Arguing About Extraterrestrial Intelligence[1]

Abstract: Avi Loeb has defended the hypothesis that the interstellar object, 'Oumuamua, detected in 2017, is in fact an extraterrestrial artefact. His hypothesis has been widely rejected by the scientific community. On examination however it is not clear *why*. The puzzle is at the level of argument structure. The scientific community's responses to Loeb's hypothesis appear to point to explanations of 'Oumuamua's properties that are mere possibilities. Yet this is something that Loeb does not contest. I appeal to broadly philosophical considerations to understand and bolster the response to Loeb. These considerations concern the structure of his argument, the role of prior confidences within it, and the presence of 'unconceived alternative' explanations. I then generalise. 'Oumuamua will surely not be the last object that does not admit of straightforward natural explanation and that is claimed to be evidence of an extraterrestrial artefact. I use the preceding discussion of Loeb's argument and the scientific community's response to make some general remarks for future debate about similar cases.

Keywords: Unconceived alternatives; extraterrestrial intelligence; SETI; epistemology; philosophy of astronomy.

In October 2017 an exotic object was photographed beyond earth's orbit. Given its trajectory astronomers were able to infer that the object - 1I/2017, 'Oumuamua – had originated from outside our solar system. In a series of joint-published scholarly articles and a recent public-interest monograph, Avi Loeb has defended the unorthodox hypothesis that:

> *Loeb's Hypothesis (LH)*: 'Oumuamua is an extraterrestrial artefact.[2]

This has been the subject of significant controversy. It is not unusual that exotic hypotheses concerning extraterrestrial intelligence should be proposed – and discussed on websites, blogs and popular magazines - but it *is* unusual that they should be defended in peer-reviewed publications by members of the scientific community with impeccable credentials. Yet Loeb is

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[2] See especially Bialy and Loeb 2018, and Loeb 2021. See also Siraj and Loeb 2019, Hoang and Loeb 2020.

the Frank B. Baird, Jr., Professor of Science in Harvard's Department of Astronomy and LH has been discussed in the pages of the top journals in the field including *Nature Astronomy* and the *Astrophysical Journal Letters*. So what should we make of LH?

I have two central aims. The first is to use the tools of philosophy to better understand and assess the debate between Loeb and his opponents. One of the reasons for proceeding in this way is that the structure of the debate is not at all clear. It can seem as though the various parties are arguing past one another; and in particular that the scientific community's response to Loeb begs the question against LH. My view is that approaching the debate philosophically helps us to make sense of this and ultimately to see how one could best argue against LH. The second aim is more general. In recent years there have been a number of high-profile cases that are structurally similar to LH; cases in which exotic hypotheses about extraterrestrial behaviours and technologies have been offered as explanations of puzzling astronomical phenomena for which we lack a plausible 'natural' explanation. We are likely to encounter more cases of this kind in the coming years as the search for extraterrestrial life gathers pace. In an interview to accompany his recent TED talk the astronomer – and current head of SETI – Seth Shostak claims that we should be relatively optimistic about detecting signals within the next twenty years.[3] I use LH as a case-study with this in mind; an attempt to get clear on argumentative structure, explanatory burdens and theoretical commitments when it comes to inevitable future claims to have encountered evidence of extraterrestrial intelligence.

1. The Case for LH

In 2017 a bright and rapidly rotating object about a quarter of a mile in length entered the solar system at a forty degree angle to the elliptical plane. It passed around the sun at a distance of one quarter of an astronomical unit before exiting at a velocity of nearly sixty miles per second. It is currently somewhere in interstellar space. The *orthodox view* is that this object, 'Oumuamua, is a comet or asteroid that was ejected from a nearby system and attracted to our own solar system by the sun's gravitational pull.[4] The view that 'Oumuamua is an extraterrestrial artefact (LH) is based in large part on scepticism about this orthodox view. I begin by very briefly explaining this scepticism. I do so by highlighting three respects - in order of increasing importance - in which defenders of LH have found the orthodox explanation problematic.[5]

[3] https://blog.ted.com/contact-with-aliens-by-2036-astronomer-seth-shostak-wants-to-believe-and-does/
[4] See e.g. Micheli et al 2018.
[5] This three-way categorisation is clear in Moro-Martin 2019b. See also Cowie 2021.

i. Origin and Number-Density

'Oumuamua was first detected with the Pan-STARRS telescope. While it was hoped that Pan-STARRS might detect rogue interstellar comets and asteroids, the detection of 'Oumuamua given the extremely limited search carried out by Pan-STARRS to-date suggests a significantly – i.e. orders of magnitude - higher number-density for such objects than predicted on standard models of their origins.[6] It follows that if 'Oumuamua is best understood via the orthodox explanation, then either its speedy detection was an extremely fortunate coincidence or the aforementioned standard models were badly wrong.[7]

ii. Constitution and Shape

Some of 'Oumuamua's most interesting properties concern its shape. Although it has not been possible to uniquely confirm the shape, both of the options under serious consideration are highly irregular. One option – favoured option among defenders of the orthodox view – is that it was an ellipsoid with an extreme ratio of length to width ('cigar'), typically estimated roughly 6:1 though some estimates are much greater.[8] Objects of these dimensions are peculiar. This much is common-ground between Loeb and his critics. In a recent *Nature Astronomy* article the International Space Science Institute's 'Oumuamua Team – otherwise highly critical of LH (I return to this below) – found that "[w]hile several models have been proposed to explain 'Oumuamua's very elongated shape, none can naturally match such an extreme axis ratio within a self-consistent framework." A second option with respect to 'Oumuamua's shape, also consistent with the data, is that it was an extreme oblate spheroid ('pancake').[9] This is an even more irregular shape with respect to known natural objects – and even harder to explain - yet intriguingly recent work suggests that it may even be the likelier of the two shapes. Mashchenko (2019) estimates the probability of an extreme oblate spheroid reproducing 'Oumuamua's lightcurve at 91%. With respect to shape then 'Oumuamua is something of a mystery. Loeb puts it as follows:

[6] See especially Moro-Martin 2018, 2019a. See also Do et al 2018, Trilling et al 2017 and the concluding section of Seligman et al 2019.
[7] Coupled with this is that 'Oumuamua's velocity was very close to that of the local average; a fact that limits the number of possible parent systems on orthodox models. This is discussed in Loeb 2021, 79-87 and cited as evidence against orthodox explanations by e.g. Moro Martin 2019b.
[8] See Belton et al 2018 for discussion. Siraj and Loeb 2019 provide a high estimate (up to 50:1).
[9] Belton et al 2018.

