Is Life Most Likely Around Sun-like Stars?

Manasvi Lingam[1]⋆ and Abraham Loeb[1]†
[1]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

1 November 2017

ABSTRACT
We consider the habitability of Earth-analogs around stars of different masses, which is regulated by the stellar lifetime, stellar wind-induced atmospheric erosion, and biologically active ultraviolet (UV) irradiance. By estimating the timescales associated with each of these items, we show that they collectively impose limits on the habitability of Earth-analogs. We conclude that planets orbiting most M-dwarfs are not likely to host life, and that the highest probability of complex biospheres is for planets around K- and G-type stars. Our analysis suggests that the current existence of life near the Sun is slightly unusual, but not significantly anomalous.

Key words: astrobiology – stars: winds, outflows – stars: low-mass – planets and satellites: atmospheres – planets and satellites: physical evolution – planets and satellites: terrestrial planets

1 INTRODUCTION

The discovery of thousands of exoplanets over the past decade has been accompanied by notable advances in our understanding of the many factors that are responsible for making a planet habitable (Cockell et al. 2016; Kaltenegger 2017). Studies of habitability should attempt to find the right balance between complexity and transparency, while also being expressible in terms of basic physical parameters that can be deduced from observations. We will adopt this approach for studying how multiple stellar properties can regulate the habitability of planets in the habitable zone (HZ), i.e. the region around the host star where liquid water can exist on the planetary surface (Kasting et al. 1993).

The first factor we take into account is the stellar lifetime, since it constitutes an upper bound on the timescale over which life-as-we-know-it can exist. The second phenomenon that we consider is the role of stellar winds in driving the erosion of planetary atmospheres - an effect that is particularly important for low-mass stars (Dong et al. 2017a; Lingam & Loeb 2017a). Our third consideration is the UV radiation environment, which has been suggested to have played an important role in facilitating prebiotic chemistry (Patel et al. 2015), and the rise in oxygen levels (Catling et al. 2001) on Earth, and planets in the HZ of other stars.

In this paper, we will study the timescales associated with each of these processes, and how they collectively set fairly stringent limits on the habitability of Earth-like planets around stars of different masses.

2 BIOACTIVE ULTRAVIOLET RADIATION AND ABIOGENESIS

A great deal remains unknown about the origin of life on Earth, such as the sites of abiogenesis and prebiotic systems chemistry (Ruiz-Mirazo et al. 2014; Luisi 2016). With regards to the latter scenario, the role of ultraviolet (UV) radiation has been widely explored. UV light may play an important role in RNA polymerization (Mulkidjanian et al. 2003), resolving the asphaltization problem (Benner et al. 2012) and enabling the synthesis of: (i) pyrimidine ribonucleotides (Powner et al. 2009), (ii) simple sugars (Ritson & Sutherland 2012), and (iii) the precursors of amino acids, nucleic acids, lips and carbohydrates (Patel et al. 2015). Evidence in favor of UV-mediated prebiotic pathways is based on the above data, as well as the stability of RNA nucleotides to UV irradiation, suggesting that they arose in a UV-rich environment (Beckstead et al. 2016).[1]

We shall posit henceforth that UV-driven prebiotic synthesis led to the origin of life, and that UV photochemistry constitutes the rate-limiting step in abiogenesis. We will consider an "Earth-analog" in the rest of the paper; by this term, we refer to an exoplanet whose basic physical parameters, e.g. the radius, effective temperature and surface pressure, are similar to those of Earth. The next step is to determine the biologically active (bioactive) UV irradiance

