Detection Technique for Artificially Illuminated Objects in the Outer Solar System and Beyond

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Abstract

Existing and planned optical telescopes and surveys can detect artificially illuminated objects, comparable in total brightness to a major terrestrial city, at the outskirts of the Solar System. Orbital parameters of Kuiper belt objects (KBOs) are routinely measured to exquisite precisions of $<10^{-3}$. Here, we propose to measure the variation of the observed flux F from such objects as a function of their changing orbital distances D . Sunlight-illuminated objects will show a logarithmic slope $\alpha \equiv (d \log F / d \log D) = -4$, whereas artificially illuminated objects should exhibit $\alpha = -2$. The proposed Large Synoptic Survey Telescope (LSST) and other planned surveys will provide superb data and allow measurement of α for thousands of KBOs. If objects with $\alpha = -2$ are found, follow-up observations could measure their spectra to determine whether they are illuminated by artificial lighting. The search can be extended beyond the Solar System with future generations of telescopes on the ground and in space that would have the capacity to detect phase modulation due to very strong artificial illumination on the nightside of planets as they orbit their parent stars. Key Words: Astrobiology—SETI—Kuiper belt objects—Artificial illumination. *Astrobiology* 12, 290–294.

1. Introduction

THE SEARCH for extraterrestrial intelligence (SETI) has been conducted mainly in the radio band (Tarter, 2001; Wilson, 2001; Shostak *et al.*, 2011), with peripheral attention to exotic signals in the optical (Horowitz *et al.*, 2001; Dyson, 2003; Ribak, 2006; Howard *et al.*, 2007; Forgan and Elvis, 2011) and thermal IR (Dyson, 1960). Possible “beacon” signals broadcasted intentionally by another civilization to announce its presence as well as the “leakage” of radiation produced for communication or other purposes (*e.g.*, radar) have been the usual targets of radio SETI observations.

As technology evolves on Earth, expectations for plausible extraterrestrial signals change. For example, the radio power emission from Earth has been declining dramatically in recent decades due to the use of cables, optical fibers, and other advances in communication technology. This indicates that eavesdropping on distant advanced civilizations might be more difficult than previously thought (Forgan and Nichol, 2011).

Here, we are guided instead by the notion that biological creatures are likely to take advantage of the natural illumination provided by the star around which their home planet orbits. As soon as such creatures develop the necessary

technology, it would be natural for them to artificially illuminate the object they inhabit during its dark diurnal phases.

Our civilization uses two basic classes of illumination: thermal (incandescent light bulbs) and quantum [light-emitting diodes (LEDs) and fluorescent lamps]. Such artificial light sources have different spectral properties than sunlight. The spectra of artificial lights on distant objects would likely distinguish them from natural illumination sources, since such emissions would be exceptionally rare in the natural thermodynamic conditions present on the surface of relatively cold objects. Therefore, artificial illumination may serve as a lamppost that signals the existence of extraterrestrial technologies and thus civilizations. Are there realistic techniques to search for the leakage of artificial illumination in the optical band?¹

It is convenient to normalize any artificial illumination in flux units of 1% of the solar daylight illumination of Earth, $f_{\oplus} \equiv 0.01(L_{\odot}/4\pi D_{\oplus}^2) = 1.4 \times 10^4 \text{ erg s}^{-1} \text{ cm}^{-2}$, where $D_{\oplus} = 1.5 \times 10^{13} \text{ cm} \equiv 1 \text{ AU}$ is the Earth-Sun distance. Crudely speaking, this unit corresponds to the illumination in a

¹Here we focus on illumination in the optical band, but identical considerations apply to creatures that evolved to sense radiation in the UV and IR bands, in which stars are also highly luminous.

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brightly lit office or to that provided by the Sun just as it rises or sets in a clear sky on Earth.²

2. Artificially Illuminated Kuiper Belt Objects

We first examine the feasibility of this new SETI technique within the Solar System, which offers the best prospects for detecting intrinsically faint sources of light.

