Colloquium: Physical constraints for the evolution of life on exoplanets

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(published 11 June 2019)

Recently, many Earth-sized planets have been discovered around stars other than the Sun that might possess appropriate conditions for life. The development of theoretical methods for assessing the putative habitability of these worlds is of paramount importance, since it serves the dual purpose of identifying and quantifying what types of biosignatures may exist and determining the selection of optimal target stars and planets for subsequent observations. This Colloquium discusses how a multitude of physical factors act in tandem to regulate the propensity of worlds for hosting detectable biospheres. The focus is primarily on planets around low-mass stars, as they are most readily accessible to searches for biosignatures. This Colloquium outlines how factors such as stellar winds, the availability of ultraviolet and visible light, the surface water and land fractions, stellar flares, and associated phenomena place potential constraints on the evolution of life on these planets.

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I. INTRODUCTION

Ever since the ancient Greeks, and probably even earlier, many have argued in favor of the existence of worlds (planets and moons) outside our Solar System. However, it was only a few decades ago that the first extrasolar planets (exoplanets) were detected, owing to the observational challenges associated with finding planets because of their extremely low brightness and masses relative to their host stars. One of the notable early discoveries was 51 Pegasi b, the first exoplanet orbiting a solar-type star (Mayor and Queloz, 1995). Many of the initial discoveries, including 51 Pegasi b, were of exoplanets whose masses were comparable to, or larger than,

that of Jupiter. A review of the early developments in exoplanetary science was given by Perryman (2000).

From the 1990s until the launch of NASA's *Kepler* space-craft in 2009 (Batalha, 2014; Borucki, 2016), exoplanets were discovered at a steady rate and numbered in the hundreds. In conjunction with the *Kepler* mission, designed with the express purpose of finding exoplanets, a flotilla of ground-based telescopes have propelled the explosive growth of exoplanetary science (Winn and Fabrycky, 2015). As of April 2019, the number of confirmed exoplanets is over 4000 with planetary systems possessing more than one exoplanet exceeding 650.[1] Thus, it would be no exaggeration to state that the field of exoplanets represents one of the most rapidly advancing frontiers in astrophysics (Perryman, 2018).

One of the most compelling reasons behind the study of exoplanets entails the prospect of detecting extraterrestrial life beyond Earth.[2] It is fair to say that the question, "Are we alone?", is one that has resonated with humanity over millenia. The identification of extraterrestrial life is fraught with immense difficulties and challenges, owing to which it is natural to commence searching for "life as we know it" on a planet that shares the basic physical properties of Earth. Water is conventionally regarded as one of the most essential requirements for life on Earth owing to its unusual physico-chemical properties (Ball, 2008). Hence, most studies tend to adopt a "follow the water" approach, i.e., to search for planets where liquid water could exist on their surfaces.

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[1]http://exoplanet.eu/catalog/.

[2]Exomoons are also of considerable interest as possible abodes for extraterrestrial life and are likely to be numerous (Heller *et al.*, 2014), but we restrict ourselves to exoplanets as they have been subjected to more theoretical and observational studies. Recently, some preliminary evidence has been presented in favor of a Neptune-sized exomoon candidate orbiting the Jupiter-sized planet Kepler-1625b (Teachey and Kipping, 2018).

Before proceeding further, we caution that solvents other than water are conceivable and biochemistries not based on carbon are feasible (Bains, 2004; Benner, Ricardo, and Carrigan, 2004; Schulze-Makuch and Irwin, 2008). One notable example in this category is Titan, which is known to possess methane lakes and seas that contribute to a methane-based hydrological cycle (Hayes, 2016; Mitchell and Lora, 2016). We will not tackle this issue herein, despite its undoubted importance, as our understanding of "life as we do not know it" is much less developed compared to our knowledge of life on Earth.[3]

The "follow the water" approach, from a theoretical and observational standpoint, has led to the identification of the circumstellar habitable zone (HZ), i.e., the annular region around the host star where a planet is theoretically capable of hosting liquid water on its surface. Aside from having a clement surface temperature, the planet needs to retain an atmosphere since water ice transforms directly into gas phase in vacuum. Mars, whose mass is one-tenth that of the Earth, is believed to have lost the majority of its atmosphere in the distant past (Jakosky *et al.*, 2017; Dong *et al.*, 2018a).

It is evident that a smaller and less hotter star would emit less radiation, and therefore its HZ would be situated closer to it. However, the HZ depends not only on stellar properties but also a wide range of planetary properties including, but not restricted to, its atmospheric composition (mixture of greenhouse gases), mass, and rotation. The HZ has a long and fascinating history dating back to at least the 19th century, which has been discussed by Gonzalez (2005). The modern formulations of the HZ have matured during the past couple of decades (Kasting, Whitmire, and Reynolds, 1993; Kopparapu *et al.*, 2013, 2014, 2016; Yang *et al.*, 2014; Zsom, 2015; Haqq-Misra *et al.*, 2016; Ramirez, 2018; Schwieterman *et al.*, 2019). Although we focus only on planets within the circumstellar HZ herein, it is worth noting the concept of the HZ has been extended to encompass both exomoons as well as planets around stellar binaries, i.e., the circumplanetary (Heller *et al.*, 2014; Dobos, Heller, and Turner, 2017) and circumbinary (Kane and Hinkel, 2013; Cuntz, 2014) habitable zones, respectively.

There are a couple of important points that must be kept in mind regarding the HZ. First, not all planets within the HZ are guaranteed to actually have liquid water on the surface. Second, even the presence of liquid water is a necessary, but not sufficient, condition for the existence of life. For example, some of the other necessary requirements include sufficient abundances of "bioessential" elements such as carbon, hydrogen, oxygen, nitrogen, and phosphorus as well as free energy flows (Hoehler, Amend, and Shock, 2007; Morowitz and Smith, 2007).[4] Hence, it is essential to avoid conflating the HZ with the much wider notion of habitability (Moore *et al.*, 2017; Tasker *et al.*, 2017). As per the 2015 NASA Astrobiology Strategy, habitability can be understood in the following terms.[5]

> Habitability has been defined as the potential of an environment (past or present) to support life of any kind … Habitability is a function of a multitude of environmental parameters whose study is biased by the effects that biology has on these parameters.

Further reviews of this multifaceted subject have been given by Dole (1964), Lammer *et al.* (2009), Javaux and Dehant (2010), Lineweaver and Chopra (2012), Seager (2013), Cockell *et al.* (2016), and Ehlmann *et al.* (2016).

Although the limitations of the HZ definition must be duly recognized, it is equally important to appreciate its strengths. As the HZ depends on a wide range of planetary and stellar parameters, it encompasses a diverse array of potentially habitable environments; an overview of the recent progress in defining and studying HZs was presented by Ramirez (2018). Perhaps, more importantly, owing to the constraints imposed by observation time and funding, the selection of suitable target stars and planets is of paramount importance (Horner and Jones, 2010; Kaltenegger *et al.*, 2010; Lingam and Loeb, 2018a). In this respect, the HZ provides a potential methodology for identifying and selecting planets for more detailed follow-up observations.

In connection with the HZ, a couple of exciting discoveries over the past few years merit special mention. An exoplanet was discovered in the HZ of Proxima Centauri, the star nearest to the Earth at a distance of 1.3 pc, namely, 4×10^{16} m (Anglada-Escudé *et al.*, 2016). This exoplanet, named Proxima Centauri b (or Proxima b for short), has a minimum mass of $1.3 M_{\oplus}$, where $M_{\oplus}$ is the mass of the Earth. The second major breakthrough entailed the discovery of seven, roughly Earth-sized, planets orbiting the star TRAPPIST-1 at a distance of 12.1 pc (Gillon *et al.*, 2016, 2017). Of these seven planets, at least three of them reside within the HZ and are therefore capable of hosting liquid water on the surface. The masses of these seven planets fall within $(0.3–1.16)M_{\oplus}$ and the radii range $(0.77–1.15)R_{\oplus}$ (Delrez *et al.*, 2018; Grimm *et al.*, 2018), where $R_{\oplus}$ is the radius of the Earth. Another discovery worth pointing out is the planet LHS 1140b, with a radius and mass of $1.4 R_{\oplus}$ and $6.6 M_{\oplus}$, respectively, in the HZ of a star at a distance of 12 pc (Dittmann *et al.*, 2017).

Before proceeding further, it is essential to articulate the scope and philosophy of this Colloquium. It is not feasible to present a comprehensive account of all aspects of habitability due to length constraints. Instead, only a few select topics that have witnessed notable advances within the past decade are tackled. Virtually all factors that we address have a physical basis and pertain to the properties of the host star. This is because we possess a relatively sound understanding of these aspects, and they are arguably less subject to systemic uncertainties.

We will, for instance, not address the issue of whether a given planet can sustain a stable and clement climate over Gyr

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[3]Whenever we employ the word "life" henceforth, it must be viewed with the proviso understanding that we actually refer to life as we know it, unless explicitly stated otherwise.

[4]As life is a far-from-equilibrium phenomenon, it is more accurate to state that the conversion of thermodynamic disequilibria facilitates its emergence (Branscomb *et al.*, 2017).

(10^9 yr) time scales, despite its relevance for habitability, because the climate depends on a diverse array of factors such as the orbital eccentricity, axial tilt (obliquity), the existence of a large moon (Laskar, Joutel, and Robutel, 1993), surface landmasses and oceans, and biological feedback mechanisms to name a few. Discussions of how some of these variables affect the climate have been given by Kasting (2010), Pierrehumbert (2010), and Catling and Kasting (2017), whereas analyses of the climates of Proxima b and the TRAPPIST-1 system include Turbet *et al.* (2016, 2018), Alberti *et al.* (2017), Boutle *et al.* (2017), Wolf (2017), Lincowski *et al.* (2018), and Meadows *et al.* (2018a). In the same spirit, we will not tackle geophysical and biogeochemical cycles herein owing to their complexity (Sarmiento and Gruber, 2006). Furthermore, the biogeochemistry of planets has not been explored in sufficient detail, despite the fact that it can give rise to feedback and buffering over short time scales (Schlesinger and Bernhardt, 2013), which are comparable to those encountered in this Colloquium.

