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RESEARCH ARTICLE

Alien technology, conjunction and ergodicity

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Abstract

In a recent refreshing paper, Cowie (2022, The Philosophical Quarterly) analyses the hypothesis of artificial origin of the mysterious interstellar object 1I/2017 U1 'Oumuamua, as well as the wider question of justification of the artefactual origin explanation for anomalous astronomical phenomena. This highly commendable philosophical project should be further developed in order to establish more general methodology for dealing with traces and manifestations of extraterrestrial intentional actors. In the present note, I demonstrate a couple of weaknesses of the standard account, mainly dealing with philosophy of technology, and suggest ways of improving upon it.

Contents

> Then, after having lost men, and vehicles, and their best equipment, they had fled – because how else could a withdrawal at this point be labelled other than as flight, plain and simple – from microscopic crystals that were the product of a desert planet, the inanimate remnants of the Lyran civilization that had overtaken that of Earth so very long ago!
>
> Stanisław Lem, *The Invincible* (1966)

Introduction

How do we conceptualize artefacts of advanced extraterrestrial civilizations? In a recent thought-provoking study, Cowie (2022) has considered the artefact explanation for the bizarre properties of interstellar asteroid-like object 1I/2017 U1 'Oumuamua from philosophical point of view. He considers the hypothesis, put forward by distinguished astrophysicist Abraham Loeb, that this small object is, in fact, artefact of an advanced extraterrestrial civilization, and that its anomalous properties are best explained as its being a solar sail (Bialy and Loeb, 2018; Loeb, 2021). Various hidden assumptions and justification pitfalls are analysed by Cowie in a masterful way. Such a study is immensely important and likely to increase in importance with the rise of our observational knowledge and theoretical sophistication in astrobiology (see also Cowie, 2021). In the era of revived interest in search for extraterrestrial intelligence (SETI) studies (now under the new title of 'search for technosignatures'; Wright

et al., 2022), philosophical issues related to recognition and justification of artefactual claims and corresponding explanatory hypotheses are a necessity rather than a luxury.

While this topic has been vaguely present from the start of the SETI era in 1959, it has rarely attracted much attention since it is, ironically enough, antithetical to concerns of *both* SETI enthusiasts *and* SETI opponents. The enthusiasts – including many of the 'founding fathers' such as Drake, Sagan, Shklovsky and others – are guided by the logic of US Supreme Justice Potter Stewart in *Jacobellis v. Ohio* (1964) that we 'will know alien manifestations when we see them'[1]. The opponents, on the other hand, are heavily invested in assuming that we shall always have *non-intentional* explanations of any piece of astronomical data (including, presumably, what Cowie dubs 'unconceived alternatives'). Therefore, we shall never be forced to take the intentional – e.g. alien – explanations seriously. In such a situation – as in many other situations often encountered in daily politics where two opposing sides agree on an unproven assumption – nobody is motivated to search for proof or even to enquire further much.

The awareness of the problem has been strongest on the margins of actual SETI research. For instance, the philosopher Lewis White Beck in his Presidential Address to the American Philosophical Association stated (Beck, 1971: 13):

> I cannot take seriously the possibility of establishing the existence of extraterrestrial civilizations by the observation of artifacts other than signals (e.g., 'Dyson spheres') because it seems to me we would be irresistably tempted by Occam's Razor to explain them as natural products. Only if we had 'direct' evidence (through intelligible signals) of the existence of extraterrestrial civilizations would an artificial origin of other artifacts appear to be a plausibly simple explanation. But I grant that the comparative simplicity of two hypotheses like these is an inexact notion, and one of them may appear more plausible at one time and the other at another. The fate of the 'canals' on Mars, however, does not inspire confidence in gross artifacts as evidence of intelligent design.

Similarly, author and philosopher Stanislaw Lem wrote in his last great novel, *Fiasco*:

> Astrophysics, besides, had advanced to the point where it possessed sufficient hypotheses to 'explain' every kind of observed emission without resorting to the existence of other beings as the senders. A paradox arose: the greater the number of theories astrophysics had at its disposal, the more difficult it became to prove the authenticity of an intentional signal.