> Either way 'Oumuamua was a rarity. If it was elongated, we had never seen any naturally occurring space object that size and elongated; if it was flat, we had never seen any naturally occurring space object that size and flat.

2021, 31.

iii. Non-Gravitational Acceleration

The most important anomaly concerns acceleration. 'Oumuamua entered the solar system at an angle to the elliptical plane, passing once around the sun – reaching perihelion at 0.25 AU; that is, roughly half-way between the sun and Mercury - before accelerating outward, returning to interstellar space. The acceleration cannot be explained solely by the gravitational forces acting on it. So what could explain it? Comets from within our own solar system can behave in this way (i.e. display 'non-gravitational acceleration'). They do so when exposure to the sun's heat causes deposits of ice on their sun-facing end to melt, generating propulsion. These comets emit a tail of fine dust and gas ('outgassing') as residue from the propulsive mechanism. So if the orthodox view were correct, we would expect 'Oumuamua to have such a tail. Yet none was detected. While it is possible that this could be a mere failure of detection it is highly unlikely. As it accelerated on its outbound orbit 'Oumuamua was tracked by the Spitzer space telescope. Had outgassing occurred Spitzer would have been expected to detect a significant trail of CN, CO and CO_2. This makes the orthodox explanation for 'Oumuamua's non-gravitational acceleration problematic.[10] Again, this is largely conceded by opponents of LH, for example, Mashchenko (2019):

> The non-detection of… outgassing… needed to drive the non-gravitational acceleration of 'Oumuamua make the cometary explanation even more problematic. If 'Oumuamua is a comet in some sense, it must be a very exotic one, with its properties… being nothing like properties of Solar System comets.

And Moro-Martin et al (2019b):

> 1I/'Oumuamua is a known interstellar interloper exhibiting a non-gravitational acceleration…that cannot be accounted for by outgassing, given its lack of cometary activity and the strict upper limits to outgassing revealed by Spitzer observations...

[10] A further problem, not discussed,is that outgassing on an irregularly shaped object would likely have produced a torque with predicted visible effects on spin (e.g. Rafikov 2018, though see Seligman 2019) and subsequent constraints on 'Oumuamua's composition.

So the orthodox explanation is problematic. Number density, shape and acceleration all pose problems. As Loeb presents it, the likelihood of the orthodox explanation can be understood as the product of a series of low likelihoods concerning these variables. He estimates "one-in-a-trillion, give or take" (2021, 86). LH is presented as the alternative. Why is it a good alternative? Firstly, if we were open to the possibility of 'Oumuamua being an extraterrestrial artefact, we would have a good, ready explanation of what it might in fact be: a 'solar sail'. The basic reason for this is that the rate of 'Oumuamua's post-perihelion non-gravitational acceleration was given by the inverse square of its distance from the sun. This would be well-explained if the force exerted on it were a result of solar radiation, which varies as inverse square of distance. It would also explain the smooth nature of that acceleration; something poorly explained by outgassing from a chaotically rotating object. Indeed even some *opponents* of LH concede this. For example, in the widely cited Micheli et al (2018) the authors write:

> The simplest physical phenomenon that could cause a radial acceleration following an r^{-2} dependency and directed away from the Sun is pressure from solar radiation…[11]

The solar radiation explanation puts strict limits on 'Oumuamua's shape and constitution. Neither comets nor asteroids fit these limits. 'Oumuamua would have to be wide, flat and thin. This fits well with the 'extreme oblate spheroid' shape that represents one of the two possibilities noted above. Secondly, we should be open to the possibility of 'Oumuamua being an extraterrestrial artefact. Loeb is up-front about the role that this important claim plays in his argument. He writes:

> It is very presumptuous for us to assume that we are the only intelligence in the vast cosmos… [I]t is most likely that we will encounter relics of extraterrestrial technologies before establishing contact with any living civilisation. This must be kept in mind as we contemplate explanations for the mysterious properties of… 'Oumuamua.
> 2021, 115

Putting these thoughts together, Loeb arrives at LH

[11] See also e.g. Moro-Martin et al 2019b. As Loeb (2021) notes, his role as Chair of the Breakthrough Starshot Initiative partially explains his initial enthusiasm for the possibility that 'Oumuamua could be a solar sail.

2. The Scientific Community's Response: A Puzzle

LH has largely been rejected by the scientific community. In this section I summarise their arguments and raise a puzzle at the level of argument structure; it is not obvious how or why the arguments they offer *actually* undermine the case for LH.

The most high-profile article with the explicit aim of rejecting LH is the ISSI 'Oumuamua Team's 2019 overview piece in *Nature Astronomy*. The authors argue that LH should be rejected primarily because 'Oumuamua can be explained in natural terms. They write in conclusion:

> While 'Oumuamua presents a number of compelling questions, we have shown that each can be answered by assuming 'Oumuamua to be a natural object. Assertions that 'Oumuamua may be artificial are not justified when the wide body of current knowledge about solar system minor bodies and planetary formation is considered.

The ISSI 'Oumuamua Team is claiming that LH should be rejected because the compelling questions that 'Oumuamua poses can be answered in natural terms. On a purely methodological level this should give us pause for thought. Are the authors merely claiming that it is *in principle possible* to provide natural explanations for each of 'Oumuamua's peculiarities or that we should be *confident* in some such explanation *for each*, or that we should be *confident* in such an explanation *for all together*? Surely to be effective against LH the authors would need to make the latter, stronger claim. After all, Loeb's rejection of the orthodox explanation is based on its improbability and is perfectly consistent with the in principle possibility of natural explanations of all of its properties. He just thinks the probability is very, very low. This is especially clear in the following passage:

> Using very conservative probabilities, based on its shape, rotation and luminosity alone, a cometary 'Oumuamua would be a one-in-a-million naturally occurring object. Attempt to explain its composition so that we can explain its deviation beyond solar gravity by outgassing that was invisible to our instruments and you still have an object that is as rare as one in thousands. But that's not all… 'Oumuamua's spin rate didn't change… Maybe just one in every thousand comets keeps a steady spin… we're now talking about a one-in-a-billion object. Then there's its lack of jerks. If there was naturally occurring outgassing… that's another one-in-a-thousand coincidence, 'Oumuamua is now one in a trillion.