Looking beyond planetary and stellar properties, high-energy astrophysical phenomena within the Galaxy also play a vital role in regulating planetary habitability. This has prompted the analysis and identification of the galactic habitable zone (Gonzalez, Brownlee, and Ward, 2001; Lineweaver, Fenner, and Gibson, 2004), but the limits of this region remain subject to uncertainty depending on the constraints adopted (Prantzos, 2008; Gowanlock and Morrison, 2018). Examples of the astrophysical risks for life include high doses of ionizing radiation emanating from quasars, supernovae, and gamma ray bursts (Thorsett, 1995; Melott and Thomas, 2011; Piran and Jimenez, 2014; Balbi and Tombesi, 2017; Sloan, Alves Batista, and Loeb, 2017; Forbes and Loeb, 2018; Lingam, Ginsburg, and Bialy, 2019).

We mostly focus on planets in the HZ of the most common stars, namely, M dwarfs. Earlier reviews of the habitability of M-dwarf exoplanets can be found in Scalo *et al.* (2007), Tarter *et al.* (2007), and Shields, Ballard, and Johnson (2016). Broadly speaking, M dwarfs are low-mass stars with a mass $M_\star$ in the range $0.075 < M_\star/M_\odot < 0.5$, where $M_\odot$ is the solar mass. M dwarfs also exhibit significant variation in their radii, effective temperatures, surface magnetic fields, and activity (Chabrier and Baraffe, 2000). One of the most notable features of M dwarfs is that they appear in two distinct "flavors" (Chabrier and Baraffe, 1997; Stassun *et al.*, 2011). M dwarfs with $M_\star \gtrsim 0.35 M_\odot$ are characterized by stellar interiors with an inner radiative zone and an outer convective envelope; in contrast, M dwarfs with $M_\star \lesssim 0.35 M_\odot$ are fully convective, i.e., they do not possess the radiative zone.

Not only are these low-mass stars the most common and long lived in the Universe (Adams and Laughlin, 1997; Chabrier, 2003; Tarter *et al.*, 2007), about 20% of them have Earth-sized planets in their HZs (Bonfils *et al.*, 2013; Dressing and Charbonneau, 2015; Mulders, Pascucci, and Apai, 2015). These planets are also comparatively accessible to detailed observations (Winn, 2010; Fujii *et al.*, 2018), mostly as a consequence of their smaller orbital radii. Finally, the nearest planets in the HZ described earlier—Proxima b, the TRAPPIST-1 system, and LHS 1140b—are located around M dwarfs.

The outline of this Colloquium is as follows. In Sec. II, we describe how stellar winds can erode planetary atmospheres and reduce the shielding offered by planetary magnetospheres. The former, in particular, are especially important since they serve as the repositories of most biomarkers, implying that their existence is necessary for detecting nontechnological extraterrestrial life outside our Solar System. We discuss how the origin and evolution of life is affected by electromagnetic radiation fluxes from the host star in Sec. III. This is followed by analyzing how stellar flares and their associated physical phenomena influence biospheres in Sec. IV. We conclude with a summary of the central results in Sec. V.

II. STELLAR WINDS

Stellar winds are streams of plasma that originate from the outer regions of stellar coronae (Parker, 1958; Priest, 2014). We discuss two primary aspects by which stellar winds influence planetary habitability. Additional effects include Ohmic heating in the upper atmosphere (Cohen *et al.*, 2014) that may be up to an order of magnitude higher than the heating from extreme ultraviolet (EUV) radiation in the wavelength range of 10–120 nm (Cohen *et al.*, 2018).

A. Planetary magnetospheres

When exoplanets possess an intrinsic magnetic field, the solar wind plasma will be deflected (Baumjohann and Treumann, 2012). The cavity created by the planetary magnetic field is the magnetosphere. The magnetopause distance (R_{mp}), which represents the outer boundary of the magnetosphere, serves as a useful proxy for its size. Here let us derive its value.

Suppose that the planet has a pure dipole magnetic field and that its strength is B_p at the surface of the planet of radius R_p. At the magnetopause distance, the corresponding magnetic field B_{mp} is given by

$$B_{mp} = B_p \left(\frac{R_p}{R_{mp}} \right)^3, \qquad (1)$$

provided that only the radial dependence has been retained. The distance R_{mp} is computed by demanding that the magnetic pressure is approximately equal to the solar wind pressure P_{sw}. The latter has contributions from the kinetic, magnetic, and thermal energies of the solar wind, but it is the first component that typically dominates, i.e., $P_{sw} \approx \rho_{sw} v_{sw}^2$, where ρ_{sw} and v_{sw} are the mass density and velocity of the solar wind, respectively. Thus, from $B_{mp}^2/(2\mu_0) = P_{sw}$, we obtain

$$R_{mp} = R_p \left(\frac{B_p^2}{2\mu_0 P_{sw}} \right)^{1/6}, \qquad (2)$$

where μ_0 is the vacuum permeability. In actuality, an additional factor of order unity must be introduced for calculating R_{mp} more accurately, due to deviations from an ideal dipole magnetic field (Gombosi, 1998); the characteristic value for the Earth is $R_{mp} \approx 10 R_\oplus$ (Kivelson and Russell,

1995). As P_{sw} is subject to temporal variations depending on the planetary orbit and stellar activity, the value of R_{mp} also varies accordingly. For instance, theoretical models indicate that P_{sw} varies by 1–3 orders of magnitude near Proxima b, which translates to a variation in R_{mp} by a factor of 2–5 (Garraffo, Drake, and Cohen, 2016). The corresponding average magnetopause distance for Proxima b equals $R_{mp} \sim (2\text{–}3)R_{\oplus}$, which is smaller than the Earth's magnetosphere by a factor of a few. A similar study has also been undertaken for the planets of the TRAPPIST-1 system (Garraffo *et al.*, 2017) [see also Dong, Jin *et al.* (2018)].

Before discussing why a smaller magnetosphere may prove to be problematic from the standpoint of habitability, it is instructive to understand, via a toy model, why R_{mp} is smaller for lower mass stars. Denoting the stellar mass-loss rate by $\dot{M}_{\star}$ and assuming the resultant wind is spherically symmetric, we have

$$\dot{M}_{\star} = 4\pi a_p^2 \rho_{sw} v_{sw}, \tag{3}$$

where a_p represents the semimajor axis of the planet. Typically, v_{sw} does not vary significantly beyond the immediate vicinity of the star (Fitzpatrick, 2014), implying that $\rho_{sw} \propto \dot{M}_{\star}/a_p^2$. Let us consider Proxima b once again. The stellar mass-loss rate of Proxima Centauri has been theoretically predicted to be comparable to that of the Sun (Garraffo, Drake, and Cohen, 2016) and is consistent with observational constraints (Wargelin and Drake, 2002); see, however, Wood *et al.* (2001). Using this estimate in conjunction with Proxima b's semimajor axis of 0.0485 AU, we find that ρ_{sw} should be about 400 times higher near Proxima b than the corresponding solar wind density at the Earth, which is roughly consistent with more detailed numerical calculations (Garraffo, Drake, and Cohen, 2016; Dong, Lingam *et al.*, 2017). A higher value of ρ_{sw} translates to higher dynamic pressure ($P_{sw} \propto \rho_{sw}$), thereby leading to a compression of the magnetopause distance.

Furthermore, M dwarfs are typically characterized by very strong magnetic fields (Reiners and Basri, 2009; Morin *et al.*, 2010; Reiners, 2012) that are 2–3 orders of magnitude higher than the average magnetic field at the Sun's surface ($\sim 10^{-4}$ T). As a result, the stellar wind pressure also includes a significant component from the star's magnetic field (Vidotto *et al.*, 2013). This serves to raise the value of P_{sw}, and thereby decrease R_{mp} in accordance with Eq. (2). In general, if P_{sw} is 2–3 orders of magnitude higher for planets in the HZ of low-mass stars, it follows from Eq. (2) that the planetary magnetic field B_p will need to be higher by a factor of $\mathcal{O}(10)$ in order to yield a magnetopause distance similar to that of the Earth. Hence, for sufficiently high magnetic fields, it is conceivable that planets could possess Earth-sized magnetospheres (See *et al.*, 2014).

However, there are grounds for supposing that B_p will be reduced for planets orbiting low-mass stars. As per dynamo theory, the magnetic field strength is expected to scale with the planet's rotation rate (Ω_p) as

$$B_p \propto \Omega_p^{\alpha}, \tag{4}$$

with $\alpha \approx 0.5\text{–}1$ for many of the classical dynamo models (Grießmeier *et al.*, 2005; López-Morales, Gómez-Pérez, and Ruedas, 2011). Other dynamo simulations, in contrast, indicate that B_p is independent of Ω_p (Christensen, 2010).[6] The majority, although not necessarily all,[7] of the planets in the HZ of low-mass stars are expected to be synchronous rotators, with their rotation periods equal to their orbital periods, owing to the tidal gravitational force of the host star (Dole, 1964; Bolmont, Raymond, and Leconte, 2011; Barnes, 2017). In this case, the rotation rate will be reduced considerably, and this leads to a corresponding reduction in the magnetic moment [see, however, Zuluaga *et al.* (2013)]. For example, a planet 0.2 AU from a star with $M_{\star} = 0.5 M_{\odot}$ will have $\Omega_p \approx 0.03\Omega_{\oplus}$, implying that $B_p \approx 0.17 B_{\oplus}$ if $\alpha = 0.5$ in Eq. (4). Here $\Omega_{\oplus}$ and $B_{\oplus}$ are the Earth's rotation rate and equatorial magnetic field, respectively.

