What's in a name: The etymology of astrobiology

Manasvi Lingam*

Department of Aerospace, Physics and Space Science, Florida Institute of Technology, Melbourne FL 32901, USA

Institute for Theory and Computation, Harvard University, Cambridge MA 02138, USA

Abraham Loeb

Institute for Theory and Computation, Harvard University, Cambridge MA 02138, USA

Abstract

Astrobiology has been gaining increasing scientific prominence and public attention as the search for life beyond Earth continues to make significant headway on multiple fronts. In view of these recent developments, the fascinating and dynamic etymology of astrobiology is elucidated, and thus shown to encompass a plethora of vivid characters drawn from different continents, religions, ideologies and centuries.

1 Introduction

Notwithstanding the fact that Shakespeare's celebrated quote from Act II, Scene II of Romeo and Juliet ("What's in a name?") has been, at times, (mis)interpreted as signifying the arbitrariness of nomenclature, there is no doubting the reality that names and words do play a major role in human culture (Locke, 1847; Cassirer, 1944; Jeshion, 2009; Alter, 2014); this aspect has been appreciated since at least the days of Confucius, who argued in favour of "rectifying" names (Gardner, 2014, pg. 57), and Plato, who wrote about the "correctness of names" in his Cratylus (Sedley, 2018). At the same time, however, it should be noted that the precise semantic status of names and words continues to attract much debate and controversy (Austin, 1975; Strawson, 2016; Cumming, 2019; Speaks, 2019).

The transdisciplinary endeavour of astrobiology has swiftly gained prominence in the realm of academia as well as the public consciousness in the past few decades (Race et al., 2012; Vakoch, 2013; Dick, 2018; Capova et al., 2018; Crawford, 2018). With the increasing scientific and media buzz surrounding astrobiology, even as we continue to make considerable progress toward resolving this question, it seems a worthwhile endeavour to step back and reflect on the origins of this word. In doing so, we shall encounter a bevy of forgotten actors, some of whom were pioneers of this variegated

^{*}Electronic address: mlingam@fit.edu

field, and consequently gain a deeper historical awareness of how the myriad meanings underpinning astrobiology have evolved and morphed over the ages.

It is essential to emphasize at the outset that this précis is *not* meant to serve as a comprehensive historical overview of the field; the reader may consult Dick (1982); Crowe (1986); Michaud (2007); Crowe and Dowd (2013); Dick (2018) for the same. Shortly after the Copernican revolution, which is often (and perhaps somewhat erroneously) credited with displacing the Earth from its privileged position at the centre of the physical universe (Kuhn, 1957; Gingerich, 1985; Huff, 2017; Carman, 2018), the philosopher Giordano Bruno (1548-1600) (in)famously averred in *De l'infinito, universo e mondi* that there exist countless stars hosting planets teeming with multifarious lifeforms, both like and very unlike those found on Earth (Boulting, 1914, pg. 144); see also Wilkinson (2013, pp. 19-20).

The postulation of extraterrestrial life and the associated notion that the Earth is not located at the centre of the biological universe has a rich (albeit neglected) history prior to the advent of Bruno, encompassing personages as diverse as Anaximander, Democritus, Epicurus, Lucretius, Muhammad al-Baqir, Moses Maimonides, Fakhr al-Din al-Razi, Albertus Magnus, Hasdai Crescas, Nicholas of Cusa, and William Vorilong (Tipler, 1981; Crowe, 1997; Brake, 2006; Schneider, 2010; Weintraub, 2014). Aside from this group of scholars, many religious traditions and myths from all over the world had also posited that the Earth is not alone in hosting life (Hetherington, 1993; Selin and Sun, 2000; Ruggles, 2005; Nazé, 2009; Weintraub, 2014); in particular, most of the major surviving South Asia religions fall under this category. In all of the above instances, while the word "astrobiology" may not have explicitly appeared as such, it is apparent that these writings constitute the forerunners of astrobiology in several respects.

Before we forge ahead, it is valuable to recapitulate the main objectives of astrobiology (Des Marais and Walter, 1999; Chyba and Hand, 2005; Lunine, 2005; Domagal-Goldman et al., 2016), which can be roughly broken down into three major questions.¹

- 1. How does life begin and evolve? (Where did we come from?)
- 2. Does life exists elsewhere in the universe? (Are we alone?)
- 3. What is lifes future on earth and beyond? (Whither are we going?)

In what follows, we will mostly direct our attention toward the second question (Question #2). Our chief rationale is that the majority of early references that explicitly invoked the word "astrobiology" did so in the context of the second question, as we shall see hereafter.

It should, however, be recognized that both the first and third questions have a long and rich history in their own right, even though the pertinent early references in these areas did not use the word "astrobiology" as such. For a history of the origin and evolution of life (Question #1) - a multi-disciplinary endeavour in its own right that draws upon fields as diverse as geochemistry and information theory - the reader may consult Schopf (1992); Chyba and McDonald (1995); Knoll (2015); Luisi (2016); Dawkins and Wong (2016); Mariscal et al. (2019). The future of life on Earth (Question #3) has garnered relatively less attention, despite the fact that the present-day dynamic environment of Earth is exerting, and will continue to exert, a profound effect on the future of life on Earth. Reviews and analyses of Question #3 can be found in Dyson (1979); Caldeira and Kasting (1992); Ćirković (2012); Vidal (2014); Wolf and Toon (2015).

At this stage, it is also necessary to clarify the difference between "exobiology" and "astrobiology", as there has been a tendency in some quarters to conflate and/or equate these two words. Exobiology forms the core of Question #2, as it primarily deals with the question of gauging the "cosmic

¹https://www.nasa.gov/50th/50th_magazine/astrobiology.html

²It could be argued that this domain, which synthesizes domains as diverse as astronomy, engineering and ecology, has received short shrift on the whole.

distribution of life", to use the phrase invoked by the Nobel laureate Joshua Lederberg in his seminal work (Lederberg, 1960, pg. 393); this paper is often credited with playing a noteworthy role in driving NASA's exobiology programs in the early years (Chyba and Hand, 2005; Dick, 2009). Hence, when viewed in this spirit, exobiology may be perceived as a sub-discipline of astrobiology; from such a perspective, it would be erroneous to conclude that astrobiology was merely an offshoot of exobiology. As we will mostly tackle astrobiology from the standpoint of Question #2 henceforth, we shall be implicitly operating in the domain of exobiology.

