On the Habitability of Exoplanets and the Potential for Extraterrestrial Biological Genesis

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Abstract

Despite the increasing catalogue of known terrestrial exoplanets expands, we have not yet identified a planet that we know to be habitable by Earth's standards. This is partly due to the technological limitations of modern exoplanet surveys, and also due to a lack of solid framework in the question of what exactly makes a planet habitable. Direct observation of exoplanets, a particularly challenging yet insightful method of detection, is our primary means of determining their characteristics beyond simple orbital parameters. Next generation optical telescopes will allow us a more detailed analysis of the nature of giant planets, and advances in our theoretical understanding of life and habitability will provide astronomers with criteria on which stellar systems to prioritise. In this paper, we will review the current state of exoplanet research and the framework by which we define extrasolar environments to be habitable. We will also consider the distinction between the concepts of habitability and urability as defined by Deamer et al. [Deamer, 2022].

1. Introduction

Since the discovery of the first extrasolar planet in 1992, the question of whether other Earth-like planets may exist has been a central area of research in modern astrophysics. Identification of terrestrial-mass planets is in itself an achievement due to the low angular separation and severe luminosity ratio between them and their host stars. However, determining more specific parameters such as atmospheric composition, internal structure, and surface features remains challenging to this day despite advances in the field of optical astronomy. The concept of a habitable world other than this one has had a stranglehold on humanity, in the realms of science, philosophy, and fiction, for centuries. Understanding the processes by which other Earth-like planets are formed would also provide valuable insight into the history of our own planet, which due to its active geology is still poorly understood. A planet may be considered habitable by our definition of the term only when four key requirements are simultaneously met: raw materials, specifically complex chemical compounds; liquid water, which is largely believed to be a fundamental necessity for all life due to its versatility as a solvent for chemical reactions [Mottl, 2007]; an energy source, potentially via photo/chemosynthesis; and suitable environmental conditions, such as protection from stellar radiation in the form of an atmosphere [Hoehler, 2007]

2. What is life?

The definition of life is somewhat contentious and so there is no universally accepted version, although a working definition of life as "a self-sustaining chemical system capable of Darwinian evolution" as proposed by NASA [Voytek, 2022] is commonly used in the field of astrobiology. Many adaptations have been suggested, such as an inclusion of the thermodynamic and information processing properties of life [Vitas, 2019]. Speculative biology offers an interesting insight into how life may have evolved in more exotic environments, but the only available criteria for a robust definition of life are derived from observations on Earth. In short, our endeavour to find life elsewhere relies heavily on those lifeforms being similar to our own. When considering the nature of life on other planets, research on Earth tends to focus on isolated extreme environments known as planetary analogues. The organisms present in these analogue sites are specialised "extremophiles" that have adapted to their thrive in the adverse conditions of their environment. Viewing these lifeforms as extreme is however a fundamentally anthropocentric view, and may unnecessarily restrict the development of catalogues of candidate habitable exoplanets [Stetter, 1999].

3. Habitable Zones

The habitable zone, colloquially known as the "Goldilocks zone" and henceforth referred to as the HZ, is the region around a star in which liquid water could exist on the surface of an orbiting planet [Kane, 2012]. The formal, quantitative definitions are the points at which runaway warming or runaway cooling would occur for the inner and outer edges respectively [Kasting, 1993]. This definition again relies on that most fundamental assumption of astrobiology that liquid water is required for the persistence of life. M-dwarfs have long been considered desirable candidates in the search for planets that could support life due to their long lifetimes and higher probability of transits [Shields, 2016][Kopparapu, 2013]. Their suitability is the subject of much debate, with prominent counterarguments such as their high rate of stellar flares which could sterilise nearby planets [Lammer, 2013]. The low orbital radius of a planet with a host M-dwarf would likely lead in most cases to tidal locking of the two bodies [Childs, 2022]. This is a process by which gravitational stresses lead to a 1:1 resonance between the rotation of the planet on its own axis and the orbital period, resulting in one side of the planet being in perpetual daytime while the other is permanently dark. Despite this extreme condition, simulations have shown that dense cloud cover could significantly increase the HZ of tidally locked planets [Yang, 2013]. Planets with highly eccentric orbits are rarely seen as desirable candidates for hosting life, but the argument could be made that so long as some portion of the orbit does lie within the HZ, organisms living on that planet could survive during the time in which the planet is outwith the HZ by going into 'stasis'. The backing for this argument comes from the ability of the micro-animal known as the tardigrade to dessicate itself when presented with an extreme environment and rehydrate when conditions improve [Guidetti, 2011]. In this way, tardigrades are known to be able to survive even in the vacuum and intense radiation of space [Weronicka, 2017].