(Lem, 1987: 88. The quote pertains to the future advanced human civilization, a couple of centuries down the line.) In other words, in sharp opposition to hopes of many naïve SETI enthusiasts, we may *not* know alien manifestations when we see them – and the reason, strangely enough, might be our extra sophistication. While Lem was somewhat ironic, this is not the case with distinguished astronomer Malcolm Longair who in his monograph on galaxy formation put it in the following manner (Longair, 2008: 419):

> There is no limit to the ingenuity of astronomers and astrophysicists in finding ways of reconciling theory and observation. As more parameters are included in the models, the easier it will be to effect the reconciliation of theory with observation.

Therefore, the problem is real and should be considered in building future comprehensive methodology of the search for technosignatures, to which Cowie's paper is a valuable contribution.

[1]The original application was to pornography, which as Justice Stewart clearly acknowledged, is difficult to define in a universal *a priori* manner.

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There are some ways in which its treatment could be improved, notably in the domain of evolutionary status of cultural artefacts and philosophy of technology in general. Notably, in the rest of this note, I wish to argue for the following claims:

- There is a tendency in SETI studies, to commit the conjunction fallacy or at least comes tantalizingly close to it, when the issue of alien artefacts come up; the case of 'Oumuamua is an excellent example of this tendency.
- Contingency and non-ergodicity of cultural evolution actually make the prior case for Dyson spheres and similar mega-engineering projects much more favourable – and possibly better than the one for the local alien probes.

Exploratory engineering and conjunction

Consider that one gives you a sheet of paper with a fair description of the anomalies associated with 'Oumuamua, together with Loeb's hypothesis and its criticisms. You are subsequently asked:

> < *DESCRIPTION* >
> *Which is more probable?*

1. 'Oumuamua is an extraterrestrial artefact.
2. 'Oumuamua is an extraterrestrial artefact and it is a solar sail.

Looks familiar? Clearly, it is analogous to the famous 'Linda experiment' of Tversky and Kahneman (1983), still the most flagrant and oft-cited example of the conjunction fallacy in the literature:

> Linda is 31 years old, single, outspoken, and very bright. She majored in philosophy. As a student, she was deeply concerned with issues of discrimination and social justice, and also participated in anti-nuclear demonstrations.
> *Which is more probable?*

1. Linda is a bank teller.
2. Linda is a bank teller and is active in the feminist movement.

The description in the preamble is logically superfluous, of course. Most people get the Linda question wrong. For Tversky and Kahneman, this happens due to the heuristic dubbed *representativeness*: most people find option 2 more representative of the description, contrary to the laws of probability.

In the 'Oumuamua case, we do not have statistical data on how frequent is the error; we have, however, the attitude of both Cowie and Loeb himself that option 2 is more representative of our conceptual framing of an alien artefact. A completely unofficial poll of about a dozen astrobiologist colleagues which I conducted by email gave results even worse than the original Linda case. This is, of course, to be *less* expected from scientists closely connected with physics and astronomy (hence more accustomed to mathematical rules of probability).

It is interesting to speculate why the fallacy seems more appealing in astrobiology than in, say, economics or social psychology. Rationally speaking, it makes little or no sense in imposing representativeness on alien artefacts: we simply have no external experience whatsoever with them, in sharp contrast to bank tellers and feminists, so there are no classes of equivalence in terms of representation. Hence, the heuristics should not operate. If anything, as will be argued in the next section, we would have rational reasons to reject the representativeness of solar sails in favour of generally more advanced artefacts.

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On the other hand, Loeb's admission – cited by Cowie – that his association with the Breakthrough Initiative (which *inter alia* promotes using solar sails for interstellar propulsion) influenced his thinking is obviously a sort of bias. However, the sources of bias are also many pop-cultural description of 'alien technology' being of the kind humans possess, just a bit or two more advanced. The underlying idea here, never explicated, is that the technological evolution is everywhere ergodic: it *gradually* improves, filling up the technological design space piece by piece. This is unlikely for many reasons, some of which will be considered in the next section. For now, one should consider how actually *un*likely it would be that the very first sign of extraterrestrial intelligence we detect is just something humans could produce in ∼10–50 years from now.