2 Tracing the etymology of astrobiology

The goal of this treatise is to trace the major milestones in the etymology of "astrobiology". Needless to say, this survey is by no means exhaustive, as there could be any number of works that have been overlooked due to the limited access to early publications in conjunction with the attendant difficulties in perusing non-English and non-European references. As a result, we will focus on four distinct cases, corresponding to the potential first appearance of this word in: (i) a scientific monograph, (ii) a publication in an established scientific journal, (iii) a "popular science" periodical or an academic journal not devoted to the sciences, and (iv) a work of fiction or outside the domain of science. Before embarking on this journey, NASA's role in developing astrobiology during its nascency is worth highlighting. Shortly after its inception in 1958, NASA commissioned a variety of far-sighted projects ranging from experiments in space biology to the construction of life-detection instruments for ambitious future missions to Mars (Dick and Strick, 2005; Dick, 2009).

2.1 Scientific monographs

Our voyage into the past begins with (i). Perhaps the very first scientific book bearing the title of Astrobiology (Russian title: Astrobiologya) was published by the Belarusian polymath Gavriil Adrianovich Tikhov (1875-1960) in 1953 (Tikhov, 1953).³ On account of having carried out his research almost exclusively in the Soviet Union, Tikhov's contributions to astrobiology remained mostly forgotten for decades. However, as illustrated by recent studies (Omarov and Tashenov, 2005; Briot, 2013), Tikhov undertook a number of visionary projects in astrobotany and astrobiology, aside from pursuing conventional topics such as variable stars, comets and the Sun. Tikhov's research in astrobiology encompassed measurements of Earthshine (Tikhov, 1914), analyses of plant physiology in extreme physicochemical conditions, and experiments to characterize the spectral properties of plants and consequently assess how their analogs could be detected on Mars (Tikhov, 1955). We find echoes of these areas in current astrobiology, ranging from studies of extremophiles (Rothschild and Mancinelli, 2001; Merino et al., 2019) to next-generation searches for the "red edge" of vegetation (induced by the presence of chlorophylls) on exoplanets (Seager et al., 2005); in principle, similar signatures, albeit of the technological kind, might also arise because of artificial photosynthesis (Lingam and Loeb, 2017).

However, even prior to Tikhov's tome, there was at least one other book that employed the word "astrobiology" in the title, albeit not in the modern scientific sense of this word. The monograph in question is La pensée de l'Asie et l'astrobiologie (1938) by the French philosopher and historian René Berthelot (1872-1960). In this work on anthropology, astrobiology signified the stage of human development in which human societies subscribed to animistic or vitalistic interpretations of natural phenomena in parallel with a certain degree of astronomical knowledge, and a belief that the latter

³Although the following books did not explicitly incorporate the word "astrobiology" in the title, notable examples from the same period and much earlier that tackled this theme include de Fontenelle (1767); Whewell (1867); Flammarion (1871); Wallace (1903); Jones (1940); Strughold (1953); Shapley (1958); Dole (1964).

shaped terrestrial phenomena (Berthelot, 1938; Lemarchand, 2010). Although Berthelot's conception of astrobiology has altogether fallen out of use in the 21st century, it was employed *in hoc sensu* by French intellectuals up to the late 20th century (Christie, 2019, pg. 4).

2.2 Scientific journals

Next, we turn our attention to (ii). It is widely supposed that Lawrence J. Lafleur (1907-1966) - a philosopher at Brooklyn College who was better known for his translations of René Descartes' works - authored the first peer-reviewed scientific publication entitled *Astrobiology* (Blumberg, 2003; Bada, 2005; Chyba and Hand, 2005), in which he defined astrobiology as, "the consideration of life in the universe elsewhere than on earth" (Lafleur, 1941, pg. 333). Although the modern interpretation and scope of astrobiology are broader, because it also encompasses the origin and evolution of life on our planet, Lafleur honed in on many of the key topics and goals of this field; in point of fact, his definition and analysis were not far removed from the much better known exposition of exobiology by Joshua Lederberg in 1960, nearly two decades later (Lederberg, 1960).

In this unusually prescient publication, Lafleur singled out many of the basic requirements for habitability, as seen from the following quote (Lafleur, 1941, pp. 333-334):

One of the important considerations is the chemical constitution, involving fairly high proportions of carbon, oxygen, nitrogen and hydrogen, together with smaller quantities of a large number of elements, and their existence in such proportions that the compounds found on earth could exist, particularly water. Other requirements include: a temperature like that on earth; a pressure at the surface not too dissimilar to conditions here ... a source of light energy adequate to keep plants alive ...

In the same article, Lafleur outlined the possibility of detecting signatures of intelligent extraterrestrial life by searching for "interstellar communication" (Lafleur, 1941, pp. 338-339), thus anticipating, to an extent, the seminal paper by Cocconi and Morrison (1959) that is conventionally regarded as having initiated the Search for Extraterrestrial Intelligence (SETI) (see Tarter 2001). At the risk of digressing, we note that the notion of employing electromagnetic signals for communication was espoused in a scientific publication as early as 1931. In the journal *Nature*, Ernest William Barnes (1874-1953), the Bishop of Birmingham, opined that (Barnes, 1931, pg. 722):

As I have already indicated, I have no doubt that there are many other inhabited worlds, and that on some of them beings exist who are immeasurably beyond our mental level. We would be rash to deny that they can use radiation so penetrating as to convey messages to the Earth. Probably such messages now come. When they are first made intelligible a new era in the history of humanity will begin.

2.3 Popular-science and non-scientific journals

Even though Lafleur has been credited by some sources as the first person to coin the word "astrobiology" (Blumberg, 2003), recent scholarship by Briot (2012) has revealed that the Polish scientist and engineer Ary J. Sternfeld (1905-1980) introduced this term in the French popular science magazine La Nature in 1935 (Sternfeld, 1935), thereby exemplifying (iii). His article was filled with a number of prescient musings, of which one of the most perspicacious was the prediction that Titan probably possessed an atmosphere; another that stands out in the context of this article is his apposite definition of astrobiology (Briot, 2012):

The development of both the natural and astronomical sciences has led to the birth of a new science whose main objective is to assess the habitability of the other worlds, this science is called astrobiology.