2021, 86.

It is curious then that when we look in detail at the ISSI 'Oumuamua Team's article, it seems that they make only the weaker of these claims; that it is in principle possible that each property can be explained in natural terms. As a simple illustration of this, note that the lengthy penultimate section of the ISSI paper entitled 'open questions' includes three sub-sections; one concerning 'Oumuamua's shape, one its rotation and one its origin. These three features of 'Oumuamua, the team contend, remain open questions – we don't really know what to say about them. But if these all remain open questions, then it is very problematic indeed to claim that natural explanations of 'Oumuamua have been shown to be compelling in any way. After all, shape, rotation and origin are three of its most interesting properties; and three of the properties that animate the case for LH.

This worry is strengthened when we think about the most important issue: non-gravitational acceleration. Here, the explanations considered by the ISSI Team are very much presented as 'possibles' and are perfectly consistent with an overall low confidence. Their central idea is that 'Oumuamua could have been driven by the effects of the sun's heat on its exposed ice in a fashion that is reconcilable with the lack of detected outgassing. In defending this view, several issues must be addressed. A preliminary issue is the failure to detect a *dust* trail, as would be expected. The ISSI 'Oumuamua Team note that while unusual, the lack of a detectable dust trail on comets is not unique; this is also true of 2P/Encke. The main issue concerns the outgassed H_2O, and carbons (CN, CO, CO_2) that drive ordinary cometary non-gravitational acceleration. Here, the ISSI 'Oumuamua Team's central idea is that because the failure to detect outgassed *H_2O* is not mysterious – the observations made were not sensitive enough to expect this to have been detected – it is likely that this was the primary driver of the non-gravitational acceleration, leaving only the problem of the non-detection of relevant carbons (CN, CO, CO_2), which one *would* have expected to be detected. This could be explained by supposing that 'Oumuamua's acceleration was the result of an unusually high ratio of H_2O to carbons. Two issues now arise. One is *how* unusual the required ratio would be. The other is *why* 'Oumuamua would have this unusual ratio. With respect to the *how* question, the ISSI Team's claim is that the CO "limit is within the range of measurements for known comets" whereas "the CO_2 upper limit is about an order of magnitude lower." With respect to the *why* question, the central idea seems to be – though this requires some interpretation – that "Oumuamua may have had an unusually depleted store of carbons owing to "repeated passages close to its host star before being ejected."

With these answers in mind, return to the question of what the ISSI 'Oumuamua Team show: do they establish the weaker conclusion that natural explanations of each of 'Oumuamua's peculiarities are in principle possible, or the stronger conclusion that natural explanations are in the round actually compelling? The answer appears to be the former. While they may succeed in showing that there *could* be natural explanations of each of 'Oumuamua's peculiarities, it is much less clear that they show that an overall natural explanation is in any way compelling; as we have seen above, with respect to outgassing alone (i.e. setting aside the three 'open questions') the ISSI 'Oumuamua Team's proposed explanation posits a CO_2 limit *an order of magnitude* out from anything presently known, caused by unevidenced, conjectured repeated passages around an unidentified home system. This is very much more of a 'possible' than a 'probable'.[12] And it's not just the ISSI 'Oumuamua Team who argue in this way. We can see a somewhat similar structure in the closing discussion of one of the other high-profile articles to explicitly discuss – and reject – LH: Seligman et al 2018. The closing discussion of this article, much like that of the ISSI 'Oumuamua Team, is perfectly consistent with the probabilistic premise behind LH; namely, that 'Oumuamua's non-gravitational behaviour, whilst *possibly* explicable in natural terms, is nonetheless a serious outlier in a number of respects. Seligman et al note, for example, that their explanation requires that 'Oumuamua's carbon to oxygen ratio was unusually low, that the percentage of mass that it must have lost on this model was unusually high, and that the number-density of comparable objects must be several orders of magnitude greater than expected.

So what is going on? Perhaps the issue is that I am missing another aspect of the case against LH. It concerns Loeb's 'solar sail hypothesis'. The solar sail hypothesis is supposed to explain 'Oumuamua's non-gravitational acceleration, which appeared to be both smooth and given by the inverse square of solar distance. The ISSI 'Oumuamua Team note however that the solar sail hypothesis could explain 'Oumuamua's smooth non-gravitational acceleration only if the sail were directly facing the sun for the duration of its period of acceleration. Yet we know that 'Oumuamua experienced significant rotation given its brightness variations, as observed from earth. So it was not facing the sun for the duration. So it cannot explain what it is meant to, or that explanation is at best very imperfect. Although the point is well-taken and strengthens the case against LH, I do not think this can be the whole story; at least if the whole story is a

[12] Compare also the ISSI Team's consideration of the hypothesis that outgassing was delayed owing to gasses being trapped beneath its surface.

persuasive case against LH. This is in part because, while there are problems with the solar sail explanation, it also fares well in other respects; respects that have since come to light. In September 2020 an object – 2020 SO – was detected by Pan STARRS. Like 'Oumuamua, it displayed non-gravitational acceleration in the absence of expected outgassing. The object was found to be a stray rocket booster; a leftover from a decades old crash-landing on the Moon. As Loeb notes in a recent essay on the subject, this lends some credence to the theory that if we allow that 'Oumuamua could have been an artefact, we would have a decent explanation of its behaviour.[13] We can, he writes, distinguish "thin artificial objects with a large surface-to-mass ratio from natural objects based on their excess push away from the sun without a cometary tail." Put slightly differently, although there are problems with the solar sail explanation, the basic idea – that 'Oumuamua's behaviour would be reasonably well explained if it were artificial, along roughly the lines of the solar sail hypothesis – has some existing support. 2020 SO's non-gravitational acceleration did indeed turn out to be, as hypothesised, a thin artificial material. Yet in the case of 'Oumuamua, we know that the object *did not* originate in the solar system.