It has been recognized for quite some time in SETI studies that we are predominantly likely to encounter much older cultures than ourselves – although this common-sensical assumption has surprisingly rarely been given explicit formulation (for exceptions see e.g. Ćirković and Vukotić, 2008; Kipping *et al*., 2020). One side of such a conclusion is pure common sense: whenever you are admitted to a club, it is expected that most of the members will have had much longer tenure. If you've just learnt to swim, how surprising is your observation that a random swimmer is much more experienced than you? Why this trivially obvious point drew the ire of some SETI critics is truly inexplicable (a particularly obnoxious example is Basalla, 2006).

The other side of the same conclusion is pure astrobiology, however. The seminal paper of Lineweaver (2001) concluded that (i) Earth-like planets start forming after a delay of ∼1.5 billion years after the onset of the Milky Way thin-disc star formation, and (ii) the *median* age of Earth-like planets is about $t_{\mathrm{med}} = (6.4 \pm 0.9) \times 10^9$ years, which is significantly greater than the Earth/Solar System age (about 4.56×10^9 years). Hence, a trivial application of the typicality principle would suggest that inhabitants of these other Earth-like planets – if they exist at all – have to be much older, hence they are likely to be more sophisticated than we are. Subsequent studies confirmed Lineweaver's results. Behroozi and Peeples (2015) calculate that the Solar System formed *after 80% of existing* Earth-like planets (in both the Milky Way and the Universe in general), and that we should expect $\sim 10^{20}$ Earth-like planets per Hubble volume. Erik Zackrisson and coworkers repeated Lineweaver's study of the inventory of Earth-like planets with improved models of galaxy formation and evolution. The results are striking since they *increase* the Lineweaver scale to ∼7.3 billion years for parent stars belonging to the standard F, G and K spectral types ('Sun-like stars'); if we include red dwarfs of the M spectral class – similar to the parent star of the TRAPPIST-1 system – this jumps up even further, to ∼8.4 billion years (Zackrisson *et al*., 2016).

Therefore, common sense is supported by the machinery of theoretical astrobiology: our average aliens should be *much older* than ourselves. Why would they utilize primitive technology such as solar sails then? The answer to this may be very much the same as the answer to another vexing question: Why don't we use horse chariots anymore?

Technological evolution and ergodicity

Should we expect to see solar sail-type artefacts or Dyson sphere-type artefacts in our technosignature searches? Cowie argues for the former:

> How do these extraterrestrial hypotheses fare relative to LH [Loeb's hypothesis]? Are they vulnerable to the same worries? LH fares considerably better. The most obvious difference is that the negative claim is much stronger for LH than for either KIC 8,462,852 or FRB's. For one thing, there is a broader space of unconceived alternatives with respect to both of these phenomena – obscure shading patterns across interstellar distances and unusual radio bursts – than with respect to solid, relatively small bodies like 'Oumuamua. Interestingly though, a secondary difference is that the non-conditional claim is easier to support in LH than in either KIC 8,462,852 or FRB's. What is the likelihood that there are solar-sail-like things? Compare that to the likelihood of planetsized radio transmitters or Dyson-spheres orbiting stars. This is of necessity speculative.

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> But Loeb stresses that the kind of technology required to make 'Oumuamua-like solar sails is not so far beyond our current capacities and ambitions. It is a fairly modest kind of thing. It is probably reasonably fair to assume that any species that can manufacture a Dyson sphere can manufacture an 'Oumuamua-sized solar sail, but that ability to manufacture the later does not entail ability to manufacture the former. So we could see how one might argue that, all else equal, we should have greater confidence in the existence of modest light sails than Dyson spheres.

At first glance, it is all sound and reasonable, since there is indeed a *technological asymmetry* between the builders of solar sails and the builders of Dyson spheres[2]. However, this account has a hidden assumption of ergodicity of cultural/technological evolution which is very hard to sustain – and which has not been sustained in the human experience so far.