4. Biosignatures

As we are unable to physically travel to distant planets, our only line of inquisition into their nature comes from the light that we receive here on Earth. A biosignature is a signal which could imply the existence of or potential for life. Pohorille and Sokolowska define biosignatures as "chemical species, features or processes that provide evidence for the presence of life." [Pohorille, 2020]. There are several

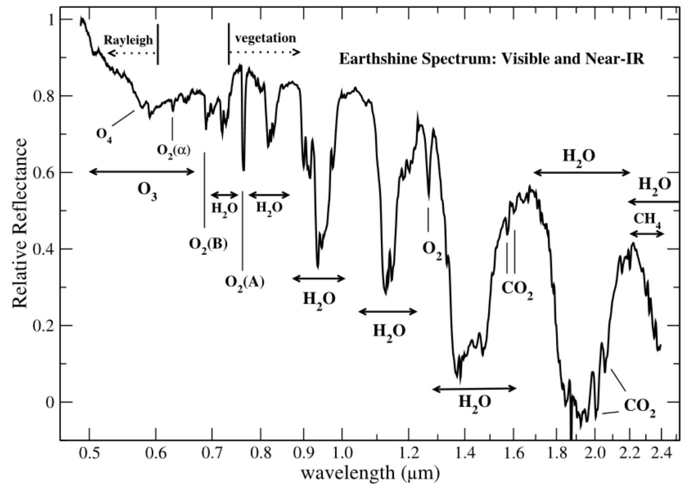

Figure 1: *Reflectance spectrum of Earth in the near infrared. Source: Turnbull et al., 2006*

different categories of biosignature, but in this section we will only consider spectral and surface types. Spectral biosignatures manifest in the absorption features in the spectrum of light transmitted through the atmospheres of exoplanets. The presence of biosignature gases in those atmospheres, organic compounds such as CH4 and CH3Cl which we know to be a byproduct of the metabolisms of certain lifeforms, could constitute evidence of the presence of Earth-like life [Segura, 2005]. The most significant disadvantage to this method is that all known biosignature gases have also been observed, although rarely, to be produced via abiotic means as well [Seager, 2012]. Surface biosignatures take the form of either chemical or electromagnetic signals from life itself, or the geological artefacts of life, such as the unusual impressions left on rock faces by chemosynthetic organisms [Westall, 2008]. One particularly strong surface biosignature for Earth, a planet we know to contain a variety of life forms, is the step-like jump in the reflectance spectrum known as the Vegetation Red Edge. This is a result of the high reflectivity of plant life at around 700nm, and could in theory be identified in the spectrum of a spatially unresolved exoplanet [Abrevaya, 2016]. In practice, this signature is heavily obscured by clouds and so would likely be difficult to identify even despite its strongly conclusive nature.

5. Optical Astronomy

Direct imaging, a detection method that involves measurement of the photons reflected or emitted by exoplanets,

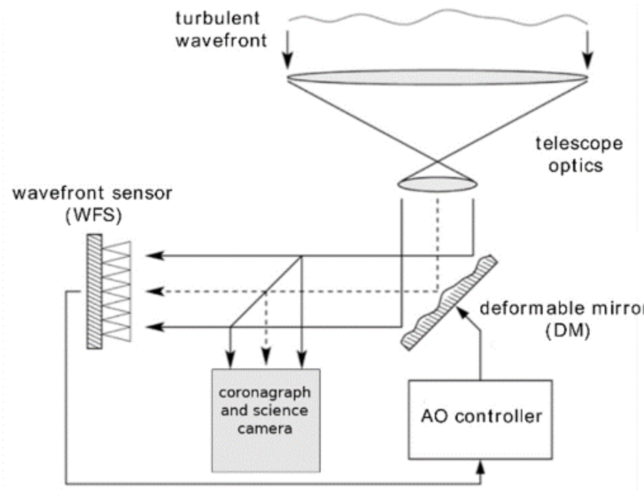

Figure 2: *Components of a modern optical telescope. Source: Rodack et al., 2021*