---

⋆ E-mail: manasvi.lingam@cfa.harvard.edu
† E-mail: aloeb@cfa.harvard.edu

[1] However, it must also be recognized that other energy sources may power prebiotic chemical reactions (Chyba & Sagan 1992), and other environments for the origin of life (e.g. hydrothermal vents) are not dependent upon the availability of UV radiation (Budin & Szostak 2010; Ruiz-Mirazo et al. 2014).
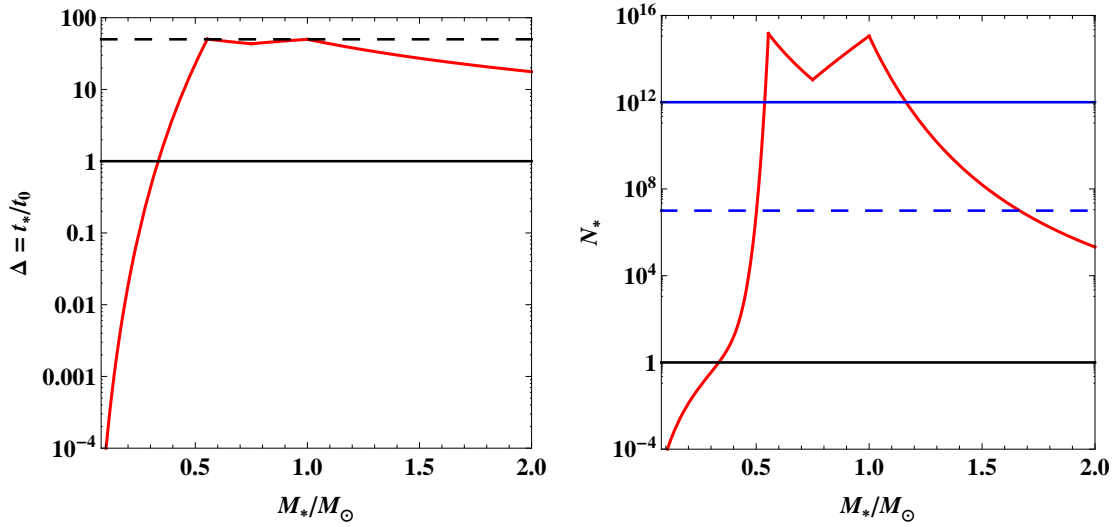
Figure 1. Left panel: maximum amplification factor $\Delta = t_\star/t_0$ as a function of stellar mass (in units of $M_\odot$). The dashed line denotes the solar value, while the solid line is the boundary below which abiogenesis would not occur. Right panel: peak diversity ($N_\star$) attainable as a function of stellar mass. The blue solid and dashed lines represent the *current* microbial and eukaryotic species diversity on Earth (Lingam & Loeb 2017b). The black solid line denotes the limit below which abiogenesis is not feasible on Earth-analogs.

$\mathcal{F}$ incident upon the Earth analog. The corresponding range of wavelengths is $200\,\text{nm} \lesssim \lambda \lesssim 400\,\text{nm}$, since photons with wavelengths $\lesssim 200\,\text{nm}$ are absorbed by CO_2 and H_2O in the atmosphere (Ranjan & Sasselov 2016). To zeroth order, it can be assumed that, under the above assumptions, $\mathcal{F}$ depends only on the stellar mass $M_\star$. In reality, it is dependent on several other parameters such as the stellar age, rotation and activity (Shkolnik & Barman 2014). Using the data tabulated in Table 3 of Rugheimer et al. (2015), we adopt the following heuristic scaling relation:

$$\mathcal{F} \sim \mathcal{F}_\odot \left(\frac{M_\star}{M_\odot}\right)^3 \quad M_\star \lesssim M_\odot$$

$$\mathcal{F} \sim \mathcal{F}_\odot \left(\frac{M_\star}{M_\odot}\right) \quad M_\star \gtrsim M_\odot \qquad (1)$$

which is valid in our region of interest ($M_\star \lesssim 2M_\odot$).[2] By assuming that the rates of prebiotic reactions necessary for abiogenesis are proportional to the bioactive UV flux and making use of (1), we obtain

$$t_0 \sim t_\oplus \left(\frac{M_\star}{M_\odot}\right)^{-3} \quad M_\star \lesssim M_\odot$$