Sternfeld's peripatetic existence led him from the small town of Sieradz, Poland (his place of birth) to Paris and thence to Moscow. Despite facing numerous hardships as a Jewish person navigating the turbulent politics of 20th century Europe, his breakthroughs in astronautics have been gaining belated recognition. In this realm, Sternfeld is known to have presented the mathematical details underpinning bi-elliptic transfer (Sternfeld, 1934) - an intricate maneuver that requires lower delta-v in comparison to the famous Hohmann transfer under certain conditions (Denny and McFadzean, 2019, pg. 82) - and coined the term "cosmonautics" in his book *Initiation á la Cosmonautique* (Ivashkin, 2003). While the above quote makes it clear that Sternfeld's view of astrobiology is eerily reminiscent of its modern interpretation, there were preceding works that espoused very different notions of what defined and comprised astrobiology.

In particular, a few publications from the first few decades of the 20th century suggested that astrobiology comprised the biological rhythms and other effects engendered by (lunar) tides. For instance, Brunelli (1908, pg. 664) described the observed correlation between the lunar and reproductive cycles for certain marine species, most notably Eunice viridis, as an "enigma astrobiologico" (astrobiological enigma). Gustavo Brunelli (1881-1960), the Italian biologist who authored this article, also wrote an altogether forgotten book in 1933 centered around the origin and evolution of life on Earth;⁴ in this early treatise, among other insights, he underscored the significance of condensation reactions for synthesizing proteins from amino acids (Brunelli, 1933, pg. 177). Another publication that emphasized the role of tides in an astrobiological context was by the French writer Maurice Privat (1889-1949). In Privat (1936), he posited the importance of "le rythme lunaire" (lunar rhythms) for comprehending the biological characteristics of humans and other species. Although similar biological implications of tides have been explored in modern astrobiology, not surprisingly, they constitute a minuscule fraction of this diverse field (Lingam and Loeb, 2018).

Before moving ahead, there is one other interesting reference that merits a mention. In the journal Archiv für systematische Philosophie, the German doctor and inventor Ferdinand Maack (1861-1930) - credited by some sources as the pioneer of Raumschach, i.e., a three-dimensional version of chess (Hooper and Whyld, 1996, pg. 419) - touched upon the subject of astrobiology in 1918. In fact, contra the majority of contemporaneous publications, Maack's notion of Astro-Biologie (astro-biology) was arguably quite modern, as evinced by the rough translation of Maack (1918, pg. 45):

We transition from mainly mechanical and physical questions to biological and psychological ones. The fourth group of problems deals with astro-biology and astro-psychology. How did the first life on Earth originate? Through spontaneous generation? Cosmic panspermia? How does the human race and life on our planet end? Is only the Earth inhabited? Or do higher, human-like, beings dwell on other worlds?

In posing the above questions, Maack echoes some of the ideas propounded by Bruno and his forebears, and it is therefore apparent that he viewed astrobiology as the science of extraterrestrial life, even if no explicit definition was furnished as such.

2.4 Non-scientific monographs and works of fiction

The last step on this winding road is (iv). The history of science is replete with words and phrases that originated in non-technical publications, arguably most notably in works of fiction, with the

⁴http://www.treccani.it/enciclopedia/gustavo-brunelli_(Dizionario-Biografico)

quintessential example being "quarks" in the realm of particle physics - a word that was adopted from James Joyce's classic *Finnegans Wake* by Murray Gell-Mann (Gell-Mann, 1994, pg. 180). There are compelling grounds for believing that "astrobiology" may constitute another such striking exemplar. A meticulous search, implemented by means of utilizing the Google Books and Google Scholar search engines among others,⁵ for this word yields only a handful of bona fide results. The majority of these sources are highly inchoate, with the rest of them displaying a predominantly theological bent.

The most coherent quotes in the latter category are interspersed across the writings of Cyrus Teed (1839-1908), a charismatic eclectic physician turned religious leader, who founded the sect known as the "Koreshan Unity" after experiencing a vision from "The Divine Motherhood" in 1869 (Millner, 2015). One of the most unusual aspects of this group was their belief in a unique variant of the Hollow Earth theory, namely, an inside-out cosmology wherein humans, the biosphere, and the celestial objects inhabited the *interior* of a hollow shell (Koresh and Morrow, 1898). The Koreshan Unity, which was based on the principles of communal living and eventually settled in Florida, reached its peak membership of 250 followers belonging to sundry backgrounds in 1908, and thereafter declined with the last member (Hedwig Michel) joining in 1940 after fleeing Nazi Germany (Millner, 2015).

In *The Cellular Cosmogony* (1898), widely regarded as the summation of Teed's thought, astrobiology was invoked in this outré passage (Koresh and Morrow, 1898, pg. 22):

... and further, that when the Lord was visibly manifest to the outer world, his inner and spiritual life was visible to the spiritual world as the astrobiological center of that sphere, and beside him there was no God.

In the June 8, 1900 issue of the magazine *The Flaming Sword*, published under the aegis of Koresh (viz., Teed),⁷ a comparatively down-to-earth and intriguing, albeit terse and therefore ambiguous, definition of astrobiology was promulgated (Koresh, 1908, pg. 4):

Cosmogony includes the earth, sun, stars, planets, and all life—in a more narrow sense, the alchemico-organic system . . . If we use the term astrobiology, we would mean the stars and all life.

This quote might very well be the first explicit semi-definition of astrobiology specified in an English-language publication, although its general tenor is manifestly removed from the current interpretation of what constitutes the domain of astrobiology. A few years thereafter, in the January 15, 1908 issue of the *The Flaming Sword*, Teed conceived of astrobiology as the "regulation of human affairs by the clock-work of the Cosmos", and argued that the function of astrobiology was "to determine career before it is brought to the birth or before conception" (Koresh, 1900).

At approximately the same time that Cyrus Teed was publishing his religious writings, the French philosopher Henry Lagrésille (1860-19xx) authored *Le Fonctionnisme Universel* in 1902, a book dealing primarily with metaphysics that was not well-received by contemporary reviewers (Morrison, 1903; Rey, 1903). In this work, he envisioned astrobiology as "loi qualitative de l'énergie" (Lagrésille, 1902, pg. 540), i.e., as the "qualitative law of energy" (Christie, 2019, pg. 4).8 In the only instance where astrobiologie (astrobiology) explicitly appears (Lagrésille, 1902, pg. 541), a rough translation of that passage is furnished below:

⁵https://books.google.com/ and https://scholar.google.com/

⁶https://www.lockhaven.edu/~dsimanek/hollow/morrow.htm

⁷It must, however, be noted that the actual author of this work remains anonymous, i.e., there is no concrete evidence that Teed wrote this article

⁸In modern astrobiology, concepts such as free energy and thermodynamic disequilibrium play a vital role in constraining the origin and evolution of putative biospheres (Hoehler, 2007; Branscomb et al., 2017).