predominantly in visible and near-IR wavelengths. The low angular separation of planets from their host stars (often near the classical diffraction limit) coupled with the immense luminosity contrast makes this method particularly difficult, and so direct imaging requires large telescopes with advanced optical systems. The benefit is a far more detailed analysis of atmospheric and surface composition, as many spectral biosignatures are present in the wavelength ranges of optical telescopes, and the identification of surface biosignatures is generally only possible via direct observation [Fujii, 2018]

Modern optical telescopes employ an adaptive optics (AO) system consisting of a wavefront sensor, which analyses incoming light to identify perturbative atmospheric effects, and an array of deformable mirrors which are rapidly and continuously adjusted to correct for those effects. The most advanced AO systems in operation, such as the SPHERE system in the ESOs Very Large Telescope, have feedback rates of around 1.5KHz [Beuzit, 2019] which allow for fully diffraction-limited observations. However, some optical artefacts are much more challenging to correct for. Quasi-static speckles, the most significant being non-common path abberations (NCPAs) are imperfections in the telescope image that occur over highly varied timescales ranging from minutes to days and are due to a number of physical influences such as temperature fluctuations and gravitational stresses on the telescope components. NCPAs are of particular concern in the identification of exoplanets as both produce similar signals [Henault, 2019]. This can lead to abberations being mis-

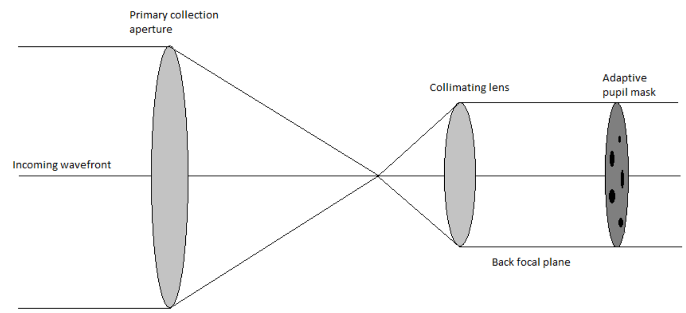

Figure 3: *Lens segment of optical train with adaptive pupil mask.*

taken as planetary systems, or worse, planetary systems being mistaken as abberations. One proposed solution to this issue would be the introduction of an adaptive mask to the back focal plane of the telescope. This mask would randomly block sections of the telescope aperture, changing the diffraction pattern and thereby turning the quasi-static NCPAs into dynamic abberations which can be averaged out over a long exposure time [Osborn, 2018].

Following the previous generation of 'Very Large Telescopes', or VLTs, the future of optical astronomy lies within several planned 'ELTs", or 'Extremely Large Telescopes'. Developments such as the 40 metre European ELT with state of the art adaptive optics systems are expected to produce "images 16 times sharper than those from the Hubble Space Telescope [ESO webpage]." Direct imaging and low-resolution spectroscopy of giant planets are among the scheduled applications of this particular telescope, and while this will surely open up fascinating new avenues of research, it also serves as a sobering reminder that the direct imaging of distant Earth-like planets is still largely beyond our capabilities. The construction of yet larger telescopes, or perhaps even more ambitious systems such as a space-based interferometer, is currently the next stage in the roadmap of exoplanet characterisation.