The flux that reaches an observer from any self-luminous source varies according to the familiar inverse square law, but the flux from scattered sunlight off an object at a distance $D \gg 1$ AU scales as D^{-4} due to the combination of the inverse square dependence of the solar flux that illuminates it combined with the inverse square dependence of the scattered component of that incident flux that reaches an observer on Earth. Thus, the observed flux from an object that is artificially illuminated at a level of $f_{\oplus}$ would be larger than the flux due to its reflected sunlight by a factor of $(A/1\%)^{-1} (D/1 \text{ AU})^2$, where A is the albedo (reflection coefficient) of the object to sunlight. The A values of objects in the outer Solar System vary widely (Stansberry *et al.*, 2008), and their colors range from neutral to very red (Doressoundiram *et al.*, 2008). This implies that the ratio of artificial illumination, with an unknown spectrum, to scattered sunlight could be a strong function of wavelength.

More than $\sim 10^3$ small bodies have already been discovered in the distance range of 30–50 AU, which is known as the Kuiper belt of the Solar System (Petit *et al.*, 2011). The number of known Kuiper belt objects (KBOs) will increase by 1–2 orders of magnitude over the next decade through wide-field surveys such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)³ and the Large Synoptic Survey Telescope (LSST)⁴. The sizes⁵ of known KBOs ($\sim 1\text{--}10^3$ km) are usually inferred by assuming a typical albedo (Grundy *et al.*, 2005) of $A \sim 4\text{--}10\%$. (The albedo of a KBO can sometimes be calibrated more reliably based on measurements of its thermal IR emission.⁶) For $A=7\%$ and a distance $D=50$ AU, an artificially $f_{\oplus}$ -illuminated object would be brighter by a factor of $\sim 3.6 \times 10^2$ than if it were sunlight-illuminated. This implies that an $f_{\oplus}$ -illuminated surface would provide the same observed flux F as a sunlight-illuminated object at that distance, if it is $\sim (3.6 \times 10^2)^{1/2} = 19$ times smaller in size. In other words, an $f_{\oplus}$ -illuminated surface of size 53 km (comparable to the scale of a major city) would appear as bright as a 10^3 km object that reflects sunlight with $A=7\%$. Since $\sim 10^3$ km objects were already found at distances beyond ~ 50 AU, we conclude that existing telescopes and surveys could detect the artificial light from a reasonably brightly illuminated region, roughly the size of a terrestrial city, located on a KBO.

Weaker artificial illumination by some factor $\varepsilon < 1$ relative to the “1% of daylight on Earth” standard represented by $f_{\oplus}$ would lower the observed flux by the same factor, since the observed flux scales as $F \propto \varepsilon$. Correspondingly, the equivalent object size needed for artificial illumination to produce the

same observed flux as due to sunlight illumination would increase by $\varepsilon^{-1/2}$. Nevertheless, existing telescopes could detect dimly illuminated regions ($\varepsilon \sim 1\%$) hundreds of kilometers in size on the surface of large KBOs.

The current artificial illumination on the nightside of Earth has an absolute r -band magnitude of roughly 44 (corresponding to 1.7×10^{13} lumens produced from $\sim 2 \times 10^{12}$ watts of electric power).^{7,8} Existing telescopes could see the artificially illuminated side of Earth out to a distance of $\sim 10^3$ AU, where its brightness in scattered sunlight and in artificial lighting (at current levels) would coincidentally be roughly equal. A present-day major terrestrial city, Tokyo for example,⁹ has an absolute r -band magnitude of very roughly 48 with apparent r -magnitudes of approximately 16 at a distance of 1 AU, 24 at 30 AU, 26 at 100 AU, and 31 (about as faint as the faintest detected objects in the Hubble Ultra-Deep Field) at 10^3 AU.

Although precise numbers depend on many detailed properties of the telescope, instrument, and observing conditions (sky brightness, image quality, etc.), representative exposure times to reach the aforementioned r -band apparent magnitudes at high (50-to-1) signal-to-noise ratio, with an 8 m class telescope, modern CCD detectors, and good observing conditions, are 1500 and 1800 seconds, respectively, for the first three cases of a terrestrial city mentioned above. Reaching $r \sim 31$ is not feasible from the ground in that it took over 3×10^5 seconds with the 2.4 m Hubble Space Telescope.

Thus, existing optical astronomy facilities are capable of detecting artificial illumination at the levels currently employed on Earth for putative extraterrestrial constructs on the scale of a large terrestrial city or greater out to the edge of the Solar System.