$$t_0 \sim t_\oplus \left(\frac{M_\star}{M_\odot}\right)^{-1} \quad M_\star \gtrsim M_\odot \qquad (2)$$

where t_0 is the timescale for life to originate, and $t_\oplus \gtrsim 200$ Myr is a fiducial timescale for abiogenesis on Earth (Bell et al. 2015; Dodd et al. 2017; Lingam & Loeb 2017b). Hence, for planets orbiting M-dwarfs, the timescale for the origin of life would be ~ 10 Gyr if the associated timescale on Earth is ~ 100 Myr, in agreement with Ranjan et al.

(2017). It would therefore appear logical to conclude that abiogenesis on M-dwarfs can occur, but it takes a long time.

In addition, one must also take into account the fact that planets around M-dwarfs are subject to rapid atmospheric erosion by the stellar wind (Lingam & Loeb 2017a). For low-mass M-dwarfs, the erosion timescale is of order $\sim 10 - 100$ Myr (Airapetian et al. 2017; Dong et al. 2017a). By employing constraints set by atmospheric erosion due to the stellar wind for a weakly magnetized planet (whose timescale we denote by t_{SW}) and the stellar lifetime, the maximum timescale $t_\star$ over which speciation can occur was presented in Lingam & Loeb (2017b):

$$t_\star \sim 1.00\,t_\odot \left(\frac{M_\star}{M_\odot}\right)^{-2.5} \quad M_\star > 0.75M_\odot \qquad (3)$$

$$t_\star \sim 0.76\,t_\odot \left(\frac{M_\star}{M_\odot}\right)^{-3.5} \quad 0.55M_\odot < M_\star \leqslant 0.75M_\odot$$

$$t_\star \sim 100\,t_\odot \left(\frac{M_\star}{M_\odot}\right)^{4.8} \quad 0.08M_\odot < M_\star \leqslant 0.55M_\odot$$

Here, $t_\odot \sim 10$ Gyr denotes the total lifetime of the Sun. The available empirical evidence on Earth indicates that the total number of species (species richness) can be modelled approximately via an exponential function (Benton 2009); naturally, this exponential amplification will not proceed *ad infinitum*. Hence, Lingam & Loeb (2017b) introduced the peak biological diversity $N_\star$ as,

$$N_\star \equiv N(t_\star) = \exp\left(\frac{t_\star}{\tau}\right) - 1, \qquad (4)$$

where τ is the associated e-folding timescale. We introduce the notation $\Delta = t_\star/t_0$ and use $t_0/\tau = \ln 2$ to rewrite the above equation as follows:

$$N_\star = 2^\Delta - 1 \qquad (5)$$

It is convenient to interpret Δ as the (maximum) amplification factor for evolution. Fig. 1 shows the values of Δ and

---

[2] Our analysis can be further refined by introducing a more sophisticated piecewise power-law or polynomial ansatz for $\mathcal{F}$, but the essential qualitative conclusions are mostly unchanged.

$N_\star$ as a function of stellar mass. Using the stellar mass function to compute the weighted value of $N_\star$ (Loeb et al. 2016) does not alter the right panel of Fig. 1 significantly, since the exponential factor in (4) is the dominant contribution.

For Earth-analogs around stars with $M_\star \lesssim 0.3 M_\odot$, we find $N_\star < 1$. Hence, such planets have minimal chances of possessing life since their atmospheres would be stripped prior to the (relatively slow) emergence of life. From the left panel of Fig. 1, we see that the amplification factor Δ is nearly constant for $0.5 \lesssim M_\star \lesssim 2 M_\odot$. Although massive stars have a shorter lifetime, they also have a higher fraction of the emitted energy in the bioactive UV range, implying that UV-mediated prebiotic pathways could operate at faster rates. Hence, the lower lifetime is counteracted by a correspondingly shorter abiogenesis timescale, thus resulting in a near-constant value of Δ. The right panel of Fig. 1 displays a double peaked structure, and the peak species richness occurs for $0.5 \lesssim M_\star \lesssim M_\odot$. Furthermore, $N_\star$ for $M_\star \sim M_\odot$ approximately attains the global maximum value.