6. Urability

Urability is a term first described by A. Deamer et al. in their 2022 paper [Deamer, 2022] to describe conditions which are not only suitable for the presence of life but in which life could emerge from non-biological compounds. A good comparison between the habitability and the urability of an environment can be drawn from the experiments conducted over the outdated theory of spontaneous generation. A flask of nutritious broth was boiled so as to sterilise it, sealed, and then left to determine whether life

$$dS > 0$$

Figure 4: *One expression of the second law of thermodynamics, which states that entropy can only increase in an isolated system.*

would emerge within it. Unsurprisingly, it did not, and only when the seal was broken were bacteria observed to populate the flask. Clearly the environment within the flask was habitable, as bacteria were able to thrive within it when introduced, but the environment was not remotely urable. We now know that such a setup could be left for billions of years without life emerging from it, and we know this to be a consequence of the infamous second law of thermodynamics. The distinction between habitability and urability is critical in the field of astrobiology, as extremophile bacteria have been identified in environments that would likely be too hostile for early life to emerge.

The mechanism by which life emerged from complex organic compounds on Earth is not yet understood, despite many theories and approaches to this question having been proposed in the past. Some researchers favour a "top-down" approach in which known forms of life are simplified and categorised to identify a 'Last Universal Common Ancestor'. Others employ a "bottom-up" method where they research how volatile environmental conditions could coax complex organic compounds into primitive forms of life. The bottom-up method highlights the significant gap in our understanding of the relationship between physics and biology.

When considering the suitability of M-dwarfs for hosting exoplanets capable of sustaining life, discussion in contemporary literature appears to focus largely on conditions of habitability rather than urability. As mentioned previously, deep cloud cover may allow for a wider CHZ around M-dwarfs [Yang, 2013]. A planet with cloud cover would also be susceptible to lightning strikes, which some researchers believe provided ideal conditions for the evolution from complex organic chemistry to life here on Earth. This adds to the argument for analysing M-dwarf systems, and particularly orbiting planets with an active atmosphere.

7. Conclusion

The current state of research into exoplanet habitability would appear to be somewhat paradoxical. To advance our understanding of these other worlds, we must better

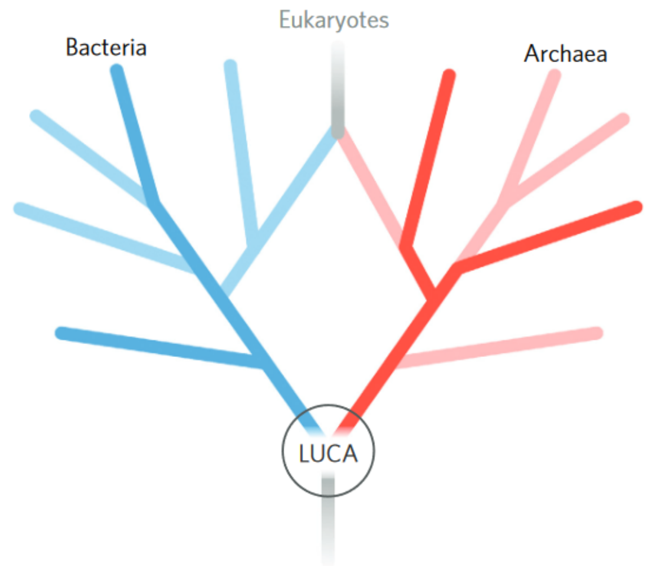

Figure 5: *Phylogenetic tree showing the 'Last Universal Common Ancestor'. Source: Weiss, 2016*

understand the processes that lead to Earth as we know it today. Conversely, due to Earth's active geology, insights into the history of our own planet would most easily be gleaned by analysing others like it. A breakthrough in either one of these questions would be mirrored in the other, highlighting the need for a decentralised approach to research in this field; one that unifies the work of scientists from multiple disciplines. Developing a more robust definition of what we consider to be life would make it easier to determine which stellar systems to prioritise. In the meantime, our current knowledge overwhelmingly indicates that M-dwarf systems should be our focus in the search for habitable, terrestrial exoplanets. Their stable HZs and the high probability of detecting transists make them ideal candidates for both photometry and radial velocity surveys. The distinction between habitability and urability is only the latest conceptual advancement in the field of astrobiology, and will serve as the basis of a stronger framework for exoplanet research. This is an endeavour that may be outwith our current technological capabilities, but as the field of optical astronomy advances we will eventually be able to resolve Earth-sized planets and provide a detailed spectral analysis on their atmospheres and surfaces.

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