To understand the problem, consider a terrestrial analogy. Suppose – as a kind of thought experiment – a hypothetical alien observes contemporary Earth with extremely high resolution. She/he/it sees feature A which is explainable (*hypothesis 1*) as a horse chariot of the kind used, for example, by King Darius III at the Battle of Gaugamela in 331 BC; she also sees a feature B which is explainable (*hypothesis 2*) as a jet airplane. Which hypothesis fares better? Clearly, this is another case of technological asymmetry analogous to the one used by Cowie, since a technological society which makes jet airplanes is capable of making chariots as well, but not *vice versa*; we know that on Earth the timescale is such that it took almost exactly 4000 years from the invention of chariots to the invention of jet planes (Kuznetsov, 2006)[3]. Hence, following Cowie's reasoning, we would expect Earth to abound in chariots relative to jet planes; therefore, we would have reasons to believe *hypothesis 1* faring much better than *hypothesis 2*.

Of course, to no one's surprise, the situation is exactly the opposite in reality. It is almost impossible to find a horse chariot anywhere on contemporary Earth, outside a few museums and live action role-playing events; this should be contrasted with millions of jet airplanes in operation every day. Therefore, *hypothesis 1* would fare extremely bad relative to *hypothesis 2*, no matter how likely or unlikely both are in absolute terms.

Why is this so? Clearly, technological evolution on Earth has been extremely non-ergodic. New technologies displace old ones, not add to them. In simplified terms, there is no pyramidal – or indeed any kind of highly regular – structure in terms of abundance: simple technologies being most abundant, following by more and more advanced technologies being rarer and rarer as we approach the summit of the pyramid. In contrast, new technologies displace and replace the older, more primitive ones in a discontinuous and contingent manner which looks more like a complex tree or bush than a pyramid. While older technologies are usually not entirely lost they become infrequent and exotic. (There are obviously instances of loss from time to time; for a spectacular example see Lu and Steinhardt, 2007.) That is one of the most fundamental characters of technological (and cultural, in general) evolution; there is no conceivable reason to expect that this will not be valid for extraterrestrial cultures.

Of course, another reason why observations of astroengineering artefacts such as Dyson spheres (Wright, 2020) should have priority is the literal, spatiotemporal size of the space of observers of the corresponding artefacts. The key parameter here is not the relative number of such entities (solar sails versus Dyson spheres), it is the number of potential observers of such entities. Solar sails – as any other extraterrestrial probe, essentially an alien analogue of our *Pioneers* and *Voyagers* – are observable, with reasonable improvement in our astronomical detection techniques, only by inhabitants of those planetary systems such probes are visiting. Even that is uncertain, especially in light of our detection of 'Oumuamua only *after* its perihelion passage. In other words, the region of space and time in which passage of a small alien probe coincides with a local civilization both having advanced

[2]Used here as a placeholder for any kind of astroengineering artefacts detectable over interstellar distances (cf. Ćirković, 2012; Wright, 2020).

[3]This is more than 50% of the entire age of human technological civilization; that is, more than half of the *maximal* conceivable technological asymmetry on Earth.

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astronomical techniques and (being young) does not have adequate insight into the distribution of intelligence in the Galaxy is likely to be very small. In terms often used in physical science, such an occurrence would require considerable fine tuning.