So there appears to be a puzzle. How, if at all, does the scientific community's case against LH actually undermine LH? Perhaps the puzzle is illusory. It *could* be that the scientific community is simply being overly modest in how it states its conclusions, and it does in fact successfully establish that natural explanations of 'Oumuamua are much more than a mere possibility. I think there is probably some truth to this. I shall simply assume however in what follows that some significant questions marks really do remain with respect to 'Oumuamua's properties; question-marks one could legitimately point to in defending LH. I think this assumption is fair given the foregoing discussion. It is also useful given my more general aim. There will surely be future cases in which the scientific community's best explanations of puzzling phenomena *are* problematic and do not rise above the merely possible. I am interested in what we should say in such cases. The remarks I make below, as I note in conclusion, generalise to these future cases.

3. Making Sense of Things

I identify two important claims that are not explicit in the scientific community's case against LH but that would help to warrant their lack of uptake with respect to LH. The first concerns the priors in the case for LH. The second concerns the role of 'unconceived alternatives'.

[13] Avi Loeb. 'Let's Search for Alien Probes, not Just Alien Signals'. *Scientific American*, December 22nd, 2020.

First Claim: The Priors for LH

The case for LH rests on two claims. The first is that the prospects for 'natural' explanations of 'Oumuamua fare badly. This is *the negative claim*. The second is that the prospects for 'extraterrestrial' explanations don't fare so badly. This is *the positive claim*. The positive claim is based on two sub-claims, each of which is important. The first is a conditional claim:

(1) If 'Oumuamua were an extraterrestrial artefact (specifically, a solar sail), we could explain its behaviour quite well.

This is clearly important. The fact that we *could* explain 'Oumuamua's properties if it were an extraterrestrial artefact is part of the case for LH. If we couldn't explain 'Oumuamua's properties on the assumption that it were an extraterrestrial artefact, then LH would have no appeal. Equally though, I think LH must rely on something like the following 'prior':

(2) The prospects of encountering extraterrestrial artefacts of this kind in the solar system are fair.

This is important because unless the prospects of encountering such a thing were fair, the resulting explanation would not be a good one. Consider an analogy. My grandfather always enjoyed listening to church music in the house. I do not. I come home one day and am surprised to hear church music playing. Might a good explanation be that my grandfather is in the house? Certainly, if he were in the house, I could explain the phenomenon very well. So can we conclude that the hypothesis that my grandfather is in the house is a good one? We cannot. My grandfather is long dead. So it is not a good explanation at all. Similarly, LH would not be a good explanation unless the prospects for encountering an extraterrestrial artefact were fair. But a serious problem now arises for a defender of LH: it is very difficult indeed to establish (2). We have very little idea how much intelligent life – if any, ourselves excluded - there is in the galaxy, let alone whether any of it manufactures artefacts, let alone whether it has sent those artefacts to other systems. So we cannot sensibly estimate the prospects for encountering extraterrestial artefacts in the solar system. So we lack justification for thinking the prospects are fair or good. Note that the claim being made here is very weak. It is *not* that the prospects are poor. It is that they are unknown. Yet this very weak claim is still enough to show that one ought not to accept LH given our current information. Why? It depends on the structure of the argument for LH; and there are several candidates. The case for LH could be either a *contrastive inference to the best* *explanation* or an *argument from elimination*. Let's take each in turn and show, for each, why our ignorance about (2) undermines the case for LH.

Suppose firstly that the case for LH is a *contrastive inference to the best explanation*. By this I mean that the case for LH is simply that the prospects for an 'extraterrestrial explanation' are better than the prospects for a natural explanation, where these are the only two options. Now suppose, as I have claimed above, that we cannot establish (2) due to uncertainty. It follows that we cannot establish how good the prospects are for an extraterrestrial explanation of 'Oumuamua. And it follows from this that we cannot conclude that the prospects for an extraterrestrial explanation of 'Oumuamua are better than the prospects for a natural explanation. So a contrastive inference to the best explanation doesn't justify LH as a conclusion. So, if the case for LH takes the form of a contrastive inference to the best explanation then uncertainty about (2) fatally undermines the case for LH.

Consider the following objection on behalf of a defender of LH. 'The above argument isn't good for the scientific community - it is *bad* for them! Suppose you are right that we are uncertain about (2). It follows, as you say, that we can't say that an extraterrestrial explanation of 'Oumuamua is better than a natural explanation. But equally we can't say it's worse. This is surely *bad* news for the scientific community.' This objection certainly sounds concerning but this is, in large part, I think, because it is easily over-interpreted. If it is claimed that we can't say of two competing explanations of some phenomenon that one is better than the other, then it is natural to infer that they are equally good or that the other one is better. And so it is easy to hear the above objection as claiming that with respect to 'Oumuamua, for all we know there's an *equally good chance* that the extraterrestrial explanation and the natural explanation respectively are true. It is easy to hear it as claiming that it's 'fifty-fifty' and that we should suspend judgment between the two competing explanations in light of this. But while in some cases that inference would be valid, in this case it would not. If you have *very little idea* how good a candidate explanation of some phenomenon is, then you can't infer that it is as good as or better than the alternative. The inference would be a bad one. And we have very little idea about one of the key priors for LH. So we have very little idea how good an explanation LH is. Saying *that* doesn't strike me as bad news for the scientific community at all.

Suppose secondly that the case for LH is an *argument from elimination*. So understood, the argument for LH is based on eliminating the candidate natural explanations of 'Oumuamua and showing that the extraterrestrial explanation remains the only viable option, however unlikely. Loeb actually characterises the case for LH in this way:

> It is an exotic hypothesis, without question... [B]ut... I went down a logical route... followed the evidence and in the grand tradition of the detective work of science... hewed closely to a maxim of Sherlock Holmes: 'When you have eliminated the impossible, whatever remains, however improbable, must be the truth. Hence out hypothesis: 'Oumuamua must be artificial.
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> 2021, 67