You can thus conceive that todays astronomy only offers celestial mechanics, and therefore provides only the abstract framework of a more concrete science, in closer conformity with [living] beings - namely astrobiology - which, if it were possible, would adopt the essence of astrology, not unlike how chemistry superseded that of alchemy. For, once the link between these two fields has been established, the more or less obscure empirical laws, which had been unveiled by intuitive revelations, would find, to a certain extent, their rational explanations in this conception of a cosmic life awash with finalities and conscious forces.

Among publications from this period, it should be noted in passing that the German art historian Willy Pastor (1867-1933) invoked *astrobiologie* a few times in his five-act play *Das Reich des Krystalls* (The Realm of the Crystals) published in 1901, but the references to this word are fleeting, vague and incoherent (Pastor, 1901, pp. 59-60, 71).

Amidst this motley crowd of early references to astrobiology, one other work stands out to some extent, which was briefly noted in Noack et al. (2015). The work in question is *Limanora: The Island of Progress*, a science-fiction novel written by Godfrey Sweven in 1903 (Sweven, 1903). *Limanora* distinguishes itself from the multitude of contemporaneous allusions to astrobiology on two fronts: (i) this term is employed several times in the book, indicating that its usage was no fluke, and (ii) it represents a genuine piece of science fiction that was inspired, at least in part, by Jonathan Swift's *Gulliver Travels* and the novels of H. G. Wells. It is worth noting that *Limanora* evinces a distinct anti-racist and anti-colonial stance in certain respects, but the novel concomitantly reified (*verdinglichte*) some of the prevalent colonialist and racist notions of its era; for example, it espoused a variant of Social Darwinism (Rieder, 2008, pp. 72-74).

The author of this book was a rather interesting personage in his own right, owing to which we shall delve into this subject briefly. Godfrey Sweven was a pseudonym utilized by the Scottish-born New Zealand academic and administrator John Macmillan Brown (1845-1935). As a academic, Brown published articles and books in areas ranging from analyses of English literature to the cultures of the Pacific islands, but his scholarship in the latter area was "regarded with scepticism and strongly criticised by Apirana Ngata and Te Rangi Hiroa" as duly pointed out in *Te Ara: The Encyclopedia of New Zealand*. Brown was also known for being an advocate of higher education for women; while he was based at Canterbury College, New Zealand, Brown purportedly played a key role in admitting Helen Connon. She subsequently became the first woman to receive a university degree with honours in the British Empire, and gained recognition as a gifted scholar and accomplished educator.

Returning to *Limanora*, the natural question that arises is: Was the phraseology of astrobiology "modern"? This is not a facile question to resolve, seeing as how an unambiguous definition of astrobiology is not spelt out in the novel. However, by undertaking a close reading of the text, the tentative answer is probably in the negative. More specifically, Brown appears to employ this term to signify something akin to present-day genetic engineering, as illustrated by the sentence following the usage of "astrobiology" (Sweven, 1903, pg. 309):

Soon would they modify and improve the lavolan to fit the conditions of interstellar space, and the faleena, if not their own organs, for venturing far into the rarest ether. And then what reports, what pictures of the invisible universes would they bring before the eyes and the firlas of their fellow-islanders!

⁹https://teara.govt.nz/en/biographies/2b41/brown-john-macmillan

3 The future of astrobiology

With our analysis concerning the etymology of astrobiology having drawn to a close, it seems apropos to end our discussion with a tour d'horizon of the past, present and future of this blossoming field. Over the past decade, we have discovered complex organic molecules within the interstellar medium and on objects within our Solar system such as meteorites, Mars and Enceladus (Schulze-Makuch and Irwin, 2018), identified Earth-sized planets in the temperate zones of other stars and refined some basic requirements for habitability (Perryman, 2018; Lingam and Loeb, 2019), designed generic prebiotic pathways that are reliant on the availability of ultraviolet radiation (Sutherland, 2017), furthered our understanding of how metals could catalyse protometabolic networks (Preiner et al., 2019), unearthed animals that lack mitochondria altogether (Yahalomi et al., 2020), expanded the parameter space of the limits tolerated by (poly)extremophiles (Merino et al., 2019), conceived novel methods of identifying biosignatures in situ as well as via remote sensing (Schwieterman et al., 2018; Neveu et al., 2018), and taken our very first steps toward undertaking high-speed interstellar travel (Popkin, 2017; Worden et al., 2018), to name a few.

Yet, at the same time, it is equally essential to recognize that the preceding picture is deliberately rosy-hued. In many respects, we are very far from settling the question(s) of how, where and when life arose and evolved on our planet, to say nothing of other worlds. Hence, it is vital to avoid misconstruing our current rate of progress and thereby lulling ourselves into a state of false complacency. As Shakespeare wisely wrote in Act II, Scene III of *All's Well That Ends Well*:

They say miracles are past; and we have our philosophical persons, to make modern and familiar, things supernatural and causeless. Hence is it that we make trifles of terrors, ensconcing ourselves into seeming knowledge, when we should submit ourselves to an unknown fear.

However, in place of succumbing to "an unknown fear", as ostensibly espoused by Shakespeare's Lafeu, we can (and should) instead opt to temper our optimistic hopes and expectations with a judicious dose of caution and skepticism, thus taking equal delight in what we discover and comprehend, and what remains unseen and unknown.

If we look ahead to the future, even as humanity braces itself to confront a host of grave challenges and growing schisms (Bostrom and Ćirković, 2008; Kolbert, 2014; Klein, 2014; Rees, 2018), we may cautiously identify multiple reasons to be optimistic about the scientific future of astrobiology in the upcoming decade(s).¹⁰ We will, in all likelihood, witness the launch of large ground- and space-based telescopes to commence the hunt for novel biosignatures (Fujii et al., 2018), life-detection missions to potentially inhabited worlds such as Europa and Mars (Neveu et al., 2018), experiments that push the boundaries of the long-term survival of biota in the harsh conditions of outer space (Moissl-Eichinger et al., 2016), theoretical and experimental breakthroughs in resolving the question of how life originated on our planet (Walker, 2017; Lingam and Loeb, 2021), advances in comprehending how Earth's biogeochemical cycles have coevolved over time and the ensuing implications for our biosphere (Knoll and Nowak, 2017), among many others.

