Novel Detection Techniques for Extraterrestrial Intelligence Beyond and Inside the Solar System

Executive Summary

1 Introduction

The scientific search for extraterritorial intelligence (SETI) began when Cocconi and Morrison (1959) pointed out that human radio technology (then achievable broadcast power and detection sensitivity) had reached a stage that would allow communication over interstellar distances. At the time, the range over which human radio technology could marginally detect and communicate with an alien civilization having identical capabilities was of order 10 pc (30 light years). Today the corresponding distance is roughly a thousand times larger.

That influential paper and its immediate implementation by Drake in the following year set the course of the vast majority of SETI efforts that have transpired during the intervening decades in three important ways: First, nearly all searches have concentrated on the radio band. Second, the paradigm of considering the possibility of detecting a technological "twin" of our own human civilization using existing or clearly foreseeable terrestrial telescopes and instrumentation has remained the dominant theoretical template for determining which of the many possible approaches to SETI are "plausible" and thus worthy of implementation. Third, Earth-like planets orbiting in the Habitable Zones (HZ) of a Sun-like stars have been presumed to be the most promising, and often the only plausible, targets for SETI observations. In short, SETI has concentrated very heavily on looking for a "mirror-image" of ourselves for over half a century, without success so far it hardly need be added.

Here we propose a systematic series of preliminary theoretical investigations of alternative approaches to SETI in which we will abandon all three of these elements of the now conventional paradigm described above.

First and most straightforwardly, we will consider wavelength bands across the whole electromagnetic (EM) spectrum and perhaps even non-EM possibilities.

Second, we will factor the usual "twin technology" standard into two components. Namely, we will ask both: *(i)* what level of activity (emission) would be required for an alien civilization to be detected using telescopes and instrumentation now or soon available to us?, and *(ii)* what detection sensitivity would we be required to achieve in order to detect a "twin" of current human civilization? The answers to both questions will obviously be a function of the distance to the alien civilization/activity, and this is a segue to the third point.

Third and perhaps most provocatively, we will abandon the traditional focus of SETI thinking on plausibly Earth-like natural environments and instead consider a very wide range of other astrophysical environments, ranging from the vicinities of stellar remnants through interstellar space to the outer parts of the Solar System.

In addition to these theoretical studies, we propose to carry out a demonstration or "pathfinder" project by implementing one alternative SETI technique via "mining" of a large PanSTARRS data set which will become available to us during the award period.

Before proceeding to say more about our planned work, we should make it clear that we do not intend either the comments above or the papers we hope to write as a criticism of the conventional approach to SETI. The logic motivating it and the discipline it imposes on ideas that might otherwise become too speculative continue to be persuasive in many ways today, just as they were five decades ago. There is no question in our minds that the ongoing efforts of conventional radio SETI should be continued and should probably remain our single most vigorous effort. We do, however, believe that SETI needs to be wary of falling into the trap of being too narrowly focus on one or a few scenarios that are all based on assuming that the unknown (them) is very much like the known (us).

The history of the discovery of exoplanets provides a valuable historical lesson in this regard. All early attempts to discover exoplanets were based on the presumption that exoplanetary systems resembled the Solar System, at least generally but sometimes in considerable detail. This assumption was allowed to set sensitivity goals for required instrumentation, influence allocations of telescope time and other resources, determine observing protocols (especially cadences) etc. However, the first recognized exoplanets to be discovered were found serendipitously orbiting a neutron star! And the first exoplanetary systems discovered via observational programs intended for the purpose revealed dynamical structures radically different from the Solar Systems. With thousands of exoplanetary systems now known, it is abundantly clear that the Galaxy is rich in systems with a very wide variety of properties that depart radically from those of the Solar System. Many of these systems are much easier to detect using a variety of techniques than the Solar System would be at similar distances. *Thus, and importantly in the present context, had astronomers not been blinkered by the perfectly plausible notion of looking for planetary systems closely resembling the Sun's, exoplanets could have been discovered at a much earlier date and far more easily than they actually were.*

Since it is surely enormously more difficult to foresee the characteristics and activities of alien intelligences and technologies than it is to predict the basic physical properties of exoplanets, it would seem prudent indeed to have a careful look at SETI techniques which do not assume that they are "just like us" in many or all relevant ways. That is the fundamental motivation of the work proposed here.