Thus, planets around low-mass stars will typically have smaller magnetospheres on account of increased stellar wind pressure and possibly weaker magnetic moments. Conventionally, weaker planetary magnetic fields and smaller magnetospheres lead to a lower degree of protection against the stellar wind, thereby resulting in enhanced atmospheric escape; we return to this topic in Sec. II.B. However, this paradigm has been challenged by recent theoretical studies, which indicate that the atmospheric escape rate does not always decline with an increase in the magnetic field strength (Blackman and Tarduno, 2018; Dong *et al.*, 2018b; Gunell *et al.*, 2018; Lingam, 2019). The basic reason can be understood qualitatively as follows. The polar caps are regions close to the magnetic poles with open magnetic field lines, which permit the escape of ions through the polar wind. The latter is dependent on the ambipolar electric field that stems from the difference in the velocities of ions and electrons (Axford, 1968); electrons typically move faster, thus causing charge separation and inducing an electric field, which accelerates the ions and permits their escape (Schunk and Nagy, 2009). The polar wind may become increasingly important for weak dipole magnetic fields with $B_p \sim 10^{-7}$ T for Mars-like exoplanets (Sakai *et al.*, 2018) [see also Lingam (2019)].

The second aspect that we highlight concerns the effect of planetary magnetic fields in regulating the amount of cosmic rays that reach the surface. This is particularly relevant since high-energy radiation can drive the radiolysis (decomposition via radiation) of complex biomolecules (Dartnell, 2011; Horvath and Galante, 2012). It is well known that the planet's magnetospheric shielding (for deflecting charged particles) influences the amount of radiation that reaches the surface (Grießmeier *et al.*, 2009), but more recent studies have revealed that the dependence on the magnetic moment $\mathcal{M}_p$ is very sensitive to the atmospheric column density

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[6]Differentiating between the various dynamo models requires the measurement of exoplanetary magnetic fields. In principle, this could be done through a number of observational avenues based on radio auroral emission, early transit ingress, H_3^+ emission, and Ly-α absorption profiles of exoplanets (Grießmeier, 2015).

[7]The presence of a thick atmosphere (Leconte *et al.*, 2015), semiliquid interior (Makarov, 2015), or a companion (Vinson and Hansen, 2017) could drive the planet into asynchronous rotation.

(Atri, Hariharan, and Grießmeier, 2013). For example, when one considers planets with an atmospheric column density equal to that of the Earth, changing the magnetic moment from $\mathcal{M}_p = 0$ to $10\mathcal{M}_\oplus$ (where $\mathcal{M}_\oplus$ is the magnetic moment of the Earth) results in the radiation dose rate dropping by a factor of about 6. In contrast, if the atmospheric column density is about 10% that of the Earth, the radiation dose rate declines by a factor of 240 as one moves from $\mathcal{M}_p = 0$ to $10\mathcal{M}_\oplus$ (Grießmeier *et al.*, 2016).

One other aspect that is not explored here concerns the effect of magnetospheric (and atmospheric) shields on the chemistry and abundances of biosignatures (Grenfell, 2017). Cosmic rays may react with N_2-O_2 atmospheres and stimulate the formation of nitrogen oxides (NO_x) and drive the depletion of ozone (O_3), the latter of which constitutes a widely studied biosignature. It turns out that high-energy particles produced during stellar flares also have similar effects, as discussed in Sec. IV.C.

B. Atmospheric escape

Atmospheric escape refers to any mechanism that imparts sufficient energy to particles, enabling them to achieve speeds higher than the threshold to escape the gravitational pull of the planet (Tian, 2015a). Most studies tend to focus on neutral particles, but it is important to appreciate the fact that charged particles can also escape the atmosphere. There are a wide array of mechanisms that enable the escape of ions, and reviews of this subject were given by Lammer *et al.* (2008) and Brain *et al.* (2016).

Charged particles are typically accelerated by electric fields in addition to deriving energy from collisions. The electric field **E** can be expressed as

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B} - \nabla p_e}{n_e e} + \eta \mathbf{J} + \cdots, \qquad (5)$$

where **v** is the plasma bulk velocity, **J** is the current, **B** represents the magnetic field, η denotes the resistivity, n_e is the electron number density, and p_e is the electron pressure. Equation (5) is known as Ohm's law and contains additional terms that have been omitted here (Freidberg, 2014; Lingam, Miloshevich, and Morrison, 2016; Lingam *et al.*, 2017). Each of the first three terms on the right-hand side of Eq. (5) are known to be capable of accelerating charged particles and enabling them to exit the atmosphere.

Apart from the polar wind encountered in Sec. II.A, which relies on ion outflow from polar regions, there are several other ion escape mechanisms. Ion pickup processes enable the acceleration of ions via electric fields embedded within the stellar wind plasma. In addition, there are a multitude of alternative mechanisms involving plasma instabilities and cool ion outflows (Lammer, 2013). Although, in principle, it is feasible to develop simple models for each of the processes and thus estimate the total loss rate, this approach is not practical within the scope of this Colloquium.

Instead, it is instructive to consider a toy model for weakly magnetized or unmagnetized planets, i.e., those that have a negligible intrinsic magnetic field. In our Solar System, Venus falls under this category and so does

Mars, although the situation with respect to the latter is more complicated owing to the presence of remnant crustal fields (Acuna *et al.*, 1998). As we have seen earlier, weak magnetic fields may be common for planets in the HZ of low-mass stars. Nonthermal escape mechanisms involving ion escape due to interactions with stellar winds could become particularly important for unmagnetized planets that are comparable to the size of the Earth (Brain *et al.*, 2016; Dong, Lingam *et al.*, 2017).

Our approach partly mirrors the derivation in Zendejas, Segura, and Raga (2010) and Zahnle and Catling (2017); see also Lingam and Loeb (2018b). To begin with, note that the momentum carried by a single proton in the solar wind is $m_p v_{sw}$. In contrast, a chemical species X in the atmosphere requires a maximal momentum gain of $m_X v_{esc}$, where m_X is the mass of the particle and

$$v_{esc} = \sqrt{2GM_p/R_p} = 11 \text{ km/s}(M_p/M_\oplus)^{1/2}(R_p/R_\oplus)^{-1/2}$$

is the gravitational escape velocity from the planet. Suppose, for instance, that we consider the loss of O_2^+ as this represents one of the major species lost from CO_2-dominated atmospheres; it can be readily verified that $m_X \approx 32m_p$. The escape velocity for Earth-sized planets is $\mathcal{O}(10)$ km/s, whereas v_{sw} is typically $\mathcal{O}(100)$ km/s, although $\sim 10^3$ km/s is also possible. Thus, in heuristic terms, the momentum of a proton in the stellar wind can be wholly imparted to a single entity of X to facilitate the escape of the latter.

Hence, if we determine the rate of protons impinging on the planet, we can also treat this as the escape rate of particles from the planet's atmosphere ($\dot{M}_p$). Recall that the stellar mass-loss rate is $\dot{M}_\star$ and the flux at a distance a_p is $\dot{M}_\star/(4\pi a_p^2)$. The cross-sectional area presented by the planet is πR_p^2. Thus, the escape rate is

$$\dot{M}_p = \frac{1}{4}\left(\frac{R_p}{a_p}\right)^2 \dot{M}_\star. \qquad (6)$$

In actuality, not all stellar wind protons will contribute to atmospheric escape, owing to which the factor of $1/4$ could be replaced with an efficiency factor ε that can be as much as 1 order of magnitude lower. If we choose $R_p = 0.53R_\oplus$ and $a_p = 1.524$ AU for Mars, along with $\dot{M}_\odot \sim 2 \times 10^{-14}\ M_\odot\,\mathrm{yr}^{-1}$ (Wargelin and Drake, 2002), we obtain $\dot{M}_p \sim 0.07$ kg/s, which is only about a factor of 2 lower than the predicted O_2^+ loss rate of $\sim 2.6 \times 10^{24}$ s^{-1} (Dong *et al.*, 2018a) that corresponds to ~ 0.14 kg/s (using $m_{O_2^+} \approx 32m_p$).[8] Numerical simulations carried out by Dong, Jin *et al.* (2018) indicate that Eq. (6) accurately reflects the trend for the expected escape rates of the seven TRAPPIST-1 planets.

Two points regarding Eq. (6) are worth mentioning. First, the quantity $\dot{M}_\star$ evolves over time and is much higher when the star is younger (Wood *et al.*, 2005), implying that the atmospheric escape rates will also be correspondingly higher.

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[8]At this rate, losing the mass of Earth's atmosphere ($\sim 5 \times 10^{18}$ kg) would require $\sim 10^{12}$ yr.

Second, it is difficult to estimate $\dot{M}_\star$ as it depends on a variety of stellar parameters such as the mass, radius, and rotation rate (Cranmer and Saar, 2011). A simple theoretical prescription that may be reasonably accurate for stars within the range $0.4 < M_\star/M_\odot < 1.1$ is (Johnstone *et al.*, 2015)

$$\frac{\dot{M}_\star}{\dot{M}_\odot} = \left(\frac{R_\star}{R_\odot}\right)^2 \left(\frac{\Omega_\star}{\Omega_\odot}\right)^{1.33} \left(\frac{M_\star}{M_\odot}\right)^{-3.36}, \qquad (7)$$

where $M_\star$, $R_\star$, and $\Omega_\star$ are the stellar mass, radius, and rotation rate, respectively; it must be noted that Eq. (7) applies only to stars with rotation rate $\Omega_\star < \Omega_c$, where $\Omega_c = 15\Omega_\odot(M_\star/M_\odot)^{2.3}$ with $\Omega_\odot$ denoting the solar rotation rate (Johnstone *et al.*, 2015). We note that the validity of Eq. (7) is questionable for most M dwarfs including Proxima Centauri and TRAPPIST-1.

