returning to the question of what message I would send in a beacon, I think the most widely-understood beacon would be one that mimicks the natural transit[4] signal. [1] pointed out an important communication method: artificial transiting objects[5]. Here, I focus on manipulating light itself, e.g., the laser pulses of [5], as more manageable from an engineering perspective.[6]

[5\ propose the clever idea of "cloaking" the ingress/egress of a transit as a clear sign of artificial lightcurve manipulation. I propose that the content of the beacon could be modulated copies of the transit lightcurve itself. A transit lightcurve (once cleaned of astrophysical and instrumental noise and, thus, already artificial in nature) consists of a steady signal that is occasionally attenuated. For example, the lightcurve could be compressed in time by $(2\pi)^n$ for multiple integer values of $n$. The artificial transit would take the form of intensity drops, but could also include shifts in frequency, phase, and/or polarization, since it is hard to say which of these properties of light would be easiest for the ETC to observe or recognize. Practically speak-

[2] The most obvious times would be when Earth is seeing a transit of an interior planet, though this is not a strict requirement.

[3] I note that the Sun-Earth L2 is the most energetically easy location from which to continuously monitor the anti-Sun direction for beacons transmitted to us during transit. Further, when Earth is included in one of the transits (which is good, but not to the exclusion of other planets), each of these regions is a subset of this anti-Sun region.

[4] Similar mimicking could be done for astrometry and radial velocities.

[5] Arnold 2005 and later works tend to focus on signals from artificial transiting objects that result from Keplerian orbits. However, the easiest planetary-sized structures to manufacture could be thin and thus significantly affected by radiation pressure. Indeed, the non-Keplerian orbit of an object would be a strong sign of artificiality. Some interstellar missions invoke enormous solar sails, which would be comparable to artificial transiting objects.

[6] It is worth noting that the "FOCAL" distance of 550 AU (where gravitational lensing of the Sun can lead to significantly enhanced astronomical ability) could also be an ideal location to broadcast to other civilizations since the focusing can partly compensate for attenuation of lasers or other light sources [6].

ing, it may be easier to broadcast “inverse” transits, e.g., bursts interspersed by no broadcast instead. The beacon could transmit at multiple interesting frequencies (e.g., wavelengths of 21 cm * π as popularized by Sagan’s *Contact*). Note that the lightcurve that is transmitted would be tailored specifically to the region of broadcast. When beaconing to a region of the sky that is currently seeing an Earth-Venus exosyzygy, *that* lightcurve would be modulated and broadcast.

The implication for SETI is to look for signals that mimick transiting lightcurves. Depending on how these are mimicked, they may be picked up by the lightcurve information criterion. Modulated “echos” of ubiquitous transit lightcurves are widely understandable, clearly artificial, and searching for them involves observations that are already scientifically desirable.

**Conclusions**

While we don’t want to overemphasize ETC’s ability to observe and understanding transiting lightcurves, among all the possible communication methods, intensity modulation of light is arguably among the most universally understandable concepts. By considering the implications for transiting lightcurves for where, when, and what ETC beacons may focus on, SETI can prioritize where, when, and what it should be looking for.

**References:** [1] Arnold 2005, *Astrophysical Journal*, 627, 1, 534-539. [2] Benford et al. 2010, arXiv:0810.3964. [3] Brakensiek & Ragozzine 2016 (BR16), *Astrophysical Journal*, 821, 1, 47. [4] Heller & Pudritz 2016, *Astrobiology*, 16, 4, 259-270. [5] Kipping & Teachey 2016 (KT16), *Monthly Notices of the Royal Astronomical Society*, 459, 2, 1233-1241. [6] Maccone 2011, *Acta Astronautica*, 68, 1-2, 76-84. [7] Ragozzine & Holman 2010, arXiv:1006.3727

Note: the Main Text above has not been modified since its submission to the SETI White Paper call on February 17, 2017, except for formatting into the new template format.

**Additional Information:**

(A) Which Question(s) of the *Alien Mindscape* article is your white paper is relevant to?

Primarily Question 3, but also Question 2.

(B) How Big Data Analysis can help you advance this project/concept (and which datasets/databases)?

Big Data Analysis could be helpful in searching Kepler, K2, and TESS lightcurves for the proposed signals.