2 Artificial Illumination in the Outer Solar System

We next give a "worked example" of the sort of approach to SETI which we propose to explore following the general guidelines and philosophy described in the previous section. The theoretical (hypothesis exploration) component of this SETI technique has already been completed and published (Loeb and Turner, 2012) and we here propose to further develop this approach by implementing a pathfinder or demonstration novel SETI project via data mining of an existing data set.

We are guided 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?

2.1 Illuminated Kuiper Belt Objects

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). (An AU is approximately the radius of the Earth's orbit around the Sun.) 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 and LSST.

The current artificial illumination on the night-side of the Earth has an absolute r-band magnitude of roughly 43.5 (corresponding to 1.7×10^{13} lumens produced from $\sim 2 \times 10^{12}$ Watts of electric power). 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, has an absolute r-band magnitude of 47.9 with apparent r-magnitudes of 16.2 at a distance of 1 AU, 23.7 at 30 AU, 26.3 at 100 AU and 31.3 at 10^3 AU. These numbers imply that such an object could be detected by typical professional ground based telescopes in long exposures out to 30 AU, by the largest existing such telescopes out to 100 AU and by the Hubble Space Telescope out to 10^3 AU, the extreme edge of the outer Solar System.

Thus, in a recent paper (Loeb and Turner, 2012) the PI and Co-I pointed out that *existing optical astronomy facilities are capable of detecting artificial illumination for putative extraterrestrial constructs on the scale of a large terrestrial city or greater out to the edge of the Solar System.*

2.2 A Flux-Distance Signature of Artificial Illumination in the Outer Solar System

Orbital parameters of Kuiper belt objects (KBOs) are routinely measured[1] 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 $8 - 10$ meter telescopes can determine their spectra and test whether they are illuminated by artificial thermal (incandescent) or quantum (LED/fluorescent) light sources.

2.3 Data Mining of PanSTARRS

In 2012-2014 Pan-STARRS1 (PS1) is expected to provide well-calibrated lightcurves of $\sim 10^4$ KBOs. We propose to analyze these lightcurves in all observed wavelength bands. The extended version of our proposal quantifies the promise of the PS1 data set for our project. Using a simulation of $\sim 10^4$ KBOs observed with weekly cadence at the expected flux uncertainty of 3%, we find that it would be feasible to identify artificially illuminated objects

[1] Long-term monitoring of KBOs may also serve to restrict deviations from Keplerian orbits due to artificial propulsion.

after ~ 2 years at a significance greater than 95%. Older exisitng data sets are not calibrated to sufficient photometric precision to be useful.

2.4 Exploring Other Planetary Systems

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.

We also propose to study how the next generation of ground-based telescopes (EELT, GMT, and TMT) as well as space telescopes (JWST, Darwin, and TPF) will be able (Riaud and Schneider, 2007) to search for artificial illumination of extra-solar planets (Schneider et al., 2010a,b). Of particular interest would be 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. 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.

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. The related civilization will 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 spectroscopically and in total brightness.

3 Other Signatures of Technological Civilizations

In addition to artificial light, we will study several other possible unconventional SETI techniques:

- *novel signatures*: such as industrial and nuclear isotope pollution in planetary atmospheres; nuclear explosions; very non-LTE thermal conditions (e.g. high brightness temperatures that are far higher than the expected thermal conditions); and leakage of low-frequency radio or other communication signals.

- *novel locations:* such as planets orbiting stellar remnants (white dwarfs and neutron stars); small bodies (asteroids or comets) that were ejected from planetary systems into interstellar space now entering or passing near the Solar System (Moro-Martin et al., 2009); and regions in which there are high concentrations of free energy (low entropy) such as the vicinity of massive compact objects (neutron stars or black holes), supernova remnants or massive stars.