Next, we may rewrite the mass of the atmosphere (M_{atm}) in terms of the surface pressure (P_s) via

$$M_{\text{atm}} = \frac{4\pi R_p^2 P_s}{g}, \qquad (8)$$

where $g \approx g_\oplus (R_p/R_\oplus)^{1.7}$ is the planet's surface gravity (Valencia, O'Connell, and Sasselov, 2006; Zeng, Sasselov, and Jacobsen, 2016), provided that the planet has a rocky composition and is larger than the size of the Earth. Here $g_\oplus$ denotes the Earth's surface gravity. With these data, we are free to compute the characteristic time scale (t_p) for the depletion of the planet's atmosphere, which is given by $t_p \sim M_{\text{atm}}/\dot{M}_p$. The advantage is that t_p is determined purely in terms of basic physical parameters based on Eqs. (6), (7), and (8). It has been implicitly supposed that the rate of atmospheric escape is much higher than the rate of outgassing from the mantle due to geological activity.

If we estimate t_p for Proxima b using the previous formulas in conjunction with $\dot{M}_\star \sim \dot{M}_\odot$ and the *fiducial* (but arbitrary) choice of $P_s = 1$ atm, we find that the time scale is $\mathcal{O}(10^8)$ yr. This result is in agreement with detailed magnetohydrodynamic numerical simulations of both magnetized and unmagnetized planets that have yielded values ranging from $\mathcal{O}(10^7)$ to $\mathcal{O}(10^9)$ yr, with many converging on $\mathcal{O}(10^8)$ yr (Airapetian, Glocer *et al.*, 2017; Dong, Lingam *et al.*, 2017; Garcia-Sage *et al.*, 2017). In contrast, for the TRAPPIST-1 system, it has been found that the innermost planet (with $P_s = 1$ atm assumed throughout) may lose its atmosphere over a time scale of $\mathcal{O}(10^8)$ yr, while the duration of atmospheric retention for the outermost planet is $\mathcal{O}(10^{10})$ yr (Dong, Jin *et al.*, 2018). The time scales for the outer TRAPPIST-1 planets are higher than Proxima b because the star TRAPPIST-1 is smaller, less active, and therefore anticipated to have less intense stellar winds.

Other notable studies of atmospheric escape driven by the stellar wind include Kislyakova *et al.* (2014) and Cohen *et al.* (2015). An important point worth mentioning here is that planets in the HZ of solar-type (G-type) stars are not likely to lose the entirety of their atmospheres over Gyr or sub-Gyr time scales through ion escape processes (Seki *et al.*, 2001; Dong, Huang *et al.*, 2017). We caution the reader that these

time scales apply only to planets with nonmassive atmospheres. If the planets have thick atmospheres—as is possible for the TRAPPIST-1 system (Grimm *et al.*, 2018)—the corresponding time scales would be increased due to $t_p \sim M_{\text{atm}}/\dot{M}_p$.

Hitherto, we have concerned ourselves with discussing unmagnetized planets when deriving Eq. (6). When it comes to magnetized planets, finding an equivalent expression is harder and subject to more uncertainty. It was proposed by Blackman and Tarduno (2018) that the analog of Eq. (6) for magnetized planets is given by $\dot{M}_p^{(\text{mag})} = \mathcal{Q}\dot{M}_p$, where the extra factor $\mathcal{Q}$ is defined as

$$\mathcal{Q} \sim 7.1\left(\frac{\chi}{0.1}\right)\left(\frac{R_{mp}/R_p}{10}\right)^2, \qquad (9)$$

where χ is a parameter that is proportional to the ratio of the speed associated with magnetic reconnection to the stellar wind speed near the planet. However, it should be cautioned that this expression has not yet been validated by numerical simulations. Thus, setting $\chi \sim 0.1$, we find $\mathcal{Q} > 1$ is achieved when $R_{mp} \gtrsim 3.75R_p$. Therefore, for magnetized planets that satisfy this criterion, their escape rates may exceed those of their unmagnetized counterparts.

The general conclusion that can be drawn (from the previous examples) is that planets in the HZ of very low-mass stars are often, but not always, susceptible to losing their atmospheres over sub-Gyr time scales, even reaching a minimum of $\mathcal{O}(10^7)$ yr. On Earth, we know that the time scale taken for the origin of life (abiogenesis) was ≤ 0.8 Gyr (Pearce *et al.*, 2018), and it required 4.5 Gyr for the emergence of technological intelligence, namely, *Homo sapiens*. Strictly speaking, we have no knowledge whatsoever of what the time scale for abiogenesis is on other planets based on just a single data point from Earth (Spiegel and Turner, 2012). Despite this important caveat, many studies assume that the corresponding time scales are similar on other worlds.

If we operate under this assumption, it seems plausible that Earth-sized planets in the HZ of M dwarfs with surface pressures comparable to the Earth might not have enough time for biological evolution to take place. Of course, on account of the near-linear dependence of the depletion time scale on P_s (Dong, Lingam *et al.*, 2017), planets with much thicker atmospheres than our own will retain them over commensurately longer periods. In the event that t_p is much less than t_{HZ}, i.e., the temporal duration of the HZ, it is the former that will serve as an upper limit on the time over which biological evolution can occur; the expression for t_{HZ} as a function of $M_\star$ is found in Rushby *et al.* (2013) and Lingam and Loeb (2019b). This is because of the fact that the presence of an atmosphere is necessary for sustaining liquid water on the surface as seen from its phase diagram.[9]

Let us suppose that t_p is $\mathcal{O}(10^8)$ yr and that $t_p \ll t_{\text{HZ}}$. This gives rise to another potential issue. Since the time scale for

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[9]In the absence of an atmosphere, surficial life is probably ruled out for the most part, but the existence of subsurface biospheres, which is not tackled herein, is still possible.

biological evolution is lower, the biodiversity may also be reduced accordingly. There are some grounds for supposing that the species richness (total number of species) on Earth has grown exponentially over time (Russell, 1983).[10] Using this approach, Lingam and Loeb (2017a) proposed that planets in the HZ of M dwarfs could attain a peak species richness that is many orders of magnitude lower than the current-day value of $\sim 10^{12}$ on Earth (Locey and Lennon, 2016), and that M dwarfs with $M_\star \lesssim 0.2 M_\odot$ were especially unlikely to host diverse biospheres. Last, we observe that atmospheric erosion will eventually result in lowered column densities, which is problematic because more cosmic rays would reach the surface resulting in enhanced harmful radiation levels, as noted in Sec. II.A.

III. STELLAR ELECTROMAGNETIC RADIATION

Of the myriad stellar factors regulating habitability, perhaps the most appreciated among them has been the role of electromagnetic radiation emitted by the star. As this represents a vast topic, we will concern ourselves with only a handful of recent developments. An overview of the positive and negative effects on habitability because of electromagnetic radiation has been provided in Table I. We have also depicted the two chief UV fluxes of interest in this Colloquium received by Earth analogs around low-mass stars as a function of $M_\star$ in Fig. 1. The phrase "Earth analogs" should be used with due caution. We refer here to rocky planets that have the same basic physical parameters as the Earth such as the effective temperature, albedo, atmospheric pressure, and radius.

A. Evaporation of oceans and buildup of oxygen

It has been known for a long time that EUV photons are capable of facilitating atmospheric escape (Lammer, 2013). Let us denote the energy flux of EUV photons near the planet by $\mathcal{F}_{EUV}$ and assume that the area over which these photons are intercepted is roughly πR_p^2. If these photons enable the particles to attain an escape velocity of $v_{esc} = \sqrt{2GM_p/R_p}$, then we have $(1/2)\dot{M}_p v_{esc}^2 \sim \pi \mathcal{F}_{EUV} R_p^2$. From this relation, we obtain

$$\dot{M}_p = \frac{\eta_{EUV}}{K_{eff}} \frac{\pi R_p^3 \mathcal{F}_{EUV}}{GM_p}, \qquad (10)$$

where η_{EUV} is the heating efficiency factor, while K_{eff} is a parameter of order unity that encapsulates the effect of stellar tidal forces (Erkaev *et al.*, 2007). In Eq. (10), we note that the EUV flux can also be replaced by the XUV flux (0.6–120 nm) that includes the contribution from x rays (Ribas *et al.*, 2016). This formula has been derived based on the assumption of energy balance, but other regimes are also conceivable (Owen, 2018); for instance, photon number limitation (as opposed to energy limitation) may regulate the atmospheric escape rate (Owen and Alvarez, 2016).

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[10]A more realistic model for the species richness is based on a series of logistic curves spliced together (Purvis and Hector, 2000).

TABLE I. Potential positive and negative biological ramifications arising from electromagnetic radiation. XUV ($\sim$0.6–120 nm), UV-C ($\sim$200–280 nm), UV-Bio ($\sim$200–400 nm), PAR ($\sim$400–750 nm). "High" and "low" refer to the energy fluxes (in the corresponding wavelength range) received by Earth analogs around M dwarfs relative to that of the Earth. The first five rows correspond to the positives, whereas the last three rows represent the negatives.