Hence, at the risk of retreading and extolling a hoary cliché, while the age-old question of "Are we alone?" has captivated humanity for millennia, it is not much of an exaggeration to contend that we might find ourselves situated on the cusp of a momentous era wherein we can hope to settle this question scientifically through the synthesis of experiments, observations and modelling. In light of the aforementioned putative future developments, a quotation from *Limanora* - which comprises one

¹⁰In the best-case scenario, astrobiology might even aid humankind in navigating the turbulent currents of the Anthropocene (Frank, 2018).

of the earliest allusions to astrobiology, as stated previously - is strikingly vatic, albeit when viewed out of context (Sweven, 1903, pg. 309):

For astrobiology they saw at a glance there was begun a new and lofty career.

Acknowledgments

We are grateful to Jean Schneider for pointing out a couple of valuable early references in the realm of astrobiology, Jeremy Riousset for generously sharing his feedback regarding a couple of translated passages, and the editor Rocco Mancinelli for his sagacious feedback. This work was supported in part by the Breakthrough Prize Foundation, Harvard University's Faculty of Arts and Sciences, and the Institute for Theory and Computation (ITC) at Harvard University.

References

- A. Alter. Drunk Tank Pink: And Other Unexpected Forces That Shape How We Think, Feel And Behave. New York, NY: Penguin Books, 2014.
- J. L. Austin. How to Do Things with Words. Oxford: Oxford University Press, 2nd edition, 1975.
- J. L. Bada. A Field with a Life of Its Own. Science, 307(5706):46-47, 2005. doi: 10.1126/science. 1106678.
- E. W. Barnes. Contributions to a British Association Discussion on the Evolution of the Universe. *Nature*, 128(3234):719–722, Oct. 1931. doi: 10.1038/128719a0.
- R. Berthelot. La pensée de l'Asie et l'astrobiologie. Paris: Payot, 1938.
- B. S. Blumberg. The NASA Astrobiology Institute: Early History and Organization. *Astrobiology*, 3 (3):463–470, Nov. 2003. doi: 10.1089/153110703322610573.
- N. Bostrom and M. M. Ćirković, editors. *Global Catastrophic Risks*. Oxford: Oxford University Press, 2008.
- W. Boulting. Giordano Bruno: His Life, Thought, and Martyrdom. London: Kegan Paul, Trench, Trübner & Co., 1914.
- M. Brake. On the plurality of inhabited worlds: a brief history of extraterrestrialism. *Int. J. Astrobiol.*, 5(2):99–107, 2006. doi: 10.1017/S1473550406002989.
- E. Branscomb, T. Biancalani, N. Goldenfeld, and M. Russell. Escapement mechanisms and the conversion of disequilibria; the engines of creation. Phys. Rep., 677:1–60, 2017. doi: 10.1016/j.physrep.2017.02.001.
- D. Briot. A Possible First Use of the Word Astrobiology? Astrobiology, 12(12):1154–1156, Dec. 2012. doi: 10.1089/ast.2012.0896.
- D. Briot. The Creator of Astrobotany, Gavriil Adrianovich Tikhov. In D. A. Vakoch, editor, Astrobiology, History, and Society, pages 175–185. Berlin: Springer-Verlag, 2013. doi: 10.1007/978-3-642-35983-5_8.

- G. Brunelli. La dottrina di Loeb sui tropismi e il metodo storico di Darwin e di Romanes. Rivista di filosofia e scienze affini, 19:645–668, 1908.
- G. Brunelli. Le teorie sull'origine e l'evoluzione della vita (da Darwin ai nostri giorni). Bologna: L. Cappelli, 1933.
- K. Caldeira and J. F. Kasting. The life span of the biosphere revisited. *Nature*, 360(6406):721–723, Dec. 1992. doi: 10.1038/360721a0.
- K. A. Capova, E. Persson, T. Milligan, and D. Dunér, editors. Astrobiology and Society in Europe Today. Cham: Springer, 2018. doi: 10.1007/978-3-319-96265-8.
- C. C. Carman. The first Copernican was Copernicus: the difference between Pre-Copernican and Copernican heliocentrism. *Arch. Hist. Exact Sci.*, 72(1):1–20, 2018. doi: 10.1007/s00407-017-0198-3.
- E. Cassirer. An Essay on Man: An Introduction to a Philosophy of Human Culture. New Haven, CT: Yale University Press, 1944.
- J. E. Christie. From Influence to Inhabitation: The Transformation of Astrobiology in the Early Modern Period, volume 228 of International Archives of the History of Ideas. Cham: Springer, 2019. doi: 10.1007/978-3-030-22169-0.
- C. F. Chyba and K. P. Hand. Astrobiology: The Study of the Living Universe. *Annu. Rev. Astron. Astrophys.*, 43(1):31–74, Sept. 2005. doi: 10.1146/annurev.astro.43.051804.102202.
- C. F. Chyba and G. D. McDonald. The Origin of Life in the Solar System: Current Issues. *Annu. Rev. Earth Planet. Sci.*, 23:215–250, Jan. 1995. doi: 10.1146/annurev.ea.23.050195.001243.
- M. M. Čirković. The Astrobiological Landscape: Philosophical Foundations of the Study of Cosmic Life. Cambridge: Cambridge University Press, 2012.
- G. Cocconi and P. Morrison. Searching for Interstellar Communications. Nature, 184(4690):844–846, Sept. 1959. doi: 10.1038/184844a0.
- I. A. Crawford. Widening perspectives: the intellectual and social benefits of astrobiology (regardless of whether extraterrestrial life is discovered or not). Int. J. Astrobiol., 17(1):57–60, Jan. 2018. doi: 10.1017/S1473550417000088.
- M. J. Crowe. The Extraterrestrial Life Debate 1750-1900: The Idea of a Plurality of Worlds from Kant to Lowell. Cambridge: Cambridge University Press, 1986.
- M. J. Crowe. A History of the Extraterrestrial Life Debate. Zygon, 32(2):147–162, 1997. doi: 10. 1111/0591-2385.801997079.
- M. J. Crowe and M. F. Dowd. The Extraterrestrial Life Debate from Antiquity to 1900. In D. A. Vakoch, editor, *Astrobiology, History, and Society*, Advances in Astrobiology and Biogeophysics, pages 3–56. Berlin: Springer, 2013. doi: 10.1007/978-3-642-35983-5_1.
- S. Cumming. Names. In E. N. Zalta, editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, fall 2019 edition, 2019.
- R. Dawkins and Y. Wong. *The Ancestor's Tale: A Pilgrimage to the Dawn of Evolution*. Boston: Mariner Books, 2nd edition, 2016.