If this were the argument for LH, then - one might think - the uncertainty surrounding (2) would be less significant. All that would matter would be whether there was a good case *against* natural explanations; and this is quite independent of (2). So – one might think - the eliminative argument for LH would still go through unscathed and our uncertainty about (2) would be beside the point. But this would be too quick. The uncertainty surrounding (2) makes trouble for an eliminative case for LH too, just as it does for a contrastive inference to the best explanation. Why? Arguments from elimination can easily be misused. Suppose that some strange phenomenon puzzles scientists and, in an attempt to solve it, an exhaustive list of ten possible explanations is devised. Each of the first nine is assessed on its merits, found to be deeply problematic and so eliminated. The tenth option is taken to be correct via elimination. This might sound like an excellent instance of eliminative reasoning but in fact it is problematic. The problem is that the tenth option may, when considered on *its* merits, be even worse than some or all of the preceding nine. Generally, one should not argue for an hypothesis by elimination if there is a reasonable likelihood that this hypothesis is (independently) worse than at least one of the eliminated options. Now think about (2). The worry is that it may be worse. That is a real possibility. To test this we must ask whether our most pessimistic reasonable guesses at the prospects for encountering extraterrestrial artefacts would render LH a worse hypothesis than the alternative. If they would, then we shouldn't argue by elimination in this case. So let's ask: what is the reasonable *lower bound* for the prospects for encountering extraterrestrial artefacts in the solar system given our limited information? I am willing to be corrected on this, but I think it is pretty clearly low enough that it debars the use of argument from elimination. This is because, while there are stories that could be told that would make the prospects for extraterrestrial encounters very good indeed, there are also no-less-reasonable stories - given our current information - that could be told that would make the prospects very poor indeed. Consider, to take just one example, a recent *Astrobiology* study (Snyder-Beattie et al 2021) concerning likelihoods for the emergence of extraterrestrial intelligence in the galaxy at large. The estimates are derived from the pair of (a) extremely conservative estimates of evolutionary transition times for the each of the stages needed to produce intelligent life from initial conditions, and (b) habitability time-frames for planets given the lifetimes of their stars. The resulting distribution is one in which more than 99% of calculated outcomes entail a likelihood of significantly less than 1% for the emergence of intelligent life on an earth-age planet. Furthermore, a significant likelihood is assigned to outcomes in which the number of earth age planets that produce intelligent life is as low as one-in-the-number-of-stars-in-the-galaxy. These are the kinds of estimates that form lower bounds. And they are surely low enough that the prospects for encountering ectraterrestrial life in our solar system are very poor. And so we shouldn't argue by elimination.

As an extension to this note even if there *were* a lot of intelligent extraterrestrial life in the galaxy, the epistemically reasonable lower bound for the prospects of *encountering* it may still be very poor. Consider: We (humans) are detectable life who have not only manufactured artefacts but have even sent some of our own artefacts (e.g. Voyager 2) beyond the limits of our solar system. Now suppose there were a million planets each of which was home to a species like ours, randomly distributed throughout the galaxy, each of which sent out its own equivalent to Voyager 2. What would the prospects be for encountering one at some point in the lifetime of our species? Plausibly very poor: space is enormous and Voyager 2 is tiny. So there are scenarios in which even if there were a huge amount of life that is not only detectable but has also actually manufactured space-faring artefacts, the prospects for encountering such an artefact would be negligible. Now of course there are equally reasonable scenarios that are much more optimistic. For example, there might be highly-advanced species that manufacture millions of unmissably enormous space-faring artefacts.[14] Or perhaps our very existence makes us a point of cosmic interest that increases the likelihood of extraterrestrial probes being sent in our direction. This is all fine. But the issue here is whether we can argue by elimination. And what matters for this is not the best-case scenario; the most optimistic scenario. It is rather whether the lower reasonable bound, given our present uncertainty, is low enough to make argument by elimination a bad strategy. And it pretty clearly is.

[14] This possibility (i.e. of even one species that possess the capability and intention to colonise the galaxy) is a standard problem for simple solutions to discussions of the Fermi paradox. See Cirkovic 2018.

So uncertainty about (2) fatally undermines the case for LH, whether it takes the form of a contrastive inference to the best explanation, or an argument from elimination. This is the first of my two claims; claims that are intended to explain how the scientific community would warrantedly respond to LH. Before moving on to the second claim, I want to briefly explore a somewhat speculative extension of the first claim. So far my argument has been modest. It merely states that the prospects for encountering extraterrestrial artefacts are highly uncertain. An inference has *not* been drawn from this uncertainty to a default low confidence in the prospects encountering extraterrestrial artefacts. But *might* one attempt to draw this inference? If so, this would certainly bolster the scientific community's case against LH. I am somewhat sceptical of this approach and – given the availability of the weaker argument my case does not depend on it – but it is worth putting on the table. I take my lead from a fascinating recent metastudy concerning the amount of detectable life in the galaxy. The purpose of the study is to use a statistical technique designed to generate a probability distribution for some outcome of interest, where very little is known about the values of the variables that determine the outcome. The test – a monte-carlo test - assigns maximally conservative values as upper and lower bounds for each of the relevant variables.[15] No assumptions beyond this are made about the shape of the distribution. Values between those bounds are then randomly assigned to each variable and a value for the outcome computed by inputting these values to the function from the variables to the outcome. This process is performed a large number of times, generating a large number of outcomes. The total set of outcomes can then be understood as a *distribution* for the outcome, based only on the upper and lower limits set at the start. This test is very imperfect but it generates a best guess at a probability distribution for an outcome given a thoroughgoing lack of knowledge with respect to the values and distributions of values of its variables. So it seems like the right kind of test to use if one is trying to generate a probability distribution for something like the spread of intelligent life in the galaxy. What result does it give? The study takes as its outcome of interest the number of detectable civilisations in the galaxy ('N') – excluding ourselves - and as its variables those that comprise 'the Drake Equation'. [16] The upper and lower bounds for the variables are those given by the large literature on the equation. As such, the resulting distribution is (intended as) a best-guess of the scientific community at large. The result of the monte-carlo test is a median value of $N = 0.32$, with a probability of $N < 1$ of 52%, and a 38% confidence in a value of N that is so low that, extrapolating, the odds would be against any non-human detectable life in the observable universe (let alone the galaxy). Suffice to say that if

[15] Compare Forgan 2009. See also Forgan 2019 (especially chapter 6).
[16] See e.g. Vokch, D. and Dowd, M. 2015.

we work with these values the prospects for encountering extraterrestrial life in our solar system are not good. So while I would prefer to simply say that *we don't know* within very wide limits what the prospects are for encountering extraterrestrial life in the solar system, if we were forced to attempt to assign a best-guess value, I would go low.