Project Description

4 Preface

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[2] http://www.bigear.org/vol1no1/ozma.htm

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5 Introduction

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).

Traditional SETI assumed that technological civilizations produce intentional signals. We adopt instead a *fishing expedition methodology*, involving a blind search across a broad range of wavelengths and techniques for leakage of artificial signals. Our proposed research will explore novel techniques and signatures that had not been studied in detail before and that, *if successful*, will revolutionize our views about life in the Universe. Broadly speaking, we propose to study:

- which leakage signals can be detected today by piggybacking on existing astronomical facilities and surveys?

- what are the most interesting signatures of technological civilizations to search for, and what are the optimal observational facilities that need to be constructed to detect them?

Let us start by demonstrating our approach in the context of a specific pathfinder project, involving a search for artifical light in the outer solar system and beyond.

6 Artificial Illumination in the Outer Solar System

We are guided 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?

It is convenient to normalize any artificial illumination in flux units of 1% of the solar daylight illumination of Earth, $f_\oplus \equiv 1\%(L_\odot/4\pi D_\oplus^2) = 1.4\times10^4$ 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.[3]

6.1 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 observed flux from scattered sunlight off an object at a distance $D \gg 1$ AU scales as D^{-4}. 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.

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[4] and LSST.[5] The sizes 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 $\sim 3.6\times10^2$ than if it were sunlight-illuminated. This implies that an $f_\oplus$-illuminated surface would provide the same

[3] http://www.brillianz.co.uk/data/documents/Lumen.pdf
[4] http://pan-starrs.ifa.hawaii.edu/public/home.html
[5] http://www.lsst.org/lsst/
[6] http://www.minorplanetcenter.org/iau/lists/Sizes.html

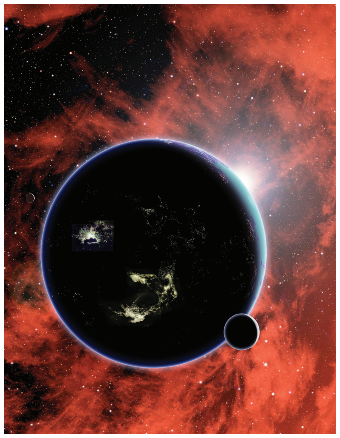

Figure 1: Artistic rendition of extensive city lights on the night side of an exoplanet, signaling the presence of an advanced technological civilization. (Credit: David Aguilar, CfA)

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 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 43.5 (corresponding to 1.7×10^{13} lumens produced from $\sim 2 \times 10^{12}$ Watts of electric power).[7] 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,[8] has an absolute r-band magnitude of 47.9 with apparent r-magnitudes of 16.2 at a distance of 1 AU, 23.7 at 30 AU, 26.3 at 100 AU and 31.3 (about as faint as the faintest detected objects in the Hubble Ultra-Deep Field) at 10^3 AU.

Thus, in a recent paper (Loeb and Turner, 2012) the PI and Co-I have argued that *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 (see Fig. 1) out to the edge of the Solar System.*

[7] http://www.lightinglab.fi/IEAAnnex45/guidebook/11_technical%20potential.pdf
[8] http://www.tepco.co.jp/en/forecast/html/kaisetsu−e.html

6.2 A Flux-Distance Signature of Artificial Illumination in the Outer Solar System

Orbital parameters of Kuiper belt objects (KBOs) are routinely measured[9] 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 $8-10$ meter telescopes can determine their spectra and test whether they are illuminated by artificial thermal (incandescent) or quantum (LED/fluorescent) light sources.[10] A complementary follow-up search for artificial radio signals can be conducted with sensitive radio observatories (Loeb and Zaldarriaga, 2007), such as GMRT,[11] LOFAR,[12] MWA,[13] and PAPER,[14] which would be able to detect extraordinarily low levels of radio emission by current terrestrial standards.