- M. de Fontenelle. Conversations on the Plurality of Worlds. London: Thomas Caslon, 2nd edition, 1767.
- M. Denny and A. McFadzean. Rocket Science: From Fireworks to the Photon Drive. Cham: Springer, 2019. doi: 10.1007/978-3-030-28080-2.
- D. J. Des Marais and M. R. Walter. Astrobiology: Exploring the Origins, Evolution, and Distribution of Life in the Universe. *Annu. Rev. Ecol. Evol. Syst.*, 30(1):397–420, 1999. doi: 10.1146/annurev. ecolsys.30.1.397.
- S. J. Dick. Plurality of worlds: the origins of the extraterrestrial life debate from Democritus to Kant. Cambridge: Cambridge University Press, 1982.
- S. J. Dick. Origins and development of NASA's exobiology program, 1958-1976. *Acta Astronaut.*, 65 (1):1–5, July 2009. doi: 10.1016/j.actaastro.2009.01.058.
- S. J. Dick. Astrobiology, Discovery, and Societal Impact, volume 9 of Cambridge Astrobiology. Cambridge: Cambridge University Press, 2018.
- S. J. Dick and J. E. Strick. *The Living Universe: NASA and the Development of Astrobiology*. New Brunswick, NJ: Rutgers University Press, 2005.
- S. H. Dole. Habitable planets for man. New York, NY: Blaisdell Pub. Co., 1964.
- S. D. Domagal-Goldman, K. E. Wright, K. Adamala, L. Arina de la Rubia, J. Bond, L. R. Dartnell, A. D. Goldman, K. Lynch, M.-E. Naud, I. G. Paulino-Lima, K. Singer, M. Walter-Antonio, X. C. Abrevaya, R. Anderson, G. Arney, D. Atri, A. Azúa-Bustos, J. S. Bowman, W. J. Brazelton, G. A. Brennecka, R. Carns, A. Chopra, J. Colangelo-Lillis, C. J. Crockett, J. DeMarines, E. A. Frank, C. Frantz, E. de la Fuente, D. Galante, J. Glass, D. Gleeson, C. R. Glein, C. Goldblatt, R. Horak, L. Horodyskyj, B. Kaçar, A. Kereszturi, E. Knowles, P. Mayeur, S. McGlynn, Y. Miguel, M. Montgomery, C. Neish, L. Noack, S. Rugheimer, E. E. Stücken, P. Tamez-Hidalgo, S. I. Walker, and T. Wong. The Astrobiology Primer v2.0. Astrobiology, 16(8):561–653, Aug. 2016. doi: 10. 1089/ast.2015.1460.
- F. J. Dyson. Time without end: Physics and biology in an open universe. Rev. Mod. Phys., 51(3): 447–460, July 1979. doi: 10.1103/RevModPhys.51.447.
- C. Flammarion. La pluralite des mondes habites. Paris: Didier et Cie, 16th edition, 1871.
- A. Frank. Light of the Stars: Alien Worlds and the Fate of the Earth. New York, NY: W. W. Norton & Company, 2018.
- Y. Fujii, D. Angerhausen, R. Deitrick, S. Domagal-Goldman, J. L. Grenfell, Y. Hori, S. R. Kane, E. Pallé, H. Rauer, N. Siegler, K. Stapelfeldt, and K. B. Stevenson. Exoplanet Biosignatures: Observational Prospects. *Astrobiology*, 18(6):739–778, June 2018. doi: 10.1089/ast.2017.1733.
- D. K. Gardner. Confucianism: A Very Short Introduction. Oxford: Oxford University Press, 2014.
- M. Gell-Mann. The Quark and the Jaguar: Adventures in the Simple and the Complex. New York, NY: W. H. Freeman, 1994.
- O. Gingerich. Did Copernicus Owe a Debt to Aristarchus. *J. Hist. Astron.*, 16:37–41, Feb. 1985. doi: 10.1177/002182868501600102.

- N. S. Hetherington, editor. Encyclopedia of Cosmology: Historical, Philosophical, and Scientific Foundations of Modern Cosmology. New York: Garland Publishing, Inc., 1993.
- T. M. Hoehler. An Energy Balance Concept for Habitability. Astrobiology, 7(6):824–838, Dec. 2007. doi: 10.1089/ast.2006.0095.
- D. Hooper and K. Whyld. *The Oxford Companion To Chess*. Oxford: Oxford University Press, 2nd edition, 1996.
- T. E. Huff. The Rise of Early Modern Science: Islam, China, and the West. Cambridge: Cambridge University Press, 3rd edition, 2017.
- V. V. Ivashkin. Analysis of space flight mechanics problems. Acta Astronaut., 52(8):663–670, 2003. doi: 10.1016/S0094-5765(02)00134-0.
- R. Jeshion. The Significance of Names. Mind Lang., 24(4):370–403, 2009. doi: 10.1111/j.1468-0017. 2009.01367.x.
- H. S. Jones. Life on Other Worlds. New York, NY: Macmillan, 1940.
- N. Klein. This Changes Everything: Capitalism Vs. The Climate. New York, NY: Simon & Schuster, 2014.
- A. H. Knoll. Life on a Young Planet: The First Three Billion Years of Evolution on Earth. Princeton Science Library. Princeton, NJ: Princeton University Press, 2nd edition, 2015.
- A. H. Knoll and M. A. Nowak. The timetable of evolution. *Sci. Adv.*, 3(5):e1603076, May 2017. doi: 10.1126/sciadv.1603076.
- E. Kolbert. The Sixth Extinction: An Unnatural History. London: Bloomsbury, 2014.
- Koresh. Exposition of the Cause of Motion. The Flaming Sword, 22(1):3-5, 1900.
- Koresh. The Science of Astro-Biology. The Flaming Sword, 14(29):6-7, 1908.
- Koresh and U. G. Morrow. *The Cellular Cosmogony; Or, The Earth a Concave Sphere*. Chicago, IL: Guiding Star Publishing House, 1898.
- T. S. Kuhn. The Copernican Revolution: Planetary Astronomy in the Development of Western Thought. Cambridge, MA: Harvard University Press, 1957.
- L. J. Lafleur. Astrobiology. Leaflet Astron. Soc. Pac., 3(143):333-340, Jan. 1941.
- H. Lagrésille. Le Fonctionnisme Universel: Essai De Synthèse Philosophique: Monde Sensible. Paris: Librairie Fischbacher, 1902.
- J. Lederberg. Exobiology: Approaches to Life beyond the Earth. Science, 132(3424):393–400, Aug. 1960. doi: 10.1126/science.132.3424.393.
- G. A. Lemarchand. Una breve historia social de la astrobiología en Iberoamérica. In G. A. Lemarchand and G. Tancredi, editors, Astrobiología: del Big Bang a las Civilizaciones, Topicos Especiales en Ciencias Básicas e Ingeniería, volume 1 of Second Iberoamerican School on Astrobiology, pages 23–52. Montevideo: UNESCO, 2010.