3. A Flux-Distance Signature of Artificial Illumination

Orbital parameters of KBOs are routinely measured¹⁰ to a precision of $< 10^{-3}$ via astrometric observations (Petit *et al.*, 2011). A simple but powerful and robust method for identifying artificially illuminated objects is to measure the variation of the observed flux F as a function of its changing distance D along its orbit. Sunlight-illuminated objects will show a logarithmic slope of $\alpha \equiv (d \log F / d \log D) = -4$, whereas artificially illuminated objects should exhibit $\alpha = -2$. The required photometric precision of better than a percent for such measurements (over timescales of years) can be easily achieved with modern telescopes.

If objects with $\alpha = -2$ are discovered, follow-up observations with long exposures on 8–10 m and space telescopes could determine their spectra and test whether they are

⁷http://www.lightinglab.fi/IEAAnnex45/guidebook/11_technical%20potential.pdf

⁸This value assumes a Sun-like spectrum in the optical band and an illumination efficiency (lumens/watt) similar to that of the Sun, which is in the range of modern fluorescent and LED lights as well. The choice of the r -band is obviously somewhat arbitrary and is meant only for illustrative purposes. The artificial illumination employed by an alien civilization might have a wide range of possible spectra, perhaps correlated with that of the primary star hosting the object on which the civilization evolved.

⁹<http://www.tepco.co.jp/en/forecast/html/kaisetsu-e.html>

¹⁰Long-term monitoring of KBOs may also serve to limit or detect deviations from Keplerian orbits due to artificial propulsion.

²<http://www.brilliantz.co.uk/data/documents/Lumen.pdf>

³<http://pan-starrs.ifa.hawaii.edu/public/home.html>

⁴<http://www.lsst.org/lsst>

⁵These sizes correspond to diameters for the larger objects, which are spherical in shape, but are merely characteristic linear scales for the smaller objects, which have irregular shapes.

⁶<http://www.minorplanetcenter.org/iau/lists/Sizes.html>

illuminated by artificial thermal (incandescent) or quantum (LED/fluorescent) light sources.¹¹ The exposure time requirements to achieve moderate signal-to-noise spectra would be extreme and run to millions of seconds or more, at the faint end of the magnitude range under consideration. However, the motivation to determine the nature and properties of an object that shows convincing $\alpha = -2$ behavior would be even more extreme. A complementary follow-up search for artificial radio signals could be conducted with sensitive radio observatories (Loeb and Zaldarriaga, 2007), such as the Very Large Array (VLA)¹², the Allen Telescope Array (ATA)¹³, the Giant Metrewave Radio Telescope (GMRT)¹⁴, the Low Frequency Array (LOFAR)¹⁵, the Murchison Widefield Array (MWA)¹⁶, and the Precision Array to Probe the Epoch of Reionization (PAPER)¹⁷, which would have the capacity to detect extraordinarily low levels of radio emission by current terrestrial standards. In general, follow-up with all available observational resources would be well justified.

Kuiper belt objects vary in brightness for reasons other than their changing distance from Earth and the Sun (Rabinowitz *et al.*, 2007; Sheppard *et al.*, 2008; Schaefer *et al.*, 2009). Specific causes include a changing phase angle (due largely to Earth's orbital motion) that would lead to changes in the contributions from coherent backscattering and surface shadowing, outgassing (*i.e.*, cometary activity), rotation of objects with nonspherical shapes or surface albedo variations, and for some objects occultation by a binary companion. Although the brightness changes associated with these effects are typically tenths of a magnitude and can be larger for some objects, their timescales are short (hours to days in most cases), and with the exception of outgassing, the resulting variations are periodic. For these reasons, it will be necessary to monitor KBO brightnesses frequently and for a period of years in order to model or, at worst, average out other contributions to variability on an object-by-object basis and allow the secular trend with changing distance (*i.e.*, the α value) to emerge. Fortunately, LSST (Ivezic *et al.*, 2008) will obtain extensive and very high-quality data of precisely this nature for unrelated and conventional purposes. Thus, the survey we propose can identify KBO (or asteroid) candidates for intensive follow-up with no investment of additional observational resources.

We note that artificial lights might also vary on short timescales due to intermittent use, beaming, or the appearance and disappearance of bright spots over the limb as the object rotates.