KBOs vary in brightness for reasons other than their changing distance from the Earth and the Sun. In particular, a changing viewing angle (due largely to the Earth's orbital motion) can lead to changes in the contributions from coherent backscattering, surface shadowing (Rabinowitz et al., 2007; Schaefer et al., 2009), and outgassing; rotation of objects with non-spherical shapes or surface albedo variations can produce short time scale (typically hours to days) variability; and for some objects occultation by a binary companion can also contribute to relatively rapid variability. For these reasons it will be advantageous to monitor KBO brightnesses frequently and for a period of years in order to average out other contributions to variability and allow the secular trend with changing distance 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 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.

6.3 Data Mining of PanSTARRS

In 2012-2014 Pan-STARRS1 (PS1) is expected to provide well-calibrated lightcurves of $\sim 10^4$ KBOs. The data will start being available to us in 2012. We propose to analyze these lightcurves in all observed wavelength bands. Below we quantify the promise of this future data set for our project.

[9] Long-term monitoring of KBOs may also serve to restrict deviations from Keplerian orbits due to artificial propulsion.

[10] 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.

[11] http://gmrt.ncra.tifr.res.in/

[12] http://www.lofar.org/

[13] http://www.mwatelescope.org/

[14] http://astro.berkeley.edu/∼dbacker/eor/

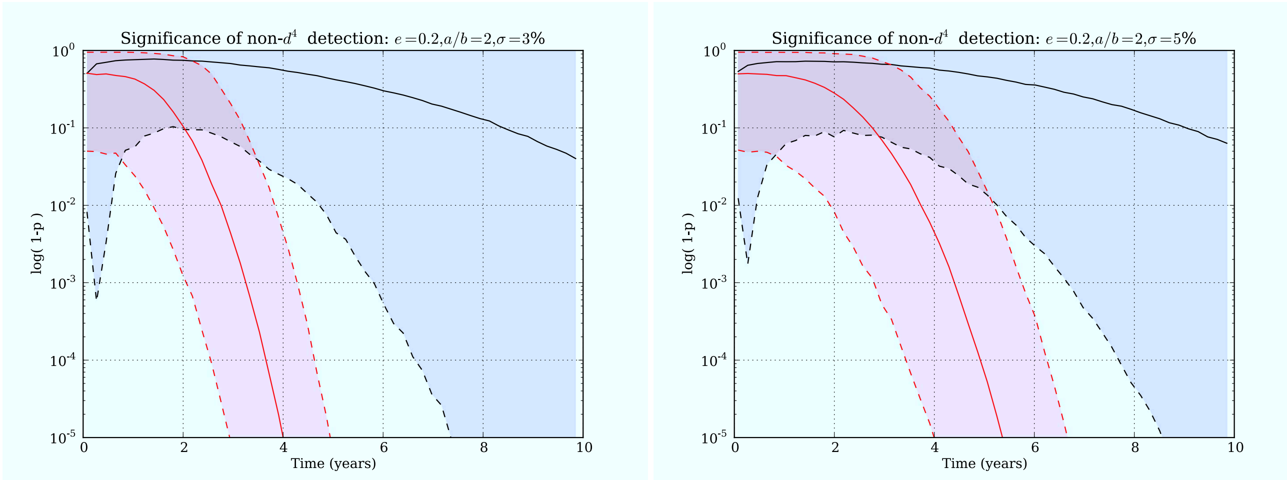

Figure 2: Strength of rejection of the null hypothesis (no correlation of H-magnitude and heliocentric distance) for reflected light TNOs (black/grey, median and 95% confidence contour) and for intrinsically luminous objects (red, median and 95% confidence contour) after sampling the objects' lightcurves with a weekly cadence over a time T. Objects are on orbits with semi-major axis $a = 40$ AU and eccentricity $e = 0.2$ around the Sun, and photometric scatter is assumed to be 3% (left) and 5% (right) for the two plots. TNOs were assumed to be randomly oriented spin poles and triaxial ellipsoid shapes with axis ratios $a/b = 2$ and $c/b = 1$, and spin periods of several hours to several days. Intrinsically luminous objects were assumed to have no intrinsic flux variation and no reflected light component.