The above results may collectively explain why we find ourselves around a K- or G-type star, and not in the HZ of an M-dwarf, despite the latter being more numerous and characterized by long stellar lifetimes (Loeb et al. 2016). When the consequences of extreme space weather events arising from large flares and superflares are taken into account, the likelihood of complex biospheres around K- and M-dwarfs will be further diminished (Lingam & Loeb 2017c). If we choose a lower bound of $\sim 0.5 M_\odot$ for stars to host complex biospheres and utilize Fig. 4 of Loeb et al. (2016), we find that terrestrial life at the present cosmic time has a probability of $\sim 10\%$. Clearly, our presence is far less anomalous compared to the scenario where all stars host complex life since that has a 0.1% probability (Loeb et al. 2016).

Before proceeding further, we wish to point out a few caveats regarding the model. As noted earlier, stellar parameters other than $M_\star$ (especially the planetary system's age) will play a notable role in regulating $\mathcal{F}$. Habitable planets around low-mass stars are capable of building up abiotic O_2 atmospheres (even up to ~ 100 bars) through several mechanisms (Tian et al. 2014; Luger & Barnes 2015; Meadows 2017). Given that more massive atmospheres will take longer to be eroded, there may exist a longer time interval for life to originate. However, elevated levels of ozone (formed via UV photolysis of O_2) would serve as a shield and prevent bioactive UV radiation from reaching the surface. Since there exist two opposing factors, it is unclear as to whether thick O_2 atmospheres would lead to beneficial or harmful ramifications.

Although we have not considered the role of flares thus far, they also give rise to both positive and negative consequences. On the one hand, it is plausible that flares could transiently deliver the requisite levels of UV radiation to power prebiotic synthesis (Ranjan et al. 2017). On the other hand, large flares on active stars are typically accompanied by high-fluence solar proton events and elevated levels of ionizing radiation, which may engender significant damage to the biosphere (Dartnell 2011; Lingam & Loeb 2017c). Moreover, during these events, atmospheric losses are enhanced by 1-2 orders of magnitude (Dong et al. 2017b).

Lastly, we note that (2) implies that t_0 varies by 2-3 orders of magnitudes in the transition from M- to G-type stars; see Lineweaver & Davis (2002) and Spiegel & Turner (2012)
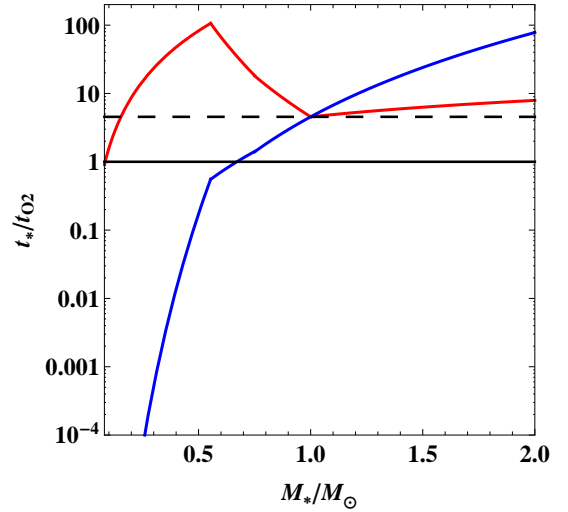
Figure 2. The ratio of the timescale for oxygenation (t_{O_2}) and the maximum duration over which evolution can take place ($t_\star$). The dashed line denotes the solar value, while the unbroken line is the boundary below which sufficient levels of oxygenation would not be feasible. The red and blue curves include and exclude the emission from stellar chromospheric activity, respectively.

for differing Bayesian analyses of t_0 and the ensuing implications. Furthermore, Fig. 1 indicates that stars $\lesssim 0.3 M_\odot$ are unlikely to host inhabited planets. These trends jointly suggest that the fraction of life-bearing planets might be rather low in the current epoch of the Universe.