On the other hand, Dyson spheres are, arguably, detectable with the present-level or slightly more advanced astronomical techniques all over the Galaxy; this is confirmed, among other things, by *our* searches for such artefacts of astroengineering (Slysh, 1985; Jugaku *et al*., 1995; Timofeev *et al*., 2000; Jugaku and Nishimura, 2003; Carrigan, 2009), which are well-defined observational research programmes. There are well-defined research programmes (e.g. in the sense of Lakatos, 1978) even for seeking Dyson spheres in external galaxies (Griffith *et al*., 2015). This suggests that a significant fraction of the potential inhabitants of ∼75 billion Earth-like planets in the Milky Way (e.g. Lineweaver and Grether, 2003) could, in the fullness of time, observe a single Dyson sphere. On the other hand, only inhabitants of individual planetary systems which have solar sail probes – slow and inefficient by their very definition – sent to them will be able to observe such artefacts. While the Dyson sphere detectability is just a function of astronomical capacity of the observer, the solar sail detectability is mostly a function of both astronomical capacity of the observer and, crucially and inherently unknowably, the position of the observer relative to the solar sail builders. In addition, the building and operating a Dyson sphere is, of necessity, protracted temporal affair; at best, we are dealing with thousands of years for construction only. Once constructed, it is reasonable to assume that a Dyson sphere could last for millions if not billions of years, even if not actively maintained. Like the Pyramids of Egypt, some artefacts are simply too large to be easily destroyed or significantly degraded even in the presence of erosion – and are, analogously, likely to outlast the civilization of their builders (compare the discussions of the durability parameter for large terrestrial artefacts in Ćirković *et al*., 2019, and the key role of longevity in artefact searches in Balbi and Ćirković, 2021). In contrast, the late, post-perihelion discovery of 'Oumuamua and the length of its observations (ca. 2 months) are representative of short-lived, transient phenomena. Even if 'typical' solar-sail observations by inhabitants of its target planetary system are longer by an order of magnitude – which is realistic for a variety of both hyperbolic orbits and configurations of the observing instruments – it is still a difference of perhaps 6–12 orders of magnitude in favour of observing Dyson spheres. Thus, taking both spatial and temporal considerations into account, we have reasonably better chances of observing something explainable by Dyson spheres than something explainable by solar sails, *ceteris paribus*[4].

Conclusions

Better insight into the history and philosophy of technology on Earth is likely to offer improved perspective on alien artefacts as well. Somewhat ironically, especially in light of the SETI-sceptical voices of the past who often charged SETI enthusiasts with a lack of philosophical sophistication, taking that history and philosophy into account is in fact making the search for 'cosmic miracles' (Lem's term) of astroengineering more scientific and more respectable.

In this sense, Sagan's famous dictum is somewhat misleading: extraordinary claims do not require extraordinary evidence. They require as much evidence as any other scientific claim. The 'extraordinary' attribute is truly a contingent social construction of human history and culture, having nothing whatsoever to do with the physical universe out there. Claims about extraterrestrial intelligence are, on the contrary, as much claims about the physical universe and physical events and processes in it as are claims about the Higgs boson or about symmetries of the $Zn_4(Si_2O_7)(OH)_2{\cdot}H_2O$ crystal, radical social constructivism and fashionable antirealism notwithstanding. That these pernicious doctrines

[4]Obviously, some further Copernican assumption is necessary here, like the *self-sampling assumption* (e.g. Bostrom, 2002): an observer should reason as if they are randomly selected from the set of all actually existent observers in their reference class. Also, a relatively uniform development of different sub-fields of observational astronomy – e.g. optical versus infrared versus radio, etc. – is assumed.

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infected our astrobiological and SETI-related thinking tells us nothing about the Universe at large. Instead, it tells us something about the sorry state of humanity still tucked in its 'cradle of the mind' (Tsiolkovsky) and afraid to leave it.

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References

Balbi A and Ćirković MM (2021) Longevity is the key factor in the search for technosignatures. *The Astronomical Journal* **161**, 222 (11pp).

Basalla G (2006) *Intelligent Life in the Universe*. Oxford: Oxford University Press.

Beck LW (1971) Extraterrestrial intelligent life. *Proceedings of the American Philosophical Association* **45**, 5–21.

Behroozi P and Peeples MS (2015) On the history and future of cosmic planet formation. *Monthly Notices of the Royal Astronomical Society* **454**, 1811–1817.

Bialy S and Loeb A (2018) Could solar radiation pressure explain 'Oumuamua's peculiar acceleration? *Astrophysical Journal Letters* **868**, L1 (5pp).

Bostrom N (2002) *Anthropic Bias: Observation Selection Effects in Science and Philosophy*. New York: Routledge.

Carrigan RA (2009) IRAS-based whole-sky upper limit on Dyson spheres. *The Astrophysical Journal* **698**, 2075–2086.