Radiation	Consequences	M-dwarf exoplanets
XUV	Water worlds to land-water planets via H_2O photolysis	High
XUV	Buildup of atmospheric O_2 via H_2O photolysis for complex life	High
UV-C	Formation of biomolecular building blocks for prebiotic chemistry	Low
UV-Bio	Selection agent for evolutionary innovations and speciation	Low
PAR	Enabling photosynthesis	Low
XUV	Complete desiccation of land-water planets via H_2O photolysis	High
UV-Bio	DNA damage	Low
UV-Bio	Inhibiting photosynthesis	Low

All stars go through a pre-main-sequence (PMS) phase, during which their luminosity is fueled mostly by gravitational contraction as opposed to the nuclear fusion of hydrogen (McKee and Ostriker, 2007). The importance of this phase, particularly for low-mass stars, stems from the fact that the luminosity during the PMS phase can be as much as 2 orders
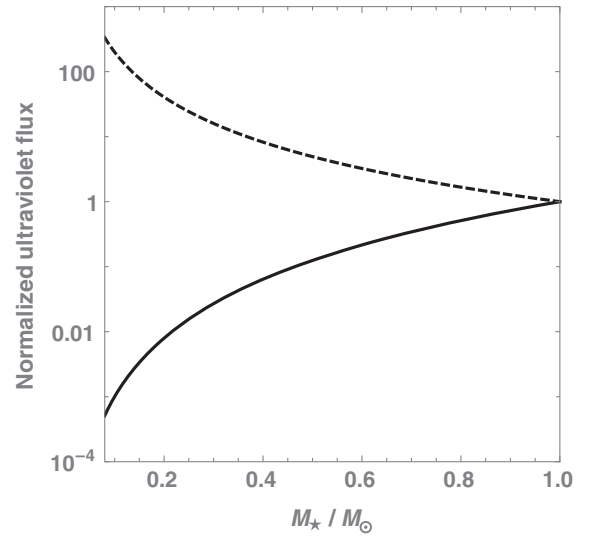

FIG. 1. Schematic representation of the UV fluxes received by Earth analogs around low-mass stars normalized with respect to the Earth as a function of the stellar mass $M_\star$ (in units of solar mass $M_\odot$). The solid curve denotes the flux of bioactive UV radiation ($\sim$200–400 nm), whereas the dashed curve denotes the flux of Lyα radiation. The former may contribute to the origin of life, driving evolutionary innovations and speciation, DNA damage, and inhibiting photosynthesis. The latter is believed to play a key role in the photolysis of molecules such as H_2O and CO_2, thus enabling water depletion and the buildup of atmospheric O_2. Scaling relations have been adopted from Lingam and Loeb (2018e).

of magnitude higher compared to the point where the star enters the main sequence (Baraffe *et al.*, 2002). Moreover, for very low-mass stars (with $M_\star \lesssim 0.1 M_\odot$), the PMS phase lasts for a few Gyr, whereas it is $\lesssim 0.1$ Gyr for solar-type stars (Ramirez and Kaltenegger, 2014). Thus, the collective effect of the PMS phase is that planets around low-mass stars that would otherwise be situated within the HZ are not located in it as a result of the enhanced luminosity. In other words, these planets exceed the runaway greenhouse threshold, thereby leading to significant losses of water (Ramirez and Kaltenegger, 2014; Luger and Barnes, 2015; Bolmont *et al.*, 2017; Tian *et al.*, 2018).

The basic expectation is that the water vapor in the atmosphere injected via the greenhouse effect would undergo photolysis to yield hydrogen and oxygen. As the former has a much lower mass, it is more susceptible to atmospheric escape. This can be verified by converting $\dot{M}_p$ in Eq. (10) from kg/yr to mole/yr, as it yields an inverse dependence on the mass of the chemical species. Hence, the hydrogen would be lost to space, leaving behind massive O_2 atmospheres. In reality, the situation is more complex and would be dependent on factors such as the EUV or XUV flux ($\mathcal{F}_{XUV}$), the planet's mass (M_p) and water inventory (Tian, 2015b). The rate of atmospheric O_2 buildup ($\dot{P}_{O_2}$) was analytically estimated by Luger and Barnes (2015) and is expressible as

$$\dot{P}_{O_2} \sim 0.138 \text{ bar/Myr} \left(\frac{\mathcal{F}_{XUV}}{\mathcal{F}_\oplus}\right) \left(\frac{R}{R_\oplus}\right)^{-1} \left(\frac{\eta_{XUV}}{0.30}\right), \quad (11)$$

where η_{XUV} denotes the XUV absorption efficiency, $\text{Myr} \equiv 10^6$ yr, and $\mathcal{F}_\oplus \approx 4.6 \times 10^{-3}$ Jm^{-2} s^{-1} is the XUV flux incident on Earth. This result can be expressed in terms of R_p by applying the mass-radius relationship $M_p \propto R_p^{3.7}$ for rocky planets (Zeng, Sasselov, and Jacobsen, 2016). However, when $\mathcal{F}_{XUV}$ exceeds a certain threshold, O_2 is "dragged" along with hydrogen (due to the emergence of strong hydrodynamic flows) and is therefore subject to escape. The corresponding threshold is given by

$$\mathcal{F}_c \sim 0.18 \text{ Jm}^{-2} \text{ s}^{-1} \left(\frac{M_p}{M_\oplus}\right)^2 \left(\frac{R_p}{R_\oplus}\right)^{-3} \left(\frac{\eta_{XUV}}{0.30}\right)^{-1}. \quad (12)$$

Hence, in the regime $\mathcal{F}_{XUV} \geq \mathcal{F}_c$, the rate of atmospheric O_2 buildup undergoes saturation and does not depend on $\mathcal{F}_{XUV}$ (Luger and Barnes, 2015). The corresponding value of $\dot{P}_{O_2}$ for $\mathcal{F}_{XUV} \geq \mathcal{F}_c$ becomes

$$\dot{P}_{O_2} \sim 5.35 \text{ bar/Myr} \left(\frac{M_p}{M_\oplus}\right)^2 \left(\frac{R_p}{R_\oplus}\right)^{-4}. \quad (13)$$

As noted, M_p can be eliminated by utilizing the mass-radius relationship for terrestrial planets. In comparison, the rate of O_2 contributed to Earth's atmosphere indirectly by photosynthesis (entailing the burial of organic matter) is ~ 0.06 bar/Myr (Holland, 2002). If Eq. (11) or (13) exceeds the atmospheric O_2 sinks for Earth-like planets, oxygen can build up in the atmosphere and produce an ozone layer (Catling and Kasting, 2017).

A number of studies have been conducted that pertain to the production of abiotic O_2 and O_3 in the atmosphere due to the photolysis of H_2O and CO_2 by XUV radiation (Segura *et al.*, 2007; Wordsworth and Pierrehumbert, 2013, 2014; Tian *et al.*, 2014; Gao *et al.*, 2015; Harman *et al.*, 2015; Narita *et al.*, 2015). Hence, the detection of O_2 and O_3 at high levels in exoplanetary atmospheres opens up the possibility of a "false positive," corresponding to the apparent detection of a biosignature despite it not being produced by biological activity. Several methods have been proposed for distinguishing abiotic O_2 from that generated by biological sources (Meadows, 2017; Meadows *et al.*, 2018b).

As the net effect of UV photolysis of water leads to the depletion of oceans, this has important ramifications for habitability since liquid water is one of the requirements for life. Before discussing this point further, some of the studies pertaining to water loss from Proxima b and the TRAPPIST-1 planets are worth mentioning. In the case of Proxima b, it has been predicted that $< 1 M_{oc,\oplus}$ has been lost over its history (Ribas *et al.*, 2016), where $M_{oc,\oplus} \approx 1.4 \times 10^{21}$ kg is the mass of Earth's oceans today. This could, however, still leave behind an O_2 atmosphere of ~ 100 bar. In the case of the TRAPPIST-1 planets, the innermost two planets (TRAPPIST-1b and TRAPPIST-1c) may have lost as much as $15 M_{oc,\oplus}$ (Bolmont *et al.*, 2017) but this value could drop below $1 M_{oc,\oplus}$ for the outer planets (Bourrier *et al.*, 2017).

One of the Earth's unique features is that the fraction of the surface covered by land (0.3) is comparable to that covered by water (0.7). However, in the majority of cases, we can expect one of two possible scenarios to arise, especially around low-mass stars. First, the initial water inventory, which depends on the physical mechanisms involved in the delivery of H_2O during terrestrial planet formation (O'Brien *et al.*, 2018), may vary widely (Raymond, Scalo, and Meadows, 2007; Mulders, Ciesla *et al.*, 2015; Raymond and Izidoro, 2017). Hence, there will be many worlds with water inventories much higher than the Earth; some of the planets in the TRAPPIST-1 system are an excellent example, as their water inventory could exceed that of the Earth by 2 orders of magnitude (Dorn *et al.*, 2018; Grimm *et al.*, 2018; Unterborn *et al.*, 2018; Unterborn, Hinkel, and Desch, 2018). These worlds are expected to comprise only oceans on the surface, thereby lacking landmasses altogether, and both observational (Rogers, 2015; Wolfgang and Lopez, 2015; Chen and Kipping, 2016; Jin and Mordasini, 2018; Lozovsky *et al.*, 2018) and theoretical (Alibert and Benz, 2017; Simpson, 2017) studies indicate they are potentially quite common. The habitability of these "water worlds" (Kuchner, 2003; Léger *et al.*, 2004) has been the subject of many studies over the past few years (Noack, Snellen, and Rauer, 2017; Kite and Ford, 2018; Ramirez and Levi, 2018).