4. Night Lights beyond the Solar System

The next generation of ground-based telescopes [the European Extremely Large Telescope (EELT)¹⁸, the Giant Ma-

gellan Telescope (GMT)¹⁹, and the Thirty Meter Telescope (TMT)²⁰], as well as space telescopes [the James Webb Space Telescope (JWST)²¹, Darwin²², and Terrestrial Planet Finder (TPF)²³] will have the capacity (Riaud and Schneider, 2007) to search for artificial illumination of extrasolar planets (Schneider, 2010; Schneider *et al.*, 2010). Although the α test proposed above for objects in the outer Solar System is not relevant for exoplanets, a search for the orbital phase (time) modulation of the observed flux from the artificial illumination of the nightside on Earth-like planets as they orbit their primary could be used in its place. The observer would see stronger artificial illumination when the dark side of the planet is more in view, which is exactly the opposite of the case with natural dayside illumination from the star. Cloud cover would mask some of the artificial illumination of an Earth-like planet in a stochastic time-dependent manner, which might significantly complicate the interpretation of such phase curves.

A preliminary broadband photometric detection could be improved through the use of narrowband filters that are tuned to the spectral features of artificial light sources (such as LEDs). For this signature to be detectable, the nightside would need to have an artificial brightness comparable to the natural illumination of the dayside. Clearly, the corresponding extraterrestrial civilization would need to employ much brighter and more extensive artificial lighting than we do since the global contrast between the dayside and nightside is a factor $\sim 6 \times 10^5$ for present-day Earth. In favorable scenarios, some proposed versions of NASA's Terrestrial Planet Finder mission would have reasonable prospects of detecting the artificial illumination of an exoplanet if it were at levels a few times greater than $f_{\oplus}$ or more.

City lights would be easier to detect on a planet that was left in the dark of a formerly habitable zone after its host star turned into a faint white dwarf. The related civilization would need to survive the intermediate red giant phase of its star. If it did, separating its artificial light from the natural light of a white dwarf would be much easier than it would be for the original star, both in contrast and in absolute brightness.

5. Concluding Remarks

In addition to the low prior probability, which in all likelihood should be assigned to the idea of an alien civilization occupying KBOs, the search proposed in this paper could fail for a host of other plausible reasons. The artificially illuminated spaces within which the civilization resides might be underground or otherwise shielded for a variety of reasons, such as to avoid wasting energy or to maintain a stealthy presence. Advanced technology, including biological alteration of sensory organs, might be employed to render very low natural illumination levels useable. Moreover, the most easily detected signatures might well be in very different bands, such as radio emissions. Thus, as for all other known SETI techniques, a null result would have no

¹¹One should also examine images of the dark side of Solar System moons, suspected of hosting liquid water. For example, city lights can be searched for in images taken by the Cassini spacecraft of the dark side of Saturn's moon, Enceladus.

¹²<http://www.vla.nrao.edu>

¹³<http://www.seti.org/ata>

¹⁴<http://gmrt.ncra.tifr.res.in>

¹⁵<http://www.lofar.org>

¹⁶<http://www.mwatelescope.org>

¹⁷<http://astro.berkeley.edu/~dbacker/eor>

¹⁸<http://www.eso.org/public/teles-instr/e-elt.html>

¹⁹<http://www.gmto.org>

²⁰<http://www.tmt.org>

²¹<http://www.jwst.nasa.gov>

²²http://www.esa.int/export/esaSC/120382_index_0_m.html

²³http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm

clear meaning. However, this is not sufficient reason to refrain from implementing a search since it is clearly impossible to predict, with any confidence, the behavior or capability of any unknown alien civilization. Further, a positive result for such a search would carry immense implications.

Artificially lit KBOs might have originated from civilizations near other stars. In particular, some small bodies may have traveled to the Kuiper belt through interstellar space after being ejected dynamically from other planetary systems (Moro-Martin *et al.*, 2009). These objects can be recognized by their hyperbolic orbits. A more hypothetical origin for artificially lit KBOs involves objects composed of rock and water/ice (asteroids or low-mass planets) that were originally in the habitable zone of the Sun, developed intelligent life, and were later ejected through gravitational scattering with other planets (such as Earth or Jupiter) into highly eccentric orbits. Such orbits spend most of their time at their farthest (turn-around) distance, $D_{\max}$. If this distance is in the Kuiper belt, then the last time these objects came close to Earth was more than $\sim 500 (D_{\max}/10^2 \text{ AU})^{3/2}$ years ago, before the advent of modern science and technology on Earth.

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Abbreviations

KBOs, Kuiper belt objects; LEDs, light-emitting diodes; LSST, the Large Synoptic Survey Telescope; SETI, the search for extraterrestrial intelligence.

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