3 ULTRAVIOLET RADIATION AND COMPLEX LIFE

Fig. 1 implies that stars with $M_\star \gtrsim 0.3 M_\odot$ may not host life-bearing planets since atmospheric erosion occurs faster than abiogenesis. Although bioactive UV radiation can power prebiotic chemistry, its propensity for causing DNA damage is well-known. Several studies have focused on this aspect (Cockell 1999; Segura et al. 2003; Kaltenegger 2017) since the absence of an ozone layer leads to higher levels of biologically effective UV radiation reaching the surface (Dartnell 2011). Typically, the UV flux also increases with the stellar mass and decreases with age.

Here, we shall explore a different role that UV radiation could play in facilitating the rise of complex life. On Earth, the following events are believed to have occurred in roughly chronological order: (i) oxygenic photosynthesis, (ii) Great Oxygenation Event (GOE), (iii) origin of eukaryotes, (iv) Neoproterozoic Oxygenation Event (NOE), and (v) emergence of large and complex organisms (Canfield 2005; Hohmann-Marriott & Blankenship 2011; Lyons et al. 2014; Knoll 2015; Knoll & Nowak 2017). The causes and timing of all these events are subject to large uncertainties; consequently, it is unclear as to whether the increase in oxygen levels had a cause-or-effect relationship with life. Despite this variability, it has been argued that oxygen is a necessary requirement for complex life on habitable planets and thus constitutes a vital limiting step (Catling et al. 2005).

One of the main hypotheses for the GOE suggests that

Table 1. Characteristic timescales for Earth-analogs orbiting stars of different masses

Star mass ($M_\odot$)	Stellar lifetime (yr)	t_{SW} (yr)	t_0 (yr)	t_{O_2} (yr)	t_ℓ (yr)
0.1	6.7×10^{12}	1.7×10^7	2×10^{11}	1.1×10^7	2×10^{11}
0.3	5.1×10^{11}	3.2×10^9	7.4×10^9	1.4×10^8	7.5×10^9
0.6	4.5×10^{10}	8.8×10^{10}	9.3×10^8	6.8×10^8	1.6×10^9
1.0	10^{10}	10^{12}	2×10^8	2.2×10^9	2.4×10^9
1.5	3.6×10^9	6.9×10^{12}	1.3×10^8	5.8×10^8	7.1×10^8

biogenic methane (produced by methanogens) undergoes UV photolysis, thereby leading to hydrogen escape to escape and irreversible oxidation (Catling et al. 2001). It has also been suggested that the buildup of oxygen on Earth may have occurred through the photolysis of water by UV radiation (Carver 1981). On low-mass stars, UV photolysis of CO_2 also leads to significant production of abiotic oxygen (Tian et al. 2014). In these scenarios, it is clear that UV light plays a significant role in enabling the rise of atmospheric oxygen. In addition to the putative role of UV irradiance (determined by stellar physics), many complex biogeochemical governing factors are not considered herein.

A similar line of reasoning concerning the role of UV photolysis in raising oxygen levels was adopted in Livio (1999) to arrive at the characteristic timescale for life. Here, we shall focus on quantifying t_{O_2}, i.e. the timescale associated with initial oxygenation. Since a significant fraction ($\gtrsim 50\%$) of both water and methane photodissociation occurs via Lyα, we will consider the Lyα flux to be a proxy for the rate of oxygenation. Thus, in analogy to (1) and (2), we identify the following scaling relations.

$$t_{O_2} \sim 0.22\, t_\odot \left(\frac{M_\star}{M_\odot} \right)^{2.3} \qquad M_\star \lesssim M_\odot$$

$$t_{O_2} \sim 0.22\, t_\odot \left(\frac{M_\star}{M_\odot} \right)^{-3.3} \qquad M_\star \gtrsim M_\odot \qquad (6)$$