Second Claim: Unconceived Alternatives

The case for LH rests on two claims: one negative, one positive. Having targeted the positive claim above, I now target the negative claim. E should be more optimistic about the prospects for natural explanations of 'Oumuamua than we may at first think.

Scientific history suggests that when the existing menu of explanations of some phenomenon appears unsatisfactory, we should take seriously that there might be an explanation that we have yet to consider: an 'unconceived alternative'.[17] This is true in the case of 'Oumuamua. The alternative would lie in the space of *natural but non-orthodox explanations* of 'Oumuamua. These are explanations according to which 'Oumuamua is natural as opposed to an extraterrestial artefact, but not – as per orthodox explanations – a comet or asteroid of the sort that we are familiar with from our own solar system.

To see why we should be optimistic about this, let's start by thinking about when one should have confidence in the existence of unconceived alternative explanations quite generally. Most obviously, one's confidence should be dependent on the *comprehensiveness* of our understanding of the relevant domain. In some domains our understanding is pretty comprehensive and we know that; we know which explanations are available and which are not. For example, suppose that we are trying to determine why a bridge collapsed. Here we know roughly what options we can expect. But in some domains we know that there is lots that we don't know, and can reasonably expect the answer to lie in that space. Fundamental physics is an obvious example. What about small-body astronomical phenomena beyond our solar system? Here our understanding is limited – more than fundamental physics, less than a bridge - and so confidence in unconceived alternative explanations of phenomena should be non-negligible. And plausibly, it should be fairly significant. In private correspondence, Karen Meech, an astronomer – and critic of LH - provides a nice example to motivate this thought. She writes of 'Oumuamua:

[17] See in particular Stanford 2006 and as applied to extraterrestrial life Vickers 2020.

> One example: Shape: we have never seen anything this size that is <u>this</u> long or <u>this</u> flat. True. What [LH] leaves out is that we have almost never studied things this size before because they are too faint and / or the investment in telescope time has not been deemed worthwhile. The first time anyone saw the moon of Saturn (Pan) - it was *bizzare*... We had *never* seen anything like it and had no theories of formation.... until a lot of people did simulations and developed theories that could reproduce the shape.

The basic point comes across clearly. Pan is a recent case in which a small-body astronomical object with properties that we hadn't seen before and that we couldn't at first explain, was subsequently modelled as a natural object. The more general thought is that there are likely to be strange (small-body astronomical) objects out there that we haven't come across and that require as-of-yet unconceived alternative natural explanations. It certainly isn't a stretch to say that we should *expect* such things. And note also that Pan isn't just a case of an unconceived alternative in recent small-body astronomy. It is a case that is similar to 'Oumuamua in some interesting respects; most obviously, it is a faint, flat-ish pancake shaped object of the same order of magnitude size-wise. So even a scientist who was fairly conservative about the prospects for unconceived alternatives in small-body astronomy could and should be relatively unsurprised if it turned out that there were bodies that are somewhat like 'Oumuamua but for which we presently lack an explanation.

What does this mean for the case against LH? The case against LH is dependent on the prospects for natural explanations of 'Oumuamua being poor. Loeb argues for this primarily by considering orthodox candidates (a comet or asteroid of broadly familiar kinds) and showing that they face serious problems. But if there is a serious possibility of an unconceived alternative explanation, then poor prospects for orthodox explanations doesn't entail poor prospects for natural explanations. This undermines the case for LH whether read as a contrastive inference to the best explanation or an argument from elimination. Suppose first of all that it is an argument from elimination. The case for LH almost certainly fails. It fails because we won't be in a position to eliminate an unconceived alternative explanation – and so a natural explanation - in this case. Suppose secondly that the case for LH is a contrastive inference to the best explanation. The possibility of an unconceived alternative weakens Loeb's negative claim by driving up the prospects for natural explanations, and thereby requires the positive claim for LH to work harder if it is to be the better prospect. And as I argued in the previous section when discussing the uncertainty in (2), this isn't something a defender of LH should want. So we wouldn't need to have very much confidence in unconceived explanations at all in order to make a defender of LH uncomfortable.

Consider the following line of objection: 'Doesn't the appeal to unconceived natural alternatives effectively write opponents of LH a blank cheque to 'explain' 'Oumuamua in natural terms? Doesn't it thereby make natural explanations pretty-well unfalsifiable? And isn't that a clearly problematic – not to mention question-begging – approach?' It is true that the appeal to unconceived natural alternatives effectively writes opponents of LH a blank cheque *to some degree* but this is reasonable. It is reasonable because there are plenty of previous cases in which we have provided natural explanations of phenomena that we were previously unable to explain. This is true in the history of science quite generally. But it is also true in the study of astronomical phenomena more specifically. I mentioned the case of Pan above. But interestingly, there are plenty of historical cases in which natural explanations - that were not initially available - have been found for phenomena that could at the time have been explained as *extraterrestrial life*. This point holds not just of 'technosignatures' but also of more mundane signatures of extraterrestrial life - 'biosignatures' - that have since been explained in abiotic terms. The Alan Hills meteorite fragment is just one prominent recent example. So there are inductive grounds for leaving a not insignificant space for the possibility of natural, as-of-yet unconceived explanations. This does not mean that natural explanations are unfalsifiable or that we should always have more confidence in any natural explanation than any alternative. I return to this in conclusion.

4. More General Lessons

'Oumuamua will not be the first of its kind. There will be more cases in which some astronomical phenomenon is found for which natural explanations are hard to find, and some more exotic explanation is suggested. The above discussion is interesting in part as a basis from which to generalise about these future cases. In the final section of this article I attempt out draw out three such general points.

First General Point: The Structure of Arguments for Extraterrestrial Hypotheses

The preceding discussion of 'Oumuamua and LH allows us to formulate a general model for similar hypotheses. Hypotheses that some phenomenon is best explained by extraterrestrial technology or artefacts - *the extraterrestrial hypothesis* - will draw a contrast between natural and extraterrestrial explanations of a target phenomenon. They will consist of a *negative claim* to the effect that the prospects for a plausible natural explanation are poor, and a *positive claim* to the effect that the phenomenon is explained as an extraterrestrial artefact or technology. This positive claim is itself the result of two sub-claims. The first – *the conditional claim* - is that if there were extraterrestrial technologies or artefacts of the relevant kind, we could explain the phenomenon. The second – *the non-conditional claim* - is that it is reasonable to have the requisite degree of confidence that there are such extraterrestrial technologies or artefacts for us to encounter. Extraterrestrial hypotheses will attempt to make both the negative claim and the positive claim as strong as possible. They can then arrange them as either eliminative arguments or contrastive inference to the best explanations. The former is appealing in that it puts the burden on one's opponent but it faces a general methodological problem. Eliminative arguments can be abused, most obviously in cases in which all of the available options have low independent probabilities.