We base our expectations for the PS1 data set on knowledge that was gathered in previous data. For example, Schwamb et al. (2010) presented a survey of 12,000 square degrees to a limiting magnitude of $R = 21.3$, in which 52 KBOs were detected. The photometric precision of PS1 is predicted to be of order 3% (Durech et al. 2005). Extrapolating using a power law luminosity function with a slope ~ 0.5–0.7, we expect there to be ~ 250 objects of this brightness detectable with the PS1 photometric precision. Each of these bright objects can be tracked for variability over the lifetime of the survey. After ~ 2 years of tracking, orbital solutions and the photometric sample will be precise enough to identify those objects with α deviating from the reflected-sunlight value of -4.

To analyse the detection statistics reliably we consider a large number of realizations for PS1 objects. Figure 2 illustrates the effect of the PS1 level of photometric precision on the ability to distinguish non-D^{-4} behavior from stochastic variation and shape effects. In these figures we illustrate the results of a simulation of 10,000 trans-Neptunian objects (TNOs) observed with flux uncertainty of 3% and 5%, given year-round observations with a weekly cadence. We neglect treating bright time and the fraction of the year when the object is set; we assume that the loss in observed time is made up for by the fact that objects will be observed in multiple bands, effectively increasing the signal-to-noise of a given epoch's observation by a similar factor.

In making this simulation, we assumed that 5,000 of the objects have luminosities dictated by reflected light, and their distance from the Sun varied as that of an object with semi-major axis of 40 AU with an eccentricity of 0.2. To be conservative, these objects are assumed to have highly non-spherical shapes (triaxial ellipsoids with $a/b = 2$ and $c = b$) with random pole orientations and spin periods of several hours to several days. Thus, as they travel around their orbit the average projected area that the observer sees changes, leading to a correlation in in flux with distance from the Sun which is not strictly D^{-4}. This manifests as an H-magnitude that varies with an object's ecliptic longitude - and therefore its distance from the Sun D; the H-magnitude is defined such that it should not change with D for $\alpha = -4$. For a description of the lightcurve model used, see Masiero et al. (2009).

We measured the statistical strength of a correlation between each object's observed H-magnitude and its distance from the Sun, given the sample of observations up to time T using a non-parametric Spearman's R rank correlation coefficient. The figures illustrate that as time goes on the detection of a correlation between heliocentric distance and H-magnitude becomes more significant.

However, we find that the significance does not grow as fast as it would if the objects were intrinsically luminous instead of shining in reflected light. The other 5,000 objects in the simulation were assumed to have no intrinsic variability, and were intrinsically luminous with no component of reflected light. They were sampled with the same cadence and photometric scatter as the reflected-light TNOs, and their distance from the Sun was varied in the same way. As illustrated in Figure 2, after ~ 2 years over 50% of all such intrinsically luminous objects would be distinguished from the reflected-light TNOs by this metric with significance greater than 95%.

While these intrinsically-luminous objects would rapidly distinguish themselves from reflected-light TNOs given the level of photometric precision obtainable for a few hundred TNOs with PS1, existing datasets are by-and-large not precise enough to distinguish such objects. The Minor Planet Center repository is well known to contain significant (~ 0.5 mag) systematic photometric errors due to the nature of the broad range of submitters (see, e.g., Parker et al. 2008). At this level of precision, the variation of intrinsically-luminous objects would never be distinguishable from the background populations. Figure 3 illustrates this by showing the pairwise difference H-magnitudes for observations of TNOs in the literature. The differences in H-magnitude each correspond to separate observations of the same object at different heliocentric distances, scaled to the reported statistical uncertainty in each measurement. The distribution is very broadly peaked around zero, consistent with no variation, but the width of the distribution is indicative of serious systematic differences in different observations of the same object. The plot also illustrates the luminosity variation slope α, and shows no strong peaks at $\alpha = -2$ or $\alpha = -4$ (the spike at 0 is due to objects which have identical heliocentric distances at the times of observation), the intrinsically-luminous and reflected-light slopes, further demonstrating that existing data are not precise enough to distinguish them.

