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 out to 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 $\alpha = -2$. Planned surveys using the proposed LSST will provide superb data that would allow measurement of α for thousands of KBOs. If objects with $\alpha = -2$ are found, follow-up observations can measure their spectra to determine if 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, which would be capable of detecting phase modulation due to very strong artificial illumination on the night-side of planets as they orbit their parent stars.

Kewords: astrobiology, SETI, Kuiper belt objects, artificial illumination

1 Introduction

The search for extraterrestrial intelligence (SETI) has been conducted mainly in the radio band (Wilson, 2001; Tarter, 2001; Shostak et al., 2011), with peripheral attention to exotic signals in the optical (Howard et al., 2007; Horowitz et al., 2001; Ribak, 2006; Dyson, 2003; Forgan and Elvis, 2011) and thermal infrared (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 of the Earth has been declining dramatically in recent decades due to the use of cables, optical fibers and other advances in communication technology, indicating 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 emission 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 which 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, $f_\oplus \equiv 0.01(L_\odot/4\pi D_\oplus^2) = 1.4 \times 10^4$ erg s^{-1} cm^{-2}, where $D_\oplus = 1.5\times10^{13}$ cm $\equiv 1$ AU is the Earth-Sun distance. Crudely speaking, this unit corresponds to the illumination in a brightly-lit office or to that provided by the Sun just as it rises or sets in a clear sky on Earth.[2]

[1]Here 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.

[2]http://www.brillianz.co.uk/data/documents/Lumen.pdf

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 reaching 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 which illuminates it combined with the inverse square dependence of the scattered component of that incident flux which 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 $(A/1\%)^{-1}(D/1\ \mathrm{AU})^2$, 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, 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 Pan-STARRS[3] and LSST.[4] The sizes[5] of known KBOs (~ 1–10^3 km) are usually inferred by assuming a typical albedo (Grundy et al., 2005) of $A \sim 4$–10%. (The albedo of a KBO can sometimes be calibrated more reliably based on measurements of its thermal infrared emission.[6]) For $A = 7\%$ and a distance $D = 50$ AU, an artificially $f_\oplus$-illuminated object would be brighter by a factor $\sim 3.6 \times 10^2$ 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 $\sim \sqrt{3.6 \times 10^2} = 19$ 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 which 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 $\epsilon < 1$ relative to the “1% of

[3] http://pan-starrs.ifa.hawaii.edu/public/home.html

[4] http://www.lsst.org/lsst/

[5] These 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

daylight on Earth" standard represented by $f_\oplus$, would lower the observed flux by the same factor, since the observed flux scales as $F \propto \epsilon$. Correspondingly, the equivalent object size needed for artificial illumination to produce the same observed flux as due to sunlight illumination, would increase by $\epsilon^{-1/2}$. Nevertheless, *existing telescopes could detect dimly illuminated regions ($\epsilon \sim$ 1%) hundreds of km in size on the surface of large KBOs.*

The current artificial illumination on the night-side of the 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 the 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, 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 are 1, 500 and 1800 seconds, respectively, for the first three cases with an 8-meter class telescope in good observing conditions and using modern CCD detectors. Reaching $r \sim 31$ is not feasible from the ground and took over 3×10^5 seconds with the 2.4-meter 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 Kuiper belt objects (KBOs) are routinely measured[10] 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*

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

[8] This 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 they evolved.

[9] http://www.tepco.co.jp/en/forecast/html/kaisetsu−e.html

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

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 $8 - 10$ meter and space telescopes could determine their spectra and test whether they are 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, running 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 showing 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 VLA,[12] ATA,[13] GMRT,[14] LOFAR,[15] MWA,[16] and PAPER,[17] which would be able to detect extraordinarily low levels of radio emission by current terrestrial standards. In general, follow-up using all available observational resources would be well justified.

KBOs vary in brightness for reasons other than their changing distance from the Earth and the Sun (Rabinowitz et al., 2007; Schaefer et al., 2009; Sheppard et al., 2008). Specific causes include a changing phase angle (due largely to the Earth's orbital motion) leading to changes in the contributions from coherent backscattering and surface shadowing, outgassing (*i.e.,* cometary activity), rotation of objects with non-spherical 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 time scales 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,

[11] One 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/

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 time scales, either due to their being turned on and off, due to beaming, or due to bright spots appearing and disappearing over the limb as the object rotates.

4 Night Lights Beyond the Solar System

The next generation of ground-based telescopes (EELT,[18] GMT,[19] and TMT[20]) as well as space telescopes (JWST,[21] Darwin,[22] and TPF[23]) will be able (Riaud and Schneider, 2007) to search for artificial illumination of extra-solar planets (Schneider et al., 2010a,b). 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 night-side 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, exactly the opposite of the case with natural day side 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 broad-band photometric detection could be improved through the use of narrow-band filters which are tuned to the spectral features of artificial light sources (such as LEDs). For this signature to be detectable, the night side needs to have an artificial brightness comparable to the natural illumination of the day side. Clearly, the corresponding extraterrestrial civilization would need to employ much brighter and more extensive artificial lighting than we do currently since the global contrast between the day and night sides is a factor $\sim 6 \times 10^5$ for the present-day Earth. In favorable scenarios, some proposed versions of NASA's TPF 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 which was left in the dark of a formerly-habitable zone after its host star turned into a faint white dwarf.

[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/
[22] http://www.esa.int/export/esaSC/120382_index_0_m.html
[23] http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm

The related civilization would need to survive the intermediate red giant phase of its star. If it does, separating its artificial light from the natural light of a white dwarf, would be much easier than for the original star, both in contrast and in absolute brightness.

5 Concluding Remarks

In addition to the low prior probability that should probably 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 might be underground or otherwise shielded for a variety of reasons, such as to avoid wasting of 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 detectable 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 clear meaning. However, this is not a sufficient reason to refrain from searching since it is clearly impossible to predict the behaviors or capabilities of unknown alien civilizations with any confidence and because a positive result would carry such 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 the Earth or Jupiter) into highly eccentric orbits. Such orbits spend most of their time at their farthest (turnaround) distance, $D_{\rm max}$. If this distance is in the Kuiper belt, then the last time these objects came close to Earth was more than $\sim 500\ (D_{\rm max}/10^2\ {\rm AU})^{3/2}$ years ago, before the modern age of science and technology began on Earth.

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