On the other hand, as we have seen previously, XUV radiation during the long PMS phase of low-mass stars is very effective at depleting several oceans worth of water. Moreover, the deep-water cycle transports water from the oceans to the underlying mantle (Hirschmann, 2006); the water reservoir in the latter may exceed the former by up to an order of magnitude on Earth (Korenaga, 2008; Ni *et al.*, 2017). In many cases, worlds with a moderate initial water inventory

could end up being desiccated and eventually transformed into desert planets (Abe *et al.*, 2011; Zsom *et al.*, 2013). In contrast, for certain water-rich worlds, XUV radiation may actually play a positive role by removing excess water and ensuring that landmasses are exposed on the surface. As per these arguments, we predict the following two features for planets in the HZ of low-mass stars: (a) worlds with Earth-like water inventories are rare, and (b) the water inventory is describable by a bimodal distribution (water or desert worlds). Both of these points appear to be consistent with numerical simulations carried out by Tian and Ida (2015); see also Zain *et al.* (2018) for a related analysis of solar-type stars.

This aspect poses major issues for habitability for the following reasons. If the worlds are covered almost entirely by land, water availability becomes an issue and the resultant arid environments are expected to have low biomass densities (Hadley and Szarek, 1981). On the other hand, if the surface consists exclusively of oceans, the availability of bioessential elements such as phosphorus—widely accepted as the ultimate limiting nutrient for the biological productivity of oceans (Tyrrell, 1999)—becomes problematic because it is primarily delivered via rivers and the atmosphere through continental weathering (Paytan and McLaughlin, 2007), implying that the absence of continents will lower the influx of dissolved phosphorus by a few orders of magnitude provided that the oceans are alkaline and water-rock interactions exist at the seafloor (Lingam and Loeb, 2018c, 2019a).

A recent analysis of the surface water fraction (f_w) proposed that $0.3 < f_w < 0.9$ is optimal for the buildup of O_2 in the atmosphere (Lingam and Loeb, 2019c), which represented a major evolutionary event. As the fraction of Earth-sized worlds in the HZ with water inventories that lie within this range is presumably small ($\lesssim 1\%$) [see Tian and Ida (2015) and Lingam and Loeb (2019c)], it seems plausible that Earth-like worlds with an admixture of landmasses and oceans are not very common.

B. Origin of life

The issue of how and where life originated remains one of science's most profound and enduring mysteries. The reader may consult McCollom (2013), Luisi (2016), and Sutherland (2016) for recent overviews of this subject. Currently, life uses deoxyribonucleic acid (DNA) for the storage and transmission of genetic information, while proteins, among several other functions, play the role of catalysts. In the 1980s, it was discovered that ribonucleic acid (RNA) was capable of carrying information as well as facilitating catalysis. This gave impetus to the idea, which was first proposed in the 1960s, that life on Earth began with self-replicating RNA molecules. The hypothesis came to be subsequently known as the RNA world (Gilbert, 1986) and has witnessed rapid advancements within the last decade (Joyce, 2002; Orgel, 2004; Neveu, Kim, and Benner, 2013; Higgs and Lehman, 2015).

Before proceeding further, it is crucial to recognize that the RNA world is not the only hypothesis for the origin of life (abiogenesis). A number of models have proposed that self-sustaining metabolic networks arose prior to the evolution of replicators like RNA (Wächtershäuser, 2007; Ruiz-Mirazo,

Briones, and de la Escosura, 2014; Goldford and Segrè, 2018). The geochemical environment in which life originated has also been subject to numerous investigations (Stüeken *et al.*, 2013; Kitadai and Maruyama, 2018). A number of hypotheses have advocated that life arose in land-based environments such as tidal pools (Romer, 1933; Lathe, 2004),[11] intermountain valleys (Benner, Kim, and Carrigan, 2012), hot springs, and geysers (Mulkidjanian *et al.*, 2012). In contrast, one of the most prominent hypotheses suggests that life originated in alkaline hydrothermal vents situated at the ocean floor (Martin *et al.*, 2008; Sojo *et al.*, 2016).

Many of the surficial geochemical environments customarily feature a wide assortment of minerals, which are believed to have played a crucial role in the emergence and early evolution of life (Cleaves *et al.*, 2012; Hazen, 2017). However, it should be recognized that most of the land-based environments in this category are not anticipated to be widely prevalent on water worlds, which were introduced in Sec. III.A. On the other hand, life's origin in environments at the ocean floor (e.g., hydrothermal vents) remains a distinct possibility unless the water content is high enough to drive the formation of high-pressure ices, thereby cutting off direct water-rock interactions (Noack *et al.*, 2016).

Broadly speaking, there are three classes of macromolecules (apart from carbohydrates) that are necessary for life as we know it. The first is nucleic acids (DNA and RNA), which serve as repositories for genetic information. The second is proteins, as they catalyze biochemical reactions as well as playing a vital role in maintaining cell structure and enabling cell signaling. The third is lipids, which form an integral part of cell membranes and also facilitate energy storage. The building blocks of nucleic acids are nucleotides—for example, RNA is synthesized from the polymerization of ribonucleotides—whereas proteins are polymers of amino acids.

Ever since the 1960s and 1970s, it has been appreciated that UV radiation enabled the synthesis of prebiotic compounds such as amino acids (Sagan and Khare, 1971). However, it is only within the last decade that the putative significance of UV radiation has been appreciated in greater detail owing to a number of recent developments outlined next (Sutherland, 2017).

- Studies have demonstrated that UV light accords a selective advantage to RNA-like molecules (Gustavsson, Improta, and Markovitsi, 2010; Šponer *et al.*, 2016), implying that it may play a crucial role in enabling their polymerization (Dibrova *et al.*, 2012).
- Several laboratory experiments display a tendency to form complex organic mixtures ("tar") that essentially represent a dead end insofar as abiogenesis is concerned. This issue is known as the "asphalt problem," but it might be bypassed in certain geochemical environments with UV radiation playing a potentially important role (Benner, Kim, and Carrigan, 2012).
- The synthesis of biomolecular building blocks is very challenging, especially without regular manual

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[11]The biological ramifications of tidal modulations arising from the presence of two planetary companions were discussed by Balbus (2014) and Lingam and Loeb (2018d).

intervention and under conditions that ostensibly resemble that of early Earth. Remarkably, several notable break-throughs have been achieved recently that rely on UV light. The organic compounds synthesized include the following: (i) RNA components, e.g., ribonucleotides (Powner, Gerland, and Sutherland, 2009; Islam and Powner, 2017), (ii) simple sugar-related molecules (Ritson and Sutherland, 2012, 2013; Todd *et al.*, 2018), (iii) precursors of nucleic acids, amino acids, lipids, and carbohydrates from interlinked pathways involving plausible feedstock molecules such as hydrogen cyanide (Patel *et al.*, 2015; Xu *et al.*, 2018), and (iv) iron-sulfur clusters, which play a vital role in metabolism (Bonfio *et al.*, 2017).

- RNA nucleotides are stable to irradiation by UV photons, which has been used to argue that they originated in the high-UV environments on early Earth (Rios and Tor, 2013; Beckstead *et al.*, 2016; Ranjan and Sasselov, 2016).

Thus, taken collectively, there is compelling, but not necessarily definitive, evidence that UV light played an important role in the origin of life on the planetary surface.

This brings us to the question of which planets in the HZ receive higher fluxes of *quiescent* (i.e., background) UV radiation. Several studies indicate planets in the HZ of M dwarfs receive bioactive UV fluxes (with $200 < \lambda < 400$ nm) at the surface that are around 100–1000 times lower compared to early Earth (Rugheimer, Segura *et al.*, 2015; Ranjan, Wordsworth, and Sasselov, 2017); see also Buccino, Lemarchand, and Mauas (2007). It must also be appreciated that the UV flux reaching the surface depends on a number of planetary characteristics such as the atmospheric composition and column density. As the bioactive UV flux depends on stellar properties, the region around the host star where the planet receives enough UV photons for prebiotic chemistry (the UV zone) will not always overlap with the classical HZ.

This issue was investigated by Guo *et al.* (2010), where it was concluded that the UV zone lies inward of the HZ when $T_{\text{eff}} < 4600$ K. A more recent analysis, based on the latest prebiotic pathways for synthesizing RNA, protein, and lipid precursors (Patel *et al.*, 2015; Xu *et al.*, 2018), found that stars with $T_{\text{eff}} < 4400$ K were not likely to drive the formation of these building blocks if the potential role of stellar flares (see Sec. IV) is neglected (Rimmer *et al.*, 2018). In addition to the stellar temperature, which serves as a rough proxy for the stellar mass, metallicity, i.e., abundance of elements other than H or He, can also influence the location of the UV zone (Oishi and Kamaya, 2016) and its overlap with the HZ.

While these studies deal with the spatial overlap between the UV zone and the HZ, it must be appreciated that the rates of these prebiotic reactions may also depend on the bioactive UV fluxes (Ranjan, Wordsworth, and Sasselov, 2017). Hence, planets in the HZ of M dwarfs could require much longer time scales for abiogenesis. This fact was utilized by Lingam and Loeb (2018e) to suggest that the time scale for abiogenesis (t_A) is

$$t_A \sim t_{A,\oplus} \left(\frac{M_\star}{M_\odot} \right)^{-\kappa}, \tag{14}$$

where $\kappa \approx 3$ for $M_\star \lesssim M_\odot$, $\kappa \approx 1$ for $M_\star \gtrsim M_\odot$, and $t_{A,\oplus}$ is the time scale for the origin of life on Earth, which has a strict upper bound of 0.8 Gyr. Coupled to the fact that Earth analogs around M dwarfs are expected to lose their atmospheres more rapidly, it was proposed that stars with $M_\star \lesssim 0.4 M_\odot$ are relatively unlikely to host biospheres (Lingam and Loeb, 2019b).

C. Evolution of complex life

We briefly discuss how stellar radiation, particularly in the UV and visible ranges, influences the trajectories of biological evolution.