6.4 Exploring Other Planetary Systems

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 ~ 500 $(D_{\rm max}/10^2\ {\rm AU})^{3/2}$ years ago, before the modern age of

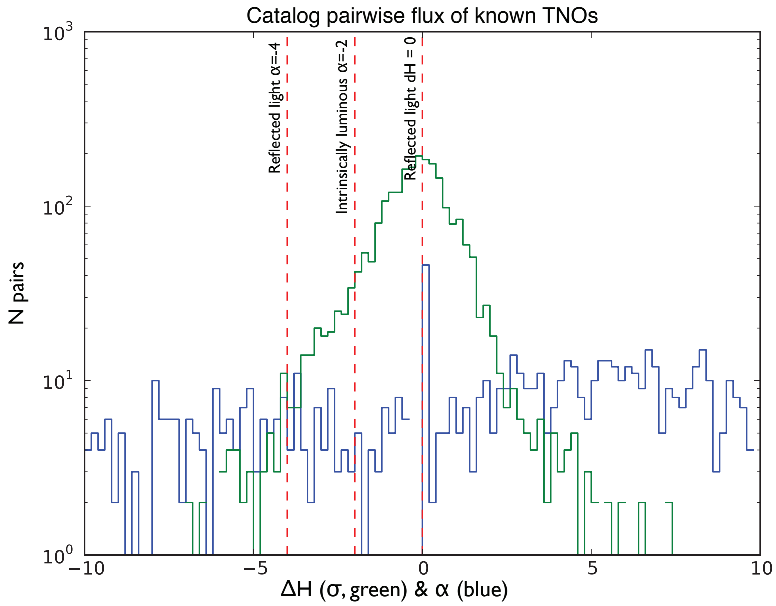

Figure 3: Example of pairwise measurements of H-magnitude for a sample of literature TNOs with $D > 25$ AU taken at different times. The broad distribution in standard deviations (blue) illustrates that there exist significant errors in the photometry presented in existing catalogs. The luminosity variation slope α is also illustrated (green) for the same pairwise observations, where 0 indicates no variation in distance between the observations.

science and technology began on Earth.

We propose to study how the next generation of ground-based telescopes (EELT,[15] GMT,[16] and TMT[17]) as well as space telescopes (JWST,[18] Darwin,[19] and TPF[20]) will be able (Riaud and Schneider, 2007) to search for artificial illumination of extra-solar planets (Schneider et al., 2010a,b). Of particular interest would be 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. 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.

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. The related civilization will 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 spectroscopically and in total brightness. Environments of other stellar remnants where planets are known to form, such as neutron stars, are also of interest.

[15] http://www.eso.org/public/teles-instr/e-elt.html
[16] http://www.gmto.org/
[17] http://www.tmt.org/
[18] http://www.jwst.nasa.gov/
[19] http://www.esa.int/export/esaSC/120382_index_0_m.html
[20] http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm

Table 1: Detectability of novel activities of intelligent life in various environments. The table entries are divided into three categories: *(i)* Earth-like signals that can be explored with existing observational facilities (labeled 'o'); *(ii)* Earth-like signals that could be detected by proposed facilities within the next 1–2 decades (labeled '*'); and *(iii)* signals that might be detectable at levels far in excess of Earth, or by instruments superior to those proposed so far (labeled 'x'). Our proposed research will study all three categories, and in particular quantify category *(iii)*.

Activities	Main-Sequence Stars	Stellar Remnants (WD,NS)	Interstellar Objects	Outer Solar System
Artificial Illumination	x	*	o	o
Nuclear Technology	x	*	o	o
Industrial Pollution	*	*	x	x
Non-LTE conditions	*	*	*	o
Communication Technology	o	o	o	o

7 Other Signatures of Technological Civilizations

Our pathfinder project focuses on the outer solar system because related data from PanSTARRS will become available in the immediate future. However, our ultimate goal is to extend this project to analogous searches outside the solar system.