Consider some recent cases that have this general form.

> *KIC 8462852*: In 2015, the Kepler space telescope discovered an unusual pattern of light variation ('flickering') on star KIC 8462852; a pattern not readily explained by the obscuring of the star by a sufficiently large orbiting planet. It was hypothesised that the unusual light pattern was caused by enormous, artificial light absorbing structures known as 'Dyson spheres'.[18]

> *FRB's*: In 2019 the Canadian Hydrogen Intensity Mapping Experiment (Chime) detected thirteen 'flash radio bursts' (FRB's) in a regular distribution pattern at unusually low frequencies. It was hypothesised that the bursts were caused by powerful, artificial, extraterrestrial radio transmitters.[19]

The hypotheses in these cases have a similar structure to that for LH. Each moves from the seeming lack of existing natural explanation of some phenomenon, coupled with a positive claim about its nature as some specific extraterrestrial technology to the extraterrestrial hypothesis.

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[18] See e.g. Dyson 1960 and Ksanfomality and Tavrov 2017.
[19] See e.g. The CHIME/FRB Collaboration 2019. See also Lingam and Loeb 2017a and Loeb 2020.

How do these extraterrestrial hypotheses fare relative to LH? 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 8462852 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 positive claim is easier to support in LH than in either KIC 8462852 or FRB's. Focus on the non-conditional claim. What is the likelihood that there are solar-sail-like things? Compare that to the likelihood of planet-sized radio-transmitters or Dyson-spheres orbiting stars. This is of necessity speculative. 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.

Second General Point: Arguing Against Hypotheses Like LH

Perhaps the most interesting general lesson concerns the nature and structure of *responses* to extraterrestrial hypotheses. As we saw earlier, it wasn't entirely obvious how the scientific community's response to LH was meant to work at the structural level; it consisted in *possibilities* for 'Oumuamua's nature that – taken at face value – looked compatible with Loeb's case for LH. My strategy has been to provide supplements to this response concerning the priors for LH and the possibility of unconceived alternatives. It may be that these supplements are already assumed – but quietly - in the scientific community's case against LH. They were certainly not apparent in the literature. Why is this and what general lessons can we take from it?

One might think that 'good science' should focus on the phenomena as they are. And so when we think about 'the claim that some puzzling object is an extraterrestrial artefact, we should attempt to defang it by doing exactly that; by studying the data and trying to build a model that explains it. The first of these claims may be true. Perhaps good science does have this focus. I'm not sure. But the second I think is less obviously true. I am not convinced that it will be *possible* to defang extraterrestrial hypotheses by focusing *just* on the phenomena as we find them. It may not be. The phenomena may leave us genuinely neutral (or worse!) between natural and extraterrestrial explanations respectively. It is, I think, a live possibility that in some cases at least if one wants to argue against an extraterrestrial hypothesis it will be necessary to enter into murkier and more philosophical territory, such as thinking about the status of dubious priors concerning encounters with extraterrestrial artefacts in the solar system. This is worth bearing in mind for future similar cases. Being somewhat cynical, if I wanted to provide a rhetorically successful argument for having encountered evidence of extraterrestrial intelligence – and to be very clear I am emphatically not accusing Loeb of this - I would highlight the shortcomings of the existing natural explanations of some phenomenon, while quietly relying on the scientific community's reticence to engage with more speculative and methodological suppositions on which my own case was based. And if I wanted to challenge such an argument – as I have done above – I would in part at least go on the attack by highlighting the positive claims on which the extraterrestrial hypothesis was based and disputing my opponent's entitlement to them given the structure of argument they are using.

Could an Hypothesis Like LH Succeed?

Perhaps this sounds too negative; as though I assume that all extraterrestrial hypotheses will be false and must be debunked. I do not assume this. However, the preceding considerations certainly point in a generally negative direction. Given the difficulty of coming up with an unambiguously strong positive case for the extraterrestrial hypothesis, it will surely be difficult to successfully defend an extraterrestrial hypothesis without showing that the prospects for natural explanations are really very poor. And given uncertainty and the existence of unconceived alternatives, it will be very difficult to do this. In this sense I agree with Carl Sagan's famous dictum that extraordinary claims require extraordinary evidence. However, the preceding discussion of LH can help to direct us toward developments that might help. Firstly, searching for evidence that could help to confirm the presence of extraterrestrial intelligence isn't *just* a matter of building bigger telescopes that can see (and listen) further. In discussing LH we saw that one of the barriers to reasonable confidence in such an exotic hypothesis is the existence of a large space of unconceived alternatives. To the extent that we can form a more complete and well-confirmed picture of the (astro)physical universe around us, this space shrinks and the proximity of viable options within it increases. So narrowing the space for unconceived alternatives should be a priority for SETI enthusiasts. A corollary of this, of course, is that in gaining the astronomical knowledge and understanding that allows us to narrow this space we will likely lower number of cases in which we are genuinely unable to provide natural explanations of any target phenomenon. A second even more intriguing development may come from the ongoing searches for evidence of *microbial* life in our solar system, most obviously Perseverance's current search for fossilised life in the ancient aqueous environments of Mars. Suppose that this mission succeeds. This could dramatically shift reasonable confidence *upwards* with respect to the sheer quantity of life in the universe. A significant enough increase in this confidence could shift confidence with respect to the quantity of *detectabl*e life too.[20] This is of course speculative. It is contestable *both* whether finding microbial life in our solar system should lead to upwards revisions of estimates about the preponderance of life in the universe as a whole, *and* whether any such revisions should drive up confidence in finding detectable or artefact manufacturing life. These are interesting questions for another day. My point is simply that there are some interesting respects, highlighted by the foregoing discussion of LH's shortcomings, in which scientific and technological progress could contribute to reasonable optimism about the ongoing search.