1. Biological damage due to UV radiation

It is well known that UV radiation, particularly in the range $180 < \lambda < 300$ nm, is capable of suppressing photosynthesis and causing damage to DNA and other biomolecules (Voet *et al.*, 1963; Sagan, 1973; Teramura and Sullivan, 1994; Cadet, Sage, and Douki, 2005). Yet, on the other hand, it must be recognized that UV radiation might potentially function as a selection agent, a driver of evolutionary innovations and speciation (Sagan, 1973; Rothschild, 1999; Evans and Gaston, 2005).

As this topic has been the subject of many investigations, we will concern ourselves with describing only a couple of recent examples. Before embarking on that discussion, we note that a number of environments effectively shield organisms from the damaging effects of UV radiation such as a layer of soil, ocean (Cleaves and Miller, 1998), hazes in the atmosphere (Arney *et al.*, 2016), and other screening compounds (Cockell and Knowland, 1999). Another possibility is that complex evolutionary adaptations, such as those evinced by a wide array of microbes (Gao and Garcia-Pichel, 2011; Jung, Lim, and Bahn, 2017; Pacelli *et al.*, 2017), could protect organisms from high doses of UV radiation.

The biologically effective irradiance (BEI) was computed for Earth analogs around different stars by Rugheimer, Segura *et al.* (2015). The BEI can be envisioned as the product of the surface UV flux and the DNA action spectrum, where the latter quantifies the extent of DNA damage at different wavelengths. Two broad conclusions can be immediately drawn. First, the BEI for very low-mass stars (with $M_\star \lesssim 0.1 M_\odot$) is always about $\gtrsim 100$ times smaller than the Earth at the *same* epoch. Second, the presence of an ozone layer, not surprisingly, plays a major role in determining the BEI. For example, it was estimated that the BEI at 3.9 Gyr ago on Earth was about 600 times the present-day value.

A similar study was undertaken by O'Malley-James and Kaltenegger (2017), who concluded that two other parameters which influence the BEI are the stellar activity and the atmospheric pressure along with the presence (or absence) of an ozone layer. It was found that planets around more active stars, with partially eroded atmospheres, are likely to receive high-UV doses at the surface. The issue of rarefied atmospheres is particularly relevant, since we have seen earlier that stellar winds and UV radiation can drive atmospheric escape and erosion. However, even in the worst-case scenario, it was

found that a combination of evolutionary adaptations and ecological niches is theoretically capable of sustaining life.

2. Photosynthesis

On Earth, most life is dependent, either directly or indirectly, upon photosynthesis. The radiation typically employed by photoautotrophs (photosynthetic organisms) ranges between wavelengths of 400 and 700 nm (Hohmann-Marriott and Blankenship, 2011) and goes by the name of photosynthetically active radiation (PAR). If we approximate the stellar spectrum as blackbody radiation, Wien's displacement law implies

$$\lambda_{\max} T_{\mathrm{eff}} = 2.9 \times 10^{-3} \ \mathrm{m\,K}, \qquad (15)$$

where $\lambda_{\max}$ is the wavelength at which the blackbody spectrum peaks. Choosing $T_{\mathrm{eff}} \approx 5778$ K for the Sun yields $\lambda_{\max} \approx 500$ nm, which sits almost in the middle of the PAR range. In qualitative terms, this makes sense because photoautotrophs may have evolved to optimize the number of photons that they collect for synthesizing organic compounds (Kiang, Siefert *et al.*, 2007).

Estimating the PAR range for other stars, especially M dwarfs, is very difficult since it depends on the spectral properties of the host star, the atmospheric composition, and the pigments that enable photosynthesis (Kiang, Siefert *et al.*, 2007; Bains, Seager, and Zsom, 2014). One of the most striking features of vegetation on Earth is the "red edge," i.e., an increase in the reflectance by roughly an order of magnitude at ~700 nm. The importance of the red edge stems from the fact that it represents a viable biosignature that could be detectable with future telescopes (Seager *et al.*, 2005; Kaltenegger, 2017). Owing to the aforementioned issues, it is not easy to predict where the analog of a red edge would exist for M dwarfs. It does, however, seem plausible that the edge would be shifted to near-infrared wavelengths around 1.1 μm (Kiang, Segura *et al.*, 2007); see, however, Takizawa *et al.* (2017). Other methods for detecting signatures of photosynthesis include distinctive features in linearly polarized spectra (Berdyugina *et al.*, 2016) and angle-dependent reflectivity (Doughty and Wolf, 2010).

If we restrict our attention to the same PAR as on Earth, we are confronted with a potential problem. As low-mass stars tend to radiate primarily in the infrared, the availability of photons in the PAR range will be reduced. This raises the question of whether photosynthesis on planets around M dwarfs is feasible. As most of the photosynthesis on Earth leads to the production of O_2 (Fischer, Hemp, and Johnson, 2016), many studies have concentrated on this particular process. The simplified reaction presented next illustrates the formation of organic matter and oxygen via oxygenic photosynthesis,

$$CO_2 + 2H_2O + h\nu \rightarrow CH_2O + H_2O + O_2. \qquad (16)$$

Gale and Wandel (2017) argued that oxygenic photosynthesis in the PAR is feasible on planets around low-mass stars, primarily because the side facing the star (assuming synchronous rotation) will receive continuous illumination that compensates for the moderate photon flux. A detailed analysis of the prospects for photosynthesis on Proxima b was undertaken by Ritchie, Larkum, and Ribas (2018); the rate of synthesis of organic compounds via photosynthesis was estimated to be ~17% that of the Earth despite the photon flux in the PAR range being only 3% of the Earth. However, it was also argued that oxygenic photosynthesis might not evolve on planets around M dwarfs as this process accords minimal competitive advantage. Lehmer *et al.* (2018) investigated whether enough photons would be available to support an Earth-like biosphere on M-dwarf exoplanets, and found that many of them are incapable of doing so; see also Lingam and Loeb (2019d). In particular, if the maximum wavelength of PAR was specified to be 750 nm, none of the TRAPPIST-1 planets in the HZ appear to have the capacity for sustaining Earth-like biospheres. Relatively sparse biospheres due to the limited PAR fluxes may also have the additional disadvantage of producing weak O_2 signals that are not easily detectable.

3. Oxygen and complex life

There are sufficient grounds to conclude that the buildup of O_2 in the atmosphere may have constituted a rate-limiting step insofar as the development of complex life is concerned on other worlds (Knoll, 1985; O'Malley and Powell, 2016; Judson, 2017). Yet, it should also be recognized that similar environmental conditions and evolutionary trajectories for complex life need not prevail on all worlds. The development of the ozone layer and the expansion of aerobic metabolism, which releases about an order of magnitude more energy compared to its anaerobic counterparts (Koch and Britton, 2008), are two examples of the profound changes triggered by the rise of O_2. The oxygen levels in Earth's atmosphere as a function of geological time were subject to fluctuations, but there is compelling evidence that the O_2 levels increased from a very small value to roughly 1% of the present atmospheric level (PAL) around ~2.4 Ga (Gumsley *et al.*, 2017; Knoll and Nowak, 2017). Many different mechanisms have been advanced to explain this rise in oxygen, known as the great oxygenation event (GOE), such as changes in volcanism and the oxidation state of continents (Kasting, 2013; Lyons, Reinhard, and Planavsky, 2014).

One of the chief hypotheses for the GOE that we focus on concerns the production of O_2 in the atmosphere through UV photolysis (Catling, Zahnle, and McKay, 2001; Catling and Kasting, 2017). Organic matter is produced from oxygenic photosynthesis via Eq. (16), and this is subsequently decomposed by other microbes to release methane (CH_4). Methane undergoes UV photolysis with H escaping to space and the carbon combining with O_2 to form CO_2. The net reaction is expressible as follows:

$$2H_2O + \text{"biosphere"} + h\nu \rightarrow O_2 + 4H(\uparrow \text{space}). \qquad (17)$$
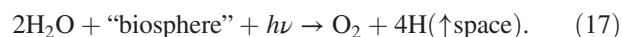
The key point is that this reaction does not represent the abiotic photolysis of water since reactions mediated by the biosphere are necessary. In addition, as we have seen in Sec. III.A, there are several abiotic pathways by which O_2 is produced through UV photolysis on planets, particularly those around low-mass stars. These mechanisms could enable the

buildup of O_2 at rates much faster than those driven by biological factors.

It is therefore conceivable that the time required for O_2 levels to reach a certain value (e.g. 1% PAL) via Eq. (17) is much shorter for planets that receive high-UV fluxes at the appropriate wavelengths. An important feature of M dwarfs is that their ratio of far-UV (117–175 nm) to near-UV (175–320 nm) fluxes is ~1000 times higher than the corresponding ratio for the Sun (Tian *et al.*, 2014), because of enhanced UV emission from the chromosphere and transition regions (Linsky, France, and Ayres, 2013). The Lyα flux (Φ_L), which is responsible for a large fraction of water and methane photolysis, for Earth analogs can be approximated by a power law of the form $\Phi_L \propto M_\star^\zeta$, where $\zeta \approx -2.3$ for $M_\star \lesssim M_\odot$ and $\zeta \approx 3.3$ for $M_\star \gtrsim M_\odot$ (Lingam and Loeb, 2018e). Note that the flux for stars more massive than the Sun is higher as a larger fraction of the blackbody radiation is emitted in the UV regime.

Hence, if the oxygenation time (t_{O_2}) scales inversely with Φ_L, the evolution of complex aerobic life from microbial anaerobic organisms may require a shorter amount of time on Earth analogs orbiting stars that have a higher mass than the Sun (Livio, 1999), although these stars are less abundant with respect to solar-mass stars.