For $M_\star \lesssim M_\odot$, we have used Fig. 9 and Table 5 of Linsky et al. (2013) for $P > 25$ days along with the stellar effective temperature-mass relation, $T_{\rm eff} \propto M_\star^{0.5}$. On the other hand, the sample size for $M_\star \gtrsim M_\odot$ is relatively small. For F-type stars, we have utilized Landsman & Simon (1993), Table 4 of Linsky et al. (2013), and Table 6 of Rugheimer et al. (2015).

We have also relied upon the fact that the GOE occurred on Earth ~ 2.4 Gyr ago (Lyons et al. 2014).[3] Note that $t_{O_2} \lesssim t_\varepsilon$, where t_ε is the timescale for eukaryogenesis (Parfrey et al. 2011), implying that t_{O_2} can be viewed as a potential lower bound for the emergence of "complex" life. We emphasize that (6) has been constructed based on observational evidence and therefore includes the Lyα flux arising from stellar chromospheres and transition regions. In contrast, if their role is ignored, we may use (Livio 1999):

$$t_{O_2} \sim 0.22\, t_\odot \left(\frac{M_\star}{M_\odot} \right)^{-6.6}. \qquad (7)$$

A striking difference between (6) and (7) is that, for $M_\star \lesssim M_\odot$, the former relation has a positive spectral index while

the latter has a negative value. Hence, in the presence (absence) of chromospheric activity, sufficient levels of oxygenation for complex life to flourish would arise over faster (slower) timescales for low-mass stars.

We are therefore in a position to compare t_{O_2} with $t_\star$. If $t_\star > t_{O_2}$, the Earth-analog would be potentially capable of giving rise to complex life, and vice-versa. In Fig. 2, the timescales for oxygenation, with and without the contributions from stellar chromospheres and transition regions - (6) and (7) respectively - have been compared to $t_\star$. When (6) is taken into account, levels of oxygen comparable to the GOE are always attainable. In contrast, when (6) is used, only stars with $M_\star > 0.67 M_\odot$ can fulfill this criterion.

One may also consider the timescale, $t_\ell = t_0 + t_{O_2}$, because t_0 and t_{O_2} are approximately the timescales for "simple" and "complex" life respectively. Hence, their sum (t_ℓ) is a heuristic measure of the total time required for complex life to originate. From (2) and (6), we find that the branch $M_\star \lesssim M_\odot$ is characterized by non-monotonic behaviour. Solving for $\partial t_\ell / \partial M_\star = 0$, we find that a minimum value is attained at $M_\star \sim 0.67 M_\odot$ corresponding to $t_\ell \sim 1.5$ Gyr.[4] Our analysis implies, *ceteris paribus*, that the fastest time for the emergence of complex life would occur on a K-dwarf when we restrict ourselves to stars $\lesssim M_\odot$. If we consider the branch $M_\star \gtrsim M_\odot$, we find that t_ℓ decreases monotonically with the mass. In this case, however, the shorter stellar lifetime would imply that speciation would take place over a shorter timescale, as seen from the right panel of Fig. 1.

We conclude by observing that (6) indicates that the timescale for raising oxygen to levels that would enable complex life to emerge is ~ 100 times lower on Earth-analogs orbiting M-dwarfs. This might imply that intelligent life could also arise much faster on certain planets. A similar result was presented in McKay (1996), albeit based on the analysis of planetary (and not stellar) constraints. However, it must be emphasized that rapid oxygenation could also result in detrimental consequences, since O_2 was toxic to early (anaerobic) organisms on Earth.