References

Belton, et al. 2017. The Excited Spin State of 1I/2017 U1 "Oumuamua. *The Astrophysical Journal Letters* 856(L21).

Bialy, S. and Loeb, A. 2018. Could Solar Radiation Pressure Explain "Oumuamua's Peculiar Acceleration? *Astrophysical Journal Letters* 868(L1).

Bostrom, N. 2008. Where Are They? *MIT Technology Review*. April 22nd.

CHIME/FRB Collaboration., Amiri, M., Bandura, K. *et al.* 2019. A second source of repeating fast radio bursts. *Nature* 566 235–238.

Cirkovic, M. 2018. The Great Silence: *The Science and Philosophy of Fermi's Paradox*. Oxford: Oxford University Press.

Cowie, C. The Oumuamua Controversy: A Philosophical Perspective. *Nature Astronomy* 5: 526-527.

Do, A., Tucker, M. A., & Tonry, J. 2018. Interstellar Interlopers: Number Density and the Origins of "Oumuamua-Like Objects. *Astrophysical Journal Letters* 855(L10).

Dyson, FJ. 1960. Search for artificial stellar sources of infrared radiation. *Science* 131(3414): 1667–1668.

[20] Compare Bostrom 2008 for an interesting perspective on the significance of this.

Forgan, Duncan. 2009. A Numerical Testbed for Hypotheses of Extraterrestrial Intelligence. *International Journal of Astrobiology* 8: 121-131.

Forgan, Duncan. 2019. *Solving Fermi's Paradox*. Cambridge University Press.

Gaidos, E. Williams, J. and Kraus, A. 2017. Origin of Interstellar Object A/2017 U1 in a Nearby Young Stellar Association?. *Research Notes of the American Astronomical Society* 1(13).

Hoang, T. and Loeb, A. 2020. Destruction of Molecular Hydrogen Ice and Implications for 1I/2017 U1 ("Oumuamua). *Astrophysical Journal Letters* 899(L23).

ISSI 'Oumuamua Team., Bannister, M.T., Bhandare, A. *et al.* 2019. The natural history of "Oumuamua. *Nature Astronomy* 3**:** 594–602.

Jackson, A. and Desch, S. 2021. 1I/"Oumuamua as an N_2 Ice Fragment of an exo-Pluto Surface: I. Size and Compositional Constraints. *JGR Planets* 126(5).

Ksanfomality, LV., and Tavrov, AV. 2017. Heritage of the *Kepler* mission: Special object KIC 8462852 and criticism of the cometary hypothesis. *Solar System Research* 51: 422–435.

Lin, H., Gonzalez Abad, G., Loeb, A. 2014. Detecting Industrial Pollution in the Atmospheres of Earth-Like Exoplanets. *Astrophysical Journal Letters* 792(L7).

Lingam, M. and Loeb, A. 2017a. Fast Radio Bursts from Extragalactic Light Sails. *Astrophysical Journal Letters* 837(L23).

Lingam, M. and Loeb, A. 2017b. Natural and Artificial Spectral Edges in Exoplanets. *Monthly Notices of the Royal Astronomical Society* 470(1): 82-86.

Lingam, M. and Loeb, A. 2019. Relative Likelihood of Success in the Search for Primitive versus Intelligent Extraterrestrial Life. *Astrobiology*. Online first: https://doi.org/10.1089/ast.2018.1936

Loeb, A. 2020. An Audacious Explanation for Fast Radio Bursts. *Scientific American* (June 24th).

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

Mashchenko, S. 2019. Modelling the light curve of "Oumuamua: evidence for torque and disc-like shape. *Monthly Notices of the Royal Astronomical Society* 489(3): 3003-3021.

Micheli, M., Farnocchia, D., Meech, K.J. *et al.* 2018. Non-gravitational acceleration in the trajectory of 1I/2017 U1 ("Oumuamua). *Nature* 559(7713): 223-226.

Moro-Martin, A. 2018. Origin of 1I/"Oumuamua. I. An Ejected Protoplanetary Disk Object? *The Astrophysical Journal Letters*. 866(L131).

Moro-Martin, A. 2019a. Origin of 1I/"Oumuamua. II. An Ejected Exo-Oort Cloud Object? *The Astrophysical Journal Letters* 157(L86).

Moro-Martin, A. 2019b. Could "Oumuamua be an Icy Fractal Aggregate?. *The Astrophysical Journal Letters* 872(L32).

Pearce, L. et al. 2021. Boyajian's Star B: The co-moving companion to KIC 8462852 A. *Astrophysical Journal*. arXiv:2101.06313.

Rafikov, RR. 2018. Spin Evolution and Cometary Interpretation of the Interstellar Minor Object 1I/2017 '"Oumuamua. *The Astrophysical Journal Letters* 867(L17).

Sandberg, Drexler and Ord 2018. Dissolving the Fermi Paradox. arXiv:1806.02404

Seligman et al. 2019. On the Anomalous Acceleration of 1I/2017 U1 "Oumuamua. *The Astrophysical Journal Letters* 876(L26).

Sekanina 2019, Z. 1I/`'Oumuamua As Debris of Dwarf Interstellar Comet That Disintegrated Before Perihelion. https://arxiv.org/abs/1901.08704

Siraj, A. and Loeb, A. 2019. "Oumuamua's Geometry Could Be More Extreme Than Previously Inferred. *Research Notes of the American Astronomical Society* 3(15).

Snyder-Beattie, E., Sandberg, A., Drexler, E. and Bonsall, M. 2021. The Timing of Evolutionary Transitions Suggests Intelligent Life is Rare. *Astrobiology*. Online first: https://doi.org/10.1089/ast.2019.2149.

Stanford, K. 2006. *Exceeding Our Grasp: Science, History and the Probelm of Unconceived Akternatives*. New York: Oxford University Press.

Stanford, K. 2019. Unconceived Alternatives and Conservatism in Science. *Synthese* 196: 3915–3932.

Trilling et al. 2017. Implications for planetary system formation from interstellar object 1I/2017 U1 (`'Oumuamua). *Astrophysical Journal Letters* 850(L38).

Vickers, P. 2020. Expecting the Unexpected in the Search for Extraterrestrial Life. *International Journal of Astrobiology* 19(6): 482-491.

Vokch, D. and Dowd, M. 2015. *The Drake Equation*. Cambridge: Cambridge University Press.