IV. STELLAR FLARES

Stellar flares are explosive phenomena on the stellar surface that lead to the release of energy in various forms such as electromagnetic radiation, plasma, and energetic particles (Benz, 2017). The central engine behind this energy release is believed to be magnetic reconnection (Priest and Forbes, 2002), which entails changes in magnetic topology through the breaking and reconnection of field lines, thus resulting in the rapid conversion of magnetic energy into other forms of energy (Biskamp, 2000). Classical magnetic reconnection models, which were originally developed in the 1950s, result in energy release over long time scales that are not supported by observations, but subsequent developments in this area have achieved much progress in terms of addressing this issue (Shibata and Magara, 2011; Priest, 2014; Comisso *et al.*, 2016).

The largest flares documented in modern history have energies of ~10^{25} J, with the largest one on record being the Carrington event from 1859 (Carrington, 1859) that released a total energy of approximately 5×10^{25} J (Cliver and Dietrich, 2013). However, it is important to appreciate that flares with energies $\geq 10^{26}$ J, known as superflares, are also feasible on theoretical and observational grounds. The *Kepler* mission has recorded a wealth of observational data regarding the statistics of superflares (Maehara *et al.*, 2012; Shibayama *et al.*, 2013; Davenport, 2016). For solar-type stars with similar rotation rates as the Sun, it has been found that

$$\frac{dN}{dE} \propto E^{-\alpha}, \qquad (18)$$

with $\alpha \approx 1.5\text{–}2$, where $N(E)$ represents the occurrence rate of superflares and E denotes the energy of these superflares

(Maehara *et al.*, 2012, 2015; Günther *et al.*, 2019). The power-law exponent is close to that documented for normal flares on the Sun (Hannah *et al.*, 2011). The maximum amount of energy that may be released, in theory, during a flare event is expressible as (Shibata *et al.*, 2013)

$$E \sim 10^{28} \text{ J} \left(\frac{\epsilon}{0.1}\right) \left(\frac{B_A}{0.1\text{T}}\right)^2 \left(\frac{f_A}{0.3}\right)^{3/2} \left(\frac{R_\star}{R_\odot}\right)^3. \qquad (19)$$

Note that $R_\star$ and $R_\odot$ are the stellar and solar radii, respectively, whereas ϵ represents the "efficiency" of converting magnetic energy into flare energy. In Eq. (19), B_A denotes the magnetic field strength in the active region(s), and f_A is the fraction of the star's surface that is covered by the active region(s). The active regions constitute the sites of solar flares and other stellar activity, and sunspots serve as indicators of active regions.

In the case of the Sun, it has been theorized that flares of ~10^{27} J can occur over a time scale of ~2000 yr (Shibayama *et al.*, 2013), but this is hard to verify on account of relatively sparse direct evidence. The studies by Miyake *et al.* (2012) and Miyake, Masuda, and Nakamura (2013), which discovered rapid variations in the concentrations of radionuclides in tree rings, might be indicative of superflare activity. The extreme upper limit on the maximum flare energy released from Sun-like stars appears to be ~10^{30} J (Schrijver *et al.*, 2012; Lingam and Loeb, 2017b), although it remains highly uncertain as to whether such superflares could actually arise in reality.

In our subsequent discussion, we will mostly concentrate on planets in the HZ of M dwarfs as these stars are known to be very active and typically, but not always, produce flares and superflares at rates higher than G-type stars like the Sun (Scalo *et al.*, 2007; Maehara *et al.*, 2012). Both TRAPPIST-1 and Proxima Centauri have been documented to produce flares regularly—the number of flares with energies $\gtrsim 10^{26}$ J is predicted to be ~10^{-2} per day based on flare statistics (Davenport *et al.*, 2016; Vida *et al.*, 2017; Howard *et al.*, 2018); see also MacGregor *et al.* (2018). Recall that these planets are situated much closer to their host stars, they may have weak magnetic fields, and they could be subjected to rapid atmospheric erosion from stellar winds.

A. Electromagnetic radiation

It has long been appreciated that flares lead to enhanced UV fluxes at the surfaces of planets within the HZ of M dwarfs (Heath *et al.*, 1999; Smith, Scalo, and Wheeler, 2004a). In the majority of instances, this has been viewed as a negative strike against the habitability of M-dwarf exoplanets, despite the fact that many UV shielding mechanisms are feasible, as described in Sec. III.C.1. Nonetheless, we highlight a couple of recent studies that illustrate the detrimental effects before discussing the potential positives later.

In an important study, Segura *et al.* (2010) simulated the fluxes of UV radiation that were delivered to the surface of an Earth analog at a distance of 0.16 AU orbiting the star AD Leonis ($M_\star \approx 0.4 M_\odot$ and age < 0.3 Gyr) during a flare with a total energy of ~10^{27} J. It was found that the amount of UV

flux increased by a factor of around 50 at the peak of the flare compared to the quiescent phase prior to the onset of the flare. Although this was seemingly a significant increase, most of the UV enhancement was in the UV-A (315–400 nm) range, which has a much weaker effect on damaging DNA (by a factor of ∼100) compared to shorter UV wavelengths. However, an important aspect worth noting is that this result presumed the existence of ozone. Taking ozone depletion into account (see Sec. IV.C), the same flare was estimated to produce higher UV-A and UV-B (280–315 nm) fluxes at the peak of the flare.

Estrela and Valio (2018) analyzed how a hypothetical Earth analog at 1 AU around the solar-analog Kepler-96 (with $M_\star \approx M_\odot$) would respond to a superflare with energy $E \sim 1.8 \times 10^{28}$ J. This led to an enhancement in the UV flux by nearly 2 orders of magnitude, and the BEI (see Sec. III.C.1) was found to exceed even that of radiation-resistant extremophile *Deinococcus radiodurans* in the absence of ozone. However, the presence of an ozone layer or an ocean depth of ∼12 m would suffice to protect microbes akin to *D. radiodurans* from the UV radiation emitted during superflares.

Moving on to the positive effects, we noted in Sec. III.B that planets around M dwarfs may be characterized by a paucity of bioactive UV radiation. However, it is possible, in principle, for prebiotic reactions to take place during the flaring phase because of the enhanced UV fluxes, while remaining inactive during the quiescent phase (Buccino, Lemarchand, and Mauas, 2007; Ranjan, Wordsworth, and Sasselov, 2017). This hypothesis requires further experimental tests before it can be confirmed or invalidated. Based on the available flare statistics, Rimmer *et al.* (2018) proposed that ∼20% of M dwarfs are sufficiently active so as to provide sufficient UV fluxes for synthesizing the precursors of biomolecules.

In the same spirit, we saw in Sec. III.C.2 that Earth-like biospheres based on photosynthesis may not be sustainable on low-mass stars. However, an important point worth recognizing is that flares can also deliver photons in the PAR range. Hence, when the effects of stellar flares are included, theoretical calculations seem to indicate that the efficiency of photosynthesis may be raised by approximately 1 order of magnitude (Mullan and Bais, 2018), although the averaged photosynthetic efficiency of planets in the HZ of M dwarfs is still anticipated to be lower than that of the Earth. Finally, the high fluxes of UV radiation incident on the surface during flaring events are expected to result in intermittently enhanced mutation rates, thereby serving as agents of ecological and evolutionary change (Smith, Scalo, and Wheeler, 2004b).

B. Coronal mass ejections

Coronal mass ejections (CMEs) are large loads of plasma and magnetic fields expelled from the host star. They are generally, but not always, linked with flares (Webb and Howard, 2012). The majority CMEs carry a mass of $\lesssim 10^{13}$ kg and move at velocities of order 100–1000 km/s. One of the important reasons for studying CMEs is that they can facilitate the acceleration of energetic particles through shock waves (Kilpua, Koskinen, and Pulkkinen, 2017), which is addressed in Sec. IV.C. We will, instead, focus on their effects on planetary magnetospheres and atmospheric erosion.

To begin with, it is instructive to consider the parameters of a sizable CME. A CME with parameters commensurate with the famous Carrington event is predicted to have a density that is ∼50 times higher than the current solar wind density and a velocity that is ∼4 times greater (Ngwira *et al.*, 2014). Thus, based on the preceding discussion in Sec. II.A, we find that the corresponding ram pressure would be ∼800 times higher than that of the present-day solar wind. Substituting this result into Eq. (2), we find that the magnetopause distance for an Earth analog would be compressed to roughly one-third of its steady-state value for the current solar wind.

From Eq. (3), we see that the mass-loss rate should be enhanced by a factor of ∼200, and utilizing Eq. (6) reveals that the atmospheric escape rate should increase by a factor of ∼200 with respect to the steady state as well. This prediction is in good agreement with numerical simulations that yield an enhancement of ∼110 (Dong, Huang *et al.*, 2017). Observational evidence from the ongoing Mars atmosphere and volatile evolution (MAVEN) mission has also revealed that CMEs (smaller than Carrington-type events) can result in the enhancement of Martian atmospheric ion escape rates by roughly an order of magnitude (Dong *et al.*, 2015; Jakosky *et al.*, 2015).

Although the previous discussion pertains to our Solar System, we observe that these two implications also apply to extrasolar systems. For instance, owing to a combination of the weak planetary magnetic fields, close-in distances, and frequency of CME impacts (Kay, Opher, and Kornbleuth, 2016), the effects of CMEs are expected to significantly compress the magnetospheres of M-dwarf exoplanets (Khodachenko *et al.*, 2007) and enhance the escape rates leading to cumulative atmospheric losses of ∼10–100 bar (Lammer *et al.*, 2007). At the same time, we underscore the fact that the mass-loss rates from active stars, especially M dwarfs, due to CMEs is not tightly constrained. This is because of the fact that most studies rely on extrapolations based on putative correlations between the x-ray fluences of flares and the kinetic energies and masses of CMEs, although the extent to which such extrapolations are valid remains unknown (Odert *et al.*, 2017). The presence of large-scale magnetic fields