4   CONCLUSION

In this paper, we explored multiple constraints on the potential habitability of Earth-analogs orbiting stars of different masses. We chose the stellar mass as our governing parameter, since it can be measured easily relative to other parameters (e.g. stellar age and activity), and it enables us to identify appropriate stellar systems for future searches of

---

[3] We will not analyze the NOE herein despite its significance from an evolutionary perspective, since its timing and causal relationship with biota remains unclear (Och & Shields-Zhou 2012).

[4] For the Earth-Sun system, we obtain $t_\ell \sim 2.4$ Gyr, slightly lower than the eukaryogenesis timescale of ~ 2.6 Gyr.

extraterrestrial life. Naturally, there exist several other stellar and planetary parameters which also play a significant role in UV habitability that were not considered here. We considered constraints set by: (i) atmospheric erosion driven by the stellar wind, (ii) stellar lifetime, (iii) availability of UV radiation to power prebiotic chemical reactions, and (iv) photolysis of molecules to enable oxygenation. The characteristic timescales for all these processes are summarized in Table 1 for Earth-analogs around different stars.

We found that stars $\lesssim 0.3 M_\odot$ are unlikely to host life-bearing planets because their atmospheres would be eroded prior to abiogenesis. Hence, the probability that the planets in the HZ of Proxima Centauri, TRAPPIST-1 and LHS 1140 are inhabited is low. Planets around higher-mass M-dwarfs could potentially have life but their prospects of hosting Earth-like complex biospheres are not high. We concluded that K- and G-type stars are most likely to host complex biospheres, as seen from Fig. 1. In fact, their peak species richness is comparable since K-dwarfs are longer lived than G-type stars but, on the other hand, the associated timescale for abiogenesis is also longer. Based on criteria (iii) and (iv), we found that Earth-analogs around stars with masses $\sim 0.67 M_\odot$ may take the least amount of time for complex (eukaryotic-type) life to originate. Planets in the HZ of F-type stars could, due to elevated levels of UV radiation, achieve abiogenesis and oxygenation more rapidly compared to the Earth.[5] Conversely, as these stars have a shorter lifetime, these planets' peak biodiversity would be lower when compared to the Earth-Sun system.

Thus, based on these considerations, it seems reasonable to suggest that future searches for life should prioritize K- and G-type stars insofar our analysis is concerned, although early M-dwarfs and F-type stars may also represent promising targets; a similar position was advocated in Kasting et al. (1993), Heller & Armstrong (2014) and Lingam & Loeb (2017b). Lastly, our analysis also suggests that our existence around a Sun-like star in the present epoch is not particularly anomalous (Loeb et al. 2016).

REFERENCES

Airapetian V. S., Glocer A., Khazanov G. V., Loyd R. O. P., France K., Sojka J., Danchi W. C., Liemohn M. W., 2017, Astrophys. J. Lett., 836, L3
Beckstead A. A., Zhang Y., de Vries M. S., Kohler B., 2016, Phys. Chem. Chem. Phys., 18, 24228
Bell E. A., Boehnke P., Harrison T. M., Mao W. L., 2015, Proc. Natl. Acad. Sci. USA, 112, 14518
Benner S. A., Kim H.-J., Carrigan M. A., 2012, Acc. Chem. Res., 45, 2025

[5] The elevated UV levels can, at the same time, also prove to be deleterious to the evolution and sustenance of life.