- M. Lingam and A. Loeb. Natural and artificial spectral edges in exoplanets. *Mon. Not. R. Astron. Soc. Lett.*, 470(1):L82–L86, Sept. 2017. doi: 10.1093/mnrasl/slx084.
- M. Lingam and A. Loeb. Implications of Tides for Life on Exoplanets. *Astrobiology*, 18(7):967–982, July 2018. doi: 10.1089/ast.2017.1718.
- M. Lingam and A. Loeb. Colloquium: Physical constraints for the evolution of life on exoplanets. *Rev. Mod. Phys.*, 91(2):021002, Apr. 2019. doi: 10.1103/RevModPhys.91.021002.
- M. Lingam and A. Loeb. Extraterrestrial Life: From Biosignatures to Technosignatures . Cambridge: Harvard University Press, 2021.
- J. Locke. An Essay Concerning Human Understanding. Philadelphia, PA: Kay & Troutman, 1847.
- P. L. Luisi. The Emergence of Life: From Chemical Origins to Synthetic Biology. Cambridge: Cambridge University Press, 2nd edition, 2016.
- J. Lunine. Astrobiology: A Multi-Disciplinary Approach. San Francisco, CA: Addison-Wesley, 2005.
- F. Maack. Astrosophie. Archiv für systematische Philosophie, 24:43-64, 1918.
- C. Mariscal, A. Barahona, N. Aubert-Kato, A. U. Aydinoglu, S. Bartlett, M. L. Cárdenas, K. Chandru, C. Cleland, B. T. Cocanougher, N. Comfort, A. Cornish-Bowden, T. Deacon, T. Froese, D. Giovannelli, J. Hernlund, P. Hut, J. Kimura, M.-C. Maurel, N. Merino, A. Moreno, M. Nakagawa, J. Peretó, N. Virgo, O. Witkowski, and H. James Cleaves. Hidden Concepts in the History and Philosophy of Origins-of-Life Studies: a Workshop Report. Orig. Life Evol. Biosph., 49(3): 111–145, Sept. 2019. doi: 10.1007/s11084-019-09580-x.
- N. Merino, H. S. Aronson, D. P. Bojanova, J. Feyhl-Buska, M. L. Wong, S. Zhang, and D. Giovannelli. Living at the Extremes: Extremophiles and the Limits of Life in a Planetary Context. Front. Microbiol., 10:780, 2019. doi: 10.3389/fmicb.2019.00780.
- M. A. G. Michaud. Contact with Alien Civilizations: Our Hopes and Fears about Encountering Extraterrestrials. New York, NY: Springer-Verlag, 2007. doi: 10.1007/978-0-387-68618-9.
- L. Millner. The Allure of Immortality: An American Cult, a Florida Swamp, and a Renegade Prophet. Gainesville, FL: University Press of Florida, 2015.
- C. Moissl-Eichinger, C. Cockell, and P. Rettberg. Venturing into new realms? microorganisms in space. FEMS Microbiol. Rev., 40(5):722–737, 2016. doi: 10.1093/femsre/fuw015.
- D. Morrison. VI.-New Books. Mind, 12(2):266-267, 1903. doi: 10.1093/mind/XII.2.266.
- Y. Nazé. L'astronomie des Anciens. Paris: Belin, 2009.
- M. Neveu, L. E. Hays, M. A. Voytek, M. H. New, and M. D. Schulte. The Ladder of Life Detection. *Astrobiology*, 18(11):1375–1402, Nov. 2018. doi: 10.1089/ast.2017.1773.
- L. Noack, C. Verseux, P. Serrano, M. Musilova, P. Nauny, T. Samuels, P. Schwendner, E. Simoncini, and A. Stevens. Astrobiology from early-career scientists' perspective. *Int. J. Astrobiol.*, 14(4): 533–535, Oct. 2015. doi: 10.1017/S1473550415000233.
- T. B. Omarov and B. T. Tashenov. Tikhov's Astrobotany as a Prelude to Modern Astrobiology. In R. B. Hoover, A. Y. Rozanov, and R. Paepe, editors, *Perspectives in Astrobiology*, pages 86–87. Amsterdam: IOS Press, Jan. 2005.