In addition to artificial light, we propose to study other signatures of intelligent life with:

- *novel techniques*: such as searching for industrial and nuclear isotope pollution in the spectrum of planetary transits; a photometric search for nuclear explosions; infrared search for non-LTE thermal signatures (e.g. high brightness temperature that is far higher than the expected thermal conditions); searching for the transit lightcurve imprint of artificial constructions on planets or satellites of giant planets; and eavesdroping on leakage of low-frequency radio signals with upcoming data from low-frequency arrays (Loeb and Zaldarriaga, 2007), such as MWA – to which we have access.
- *novel locations:* such as stellar remnants (white dwarfs and neutron stars); planetesimal-size objects that were ejected from planetary systems into interstellar space and are now entering or passing near the Solar System (Moro-Martin et al., 2009); and regions in which there are high concentrations of free energy (low entropy) such as the vicinity of massive compact objects (neutron stars or black holes), supernova remnants or massive stars.

Table 1 summarizes the feasibility of exploring various signatures with existing facilities. We propose to study quantitatively all or most of the table entries.

7.1 Flashes from Artificial Nuclear Explosions

In §2 we demonstrated that the light generated (with an efficiency of $\sim 10\%$) by the current terrestrial output of $\sim 2\times10^{12}$ Watts of electric power can be seen by existing telescopes out to a distance of $\sim 10^3$ AU. *How far away can the flash of a nuclear explosion be detected?* A large explosion of $\sim 10^2$ Megaton produces $\sim 4\times10^{17}$ J. If the radiation flash carries a significant fraction of this energy and lasts a fraction of a minute, then its total power is $\sim 10^{16}$ Watts. The resulting thermal flash can be detected by existing telescopes out to ~ 1 pc, roughly the distance of the nearest star. The challenge is to monitor nearby stars over long periods of time and to distinguish the flash based on its color from common variability in the light output of the parent star. An artificial nuclear explosion might also produce a γ-ray flash that is not naturally produced by stellar variability. The Fermi γ-ray telescope can barely detect such a flash from a source at distances $\lesssim 0.1$ pc. Of course, one can imagine more powerful explosions, potentially accounting for known X-ray flashes by a large population of advanced civilizations at larger distances.

We will examine the detectability of other unusual signals from nuclear weapons, such as the electromagnetic pulse (EMP) and the optical double pulse. Of particular interest would be a highly sensitive bhangmeter, which is a photometer used on reconnaissance satellites the double optical-UV pulse due to detect atmospheric nuclear detonations.

7.2 Pollutants in the Atmospheres of Terrestrial Exoplanets

Spectroscopic determination of the atmospheric composition of terrestrial planets orbiting in the habitable zones of their primary star is a (or even "the") primary long-term goal for ambitious next generation exoplanet research facilities and projects. A variety of approaches are being considered; these include transit spectroscopy (a technique which has already succeeded in producing low quality spectra of some hot-Jupiter exoplanets), subtraction spectroscopy in and out of secondary eclipse and direct spectroscopy of exoplanets that have been resolved from their primary star's light via advanced high-contrast imaging techniques from space or perhaps even from the ground via extreme adaptive optics technology (*e.g.,* the proposed SEIT instrument for TMT (Matsuo and Tamura, 2010).

The conventional scientific motivation for this consensus science goal in the exoplanet research community is the search for molecular water, oxygen, methane and other atmospheric constituents which might indicate conditions suitable for life or even its presence. We will explore the more challenging and provocative possibility that data of this sort could reveal indications of the presence of intelligent and massively technological life such as industrial or other artificial pollutants in an exoplanets atmosphere. It might even be possible, though tragic, to detect heavy pollution of a planets atmosphere by the radioactive isotopes which would be produced by a large number of nuclear explosions. In this investigation we will be guided by extensive spectroscopic data on industrial pollution in the Earth's atmosphere obtained via observations from satellites (Chance, 2006). Ground based observations from future extremely large aperture telescopes would be particularly powerful for this application because they would offer the possibility of detecting weak absorption lines associated with relatively minor constituents of an exoplanet's atmosphere.

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