Benton M. J., 2009, Science, 323, 728
Budin I., Szostak J. W., 2010, Annu. Rev. Biophys., 39, 245
Canfield D. E., 2005, Annu. Rev. Earth Planet. Sci., 33, 1
Carver J. H., 1981, Nature, 292, 136
Catling D. C., Zahnle K. J., McKay C. P., 2001, Science, 293, 839
Catling D. C., Glein C. R., Zahnle K. J., McKay C. P., 2005, Astrobiology, 5, 415
Chyba C., Sagan C., 1992, Nature, 355, 125
Cockell C. S., 1999, Icarus, 141, 399
Cockell C. S., et al., 2016, Astrobiology, 16, 89
Dartnell L. R., 2011, Astrobiology, 11, 551
Dodd M. S., Papineau D., Grenne T., Slack J. F., Rittner M., Pirajno F., O'Neil J., Little C. T. S., 2017, Nature, 543, 60
Dong C., Lingam M., Ma Y., Cohen O., 2017a, Astrophys. J. Lett., 837, L26
Dong C., Huang Z., Lingam M., Tóth G., Gombosi T., Bhattacharjee A., 2017b, Astrophys. J. Lett., 847, L4
Heller R., Armstrong J., 2014, Astrobiology, 14, 50
Hohmann-Marriott M. F., Blankenship R. E., 2011, Annu. Rev. Plant Biol., 62, 515
Kaltenegger L., 2017, Annu. Rev. Astron. Astrophys., 55, 433
Kasting J. F., Whitmire D. P., Reynolds R. T., 1993, Icarus, 101, 108
Knoll A. H., 2015, Life on a Young Planet: The First Three Billion Years of Evolution on Earth. Princeton Science Library, Princeton Univ. Press
Knoll A. H., Nowak M. A., 2017, Sci. Adv., 3, e1603076
Landsman W., Simon T., 1993, Astrophys. J., 408, 305
Lineweaver C. H., Davis T. M., 2002, Astrobiology, 2, 293
Lingam M., Loeb A., 2017a, Int. J. Astrobiol.,
Lingam M., Loeb A., 2017b, Astrophys. J. Lett., 846, L21
Lingam M., Loeb A., 2017c, Astrophys. J., 848, 41
Linsky J. L., France K., Ayres T., 2013, Astrophys. J., 766, 69
Livio M., 1999, Astrophys. J., 511, 429
Loeb A., Batista R. A., Sloan D., 2016, J. Cosmol. Astropart. Phys., 8, 040
Luger R., Barnes R., 2015, Astrobiology, 15, 119
Luisi P. L., 2016, The Emergence of Life: From Chemical Origins to Synthetic Biology. Cambridge Univ. Press
Lyons T. W., Reinhard C. T., Planavsky N. J., 2014, Nature, 506, 307
McKay C. P., 1996, in Doyle L. R., ed., Circumstellar Habitable Zones. pp 405–419
Meadows V. S., 2017, Astrobiology, 17, 1022
Mulkidjanian A. Y., Cherepanov D. A., Galperin M. Y., 2003, BMC Evol. Biol., 3, 12
Och L. M., Shields-Zhou G. A., 2012, Earth Sci. Rev., 110, 26
Parfrey L. W., Lahr D. J. G., Knoll A. H., Katz L. A., 2011, Proc. Natl. Acad. Sci. USA, 108, 13624
Patel B. H., Percivalle C., Ritson D. J., Duffy C. D., Sutherland J. D., 2015, Nat. Chem., 7, 301
Powner M. W., Gerland B., Sutherland J. D., 2009, Nature, 459, 239
Ranjan S., Sasselov D. D., 2016, Astrobiology, 16, 68
Ranjan S., Wordsworth R., Sasselov D. D., 2017, Astrophys. J., 843, 110
Ritson D., Sutherland J. D., 2012, Nat. Chem., 4, 895
Rugheimer S., Segura A., Kaltenegger L., Sasselov D., 2015, Astrophys. J., 806, 137
Ruiz-Mirazo K., Briones C., de la Escosura A., 2014, Chem. Rev., 114, 285
Segura A., Krelove K., Kasting J. F., Sommerlatt D., Meadows V., Crisp D., Cohen M., Mlawer E., 2003, Astrobiology, 3, 689
Shkolnik E. L., Barman T. S., 2014, Astron. J., 148, 64
Spiegel D. S., Turner E. L., 2012, Proc. Natl. Acad. Sci. USA, 109, 395
Tian F., France K., Linsky J. L., Mauas P. J. D., Vieytes M. C., 2014, Earth Planet. Sci. Lett., 385, 22