- W. Pastor. Das Reich des Krystalls: Schauspiel in fünf Akten. Leipzig: Georg Heinrich Meyer, 1901.
- M. Perryman. The Exoplanet Handbook. Cambridge: Cambridge University Press, 3rd edition, 2018.
- G. Popkin. What it would take to reach the stars. Nature, 542(7639):20–22, Feb. 2017. doi: 10.1038/542020a.
- M. Preiner, J. C. Xavier, A. do Nascimento Vieira, K. Kleinermanns, J. F. Allen, and W. F. Martin. Catalysts, autocatalysis and the origin of metabolism. *Interface Focus*, 9(6):20190072, 2019. doi: 10.1098/rsfs.2019.0072.
- M. Privat. La loi des étoiles: Philosophie de l'astrologie. Paris: Éditions Grasset, 5th edition, 1936.
- M. Race, K. Denning, C. M. Bertka, S. J. Dick, A. A. Harrison, C. Impey, and R. Mancinelli. Astrobiology and Society: Building an Interdisciplinary Research Community. *Astrobiology*, 12 (10):958–965, Oct. 2012. doi: 10.1089/ast.2011.0723.
- M. Rees. On the Future: Prospects for Humanity. Princeton, NJ: Princeton University Press, 2018.
- A. Rey. Analyses. Revue Philosophique de la France et de l'Étranger, 55:425-428, 1903.
- J. Rieder. Colonialism and the Emergence of Science Fiction. Middletown, CT: Wesleyan University Press, 2008.
- L. J. Rothschild and R. L. Mancinelli. Life in extreme environments. Nature, 409(6823):1092–1101, Feb. 2001. doi: 10.1038/35059215.
- C. L. N. Ruggles. Ancient astronomy: an encyclopedia of cosmologies and myth. Santa Barbara, CA: ABC-Clio, 2005.
- J. Schneider. The Extraterrestrial Life Debate in Different Cultures. In V. Coudé du Foresto, D. M. Gelino, and I. Ribas, editors, Pathways Towards Habitable Planets, volume 430 of Astronomical Society of the Pacific Conference Series, pages 324–330. San Francisco, CA: Astronomical Society of the Pacific, 2010.
- J. W. Schopf, editor. Major Events in the History of Life. Boston: Jones & Bartlett Publishers, 1992.
- D. Schulze-Makuch and L. N. Irwin. *Life in the Universe: Expectations and Constraints*. Cham: Springer, 3rd edition, 2018. doi: 10.1007/978-3-319-97658-7.
- E. W. Schwieterman, N. Y. Kiang, M. N. Parenteau, C. E. Harman, S. DasSarma, T. M. Fisher, G. N. Arney, H. E. Hartnett, C. T. Reinhard, S. L. Olson, V. S. Meadows, C. S. Cockell, S. I. Walker, J. L. Grenfell, S. Hegde, S. Rugheimer, R. Hu, and T. W. Lyons. Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life. *Astrobiology*, 18(6):663–708, June 2018. doi: 10.1089/ast.2017.1729.
- S. Seager, E. L. Turner, J. Schafer, and E. B. Ford. Vegetation's Red Edge: A Possible Spectroscopic Biosignature of Extraterrestrial Plants. *Astrobiology*, 5(3):372–390, June 2005. doi: 10.1089/ast. 2005.5.372.
- D. Sedley. Plato's Cratylus. In E. N. Zalta, editor, The Stanford Encyclopedia of Philosophy. Metaphysics Research Lab, Stanford University, fall 2018 edition, 2018.

- H. Selin and X. Sun. Astronomy across cultures: the history of non-Western astronomy. Dordrecht: Kluwer Academic Publishers, 2000.
- H. Shapley. Of Stars and Men: The Human Response to an Expanding Universe. Boston: Beacon Press, 1958.
- J. Speaks. Theories of meaning. In E. N. Zalta, editor, The Stanford Encyclopedia of Philosophy. Metaphysics Research Lab, Stanford University, winter 2019 edition, 2019.
- A. Sternfeld. Sur les trajectoires permettant d'approcher d'un corps attractifs central à partir d'une orbite Keplérienne donnée. C. R. Acad. Sci., 198:711–713, 1934.
- A. J. Sternfeld. La vie dans l'Univers. La Nature, Masson et Cie Eds., 2956:1-12, 1935.
- P. F. Strawson. Subject and Predicate in Logic and Grammar. New York, NY: Routledge, 2016.
- H. Strughold. The Green and Red Planet: A Physiological Study of the Possibility of Life on Mars. Albuquerque, NM: University of New Mexico Press, 1953.
- J. D. Sutherland. Opinion: Studies on the origin of lifethe end of the beginning. Nat. Rev. Chem., 1 (2):1–7, 2017. doi: 10.1038/s41570-016-0012.
- G. Sweven. Limanora: The Island of Progress. New York, NY: G. P. Putnam's Sons, 1903.
- J. Tarter. The Search for Extraterrestrial Intelligence (SETI). Annu. Rev. Astron. Astrophys., 39: 511–548, Jan. 2001. doi: 10.1146/annurev.astro.39.1.511.
- G. A. Tikhov. Etude de la lumière cendrée de la Lune au moyen des filtres sélecteurs. *Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowo*, 62(6):15–25, Jan. 1914.
- G. A. Tikhov. Astrobiology. Moscow: Molodaya Gvardia, 1953.
- G. A. Tikhov. Is Life Possible on Other Planets? J. Br. Astron. Assoc., 65(5):193-204, 1955.
- F. J. Tipler. A Brief History of the Extraterrestrial Intelligence Concept. Q. J. R. Astron. Soc., 22: 133–145, June 1981.
- D. A. Vakoch, editor. Astrobiology, History, and Society. Berlin: Springer-Verlag, 2013. doi: 10.1007/978-3-642-35983-5.
- C. Vidal. The Beginning and the End: The Meaning of Life in a Cosmological Perspective. The Frontiers Collection. Cham: Springer, 2014. doi: 10.1007/978-3-319-05062-1.
- S. I. Walker. Origins of life: a problem for physics, a key issues review. *Rep. Prog. Phys.*, 80(9): 092601, Sept. 2017. doi: 10.1088/1361-6633/aa7804.
- A. R. Wallace. Man's Place in the Universe: A Study of the Results of Scientific Research in Relation to the Unity or Plurality of Worlds. New York, NY: McClure, Phillips & Co., 1903.
- D. A. Weintraub. Religions and Extraterrestrial Life: How Will We Deal With It? Cham: Springer, 2014. doi: 10.1007/978-3-319-05056-0.
- W. Whewell. Of the Plurality of Worlds: An Essay: Also, a Dialogue on the Same Subject. London: Longmans, Green, Reader, and Dyer, 1867.

- D. Wilkinson. Science, Religion, and the Search for Extraterrestrial Intelligence. Oxford: Oxford University Press, 2013.
- E. T. Wolf and O. B. Toon. The evolution of habitable climates under the brightening Sun. J. $Geophys.\ Res.\ D,\ 120(12):5775-5794$, June 2015. doi: 10.1002/2015JD023302.
- S. P. Worden, J. Drew, and P. Klupar. Philanthropic Space Science: The Breakthrough Initiatives. *New Space*, 6(4):262–268, Dec 2018. doi: 10.1089/space.2018.0027.
- D. Yahalomi, S. D. Atkinson, M. Neuhof, E. S. Chang, H. Philippe, P. Cartwright, J. L. Bartholomew, and D. Huchon. A cnidarian parasite of salmon (Myxozoa: *Henneguya*) lacks a mitochondrial genome. *Proc. Natl. Acad. Sci. USA*, 117(10):5358–5363, 2020. doi: 10.1073/pnas.1909907117.