Ćirković MM (2012) *The Astrobiological Landscape: Philosophical Foundations of the Study of Cosmic Life*. Cambridge: Cambridge University Press.

Ćirković MM and Vukotić B (2008) Astrobiological phase transition: towards resolution of Fermi's paradox. *Origins of Life and Evolution of Biospheres* **38**, 535–547.

Ćirković MM, Vukotić B and Stojanović M (2019) Persistence of technosignatures: a comment on Lingam and Loeb. *Astrobiology* **19**, 1300–1302.

Cowie C (2021) The 'Oumuamua controversy. *Nature Astronomy* **5**, 526–527.

Cowie C (2022) Arguing about extraterrestrial intelligence. *The Philosophical Quarterly* **73**, 64–83.

Griffith RL, Wright JT, Maldonado J, Povich MS, Sigurdsson S and Mullan B (2015) The Ĝ infrared search for extraterrestrial civilizations with large energy supplies. III. The reddest extended sources in WISE. *The Astrophysical Journal Supplement Series* **217**, article id. 25 (34pp).

Jugaku J and Nishimura S (2003) A search for Dyson spheres around late-type stars in the solar neighborhood. In Norris R and Stootman F (eds), *Bioastronomy 2002: Life Among the Stars, Proceedings of IAU Symposium # 213*. San Francisco: Astronomical Society of the Pacific, pp. 437–438.

Jugaku J, Noguchi K and Nishimura S (1995) A search for Dyson spheres around late-type stars in the solar neighborhood. In Seth Shostak G (ed.), *Progress in the Search for Extraterrestrial Life*. San Francisco: Astronomical Society of the Pacific, pp. 381–385.

Kipping D, Frank A and Scharf C (2020) Contact inequality: first contact will likely be with an older civilization. *International Journal of Astrobiology* **19**, 430–437.

Kuznetsov PF (2006) The emergence of bronze age chariots in Eastern Europe. *Antiquity* **80**, 638–645.

Lakatos I (1978) *The Methodology of Scientific Research Programmes: Philosophical Papers*, Vol. **1**. Cambridge: Cambridge University Press.

Lem S ([1966] 2018) *The Invincible* (translated by B. Johnston). Krakow: Pro Auctore Wojciech Zemek.

Lem S (1987) *Fiasco*. San Diego: Harcourt Brace.

Lineweaver CH (2001) An estimate of the age distribution of terrestrial planets in the universe: quantifying metallicity as a selection effect. *Icarus* **151**, 307–313.

Lineweaver CH and Grether D (2003) What fraction of sun-like stars have planets? *The Astrophysical Journal* **598**, 1350–1360.

Loeb A (2021) *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth*. London: John Murray.

Longair M (2008) *Galaxy Formation*. Berlin: Springer Verlag.

Lu PJ and Steinhardt PJ (2007) Decagonal and quasi-crystalline tilings in medieval Islamic architecture. *Science (New York, N.Y.)* **315**, 1106–1110.

Slysh VI (1985) A search in the infrared for astroengineering activity. In Papagiannis MD (ed.), *The Search for Extraterrestrial Life: Recent Developments*. Dordrecht: IAU, Reidel Publishing Co., pp. 315–319.

Timofeev MY, Kardashev NS and Promyslov VG (2000) Search of the IRAS database for evidence of Dyson spheres. *Acta Astronautica* **46**, 655–659.

Tversky A and Kahneman D (1983) Extension versus intuitive reasoning: the conjunction fallacy in probability judgment. *Psychological Review* **90**, 293–315.

Wright JT (2020) Dyson spheres. *Serbian Astronomical Journal* **200**, 1–18.

Wright JT, Haqq-Misra J, Frank A, Kopparapu R, Lingam M and Sheikh SZ (2022) The case for technosignatures: why they may be abundant, long-lived, highly detectable, and unambiguous. *The Astrophysical Journal Letters* **927**, L30.

Zackrisson E, Calissendorff P, González J, Benson A, Johansen A and Janson M (2016) Terrestrial planets across space and time. *The Astrophysical Journal* **833**, article id. 214 (12 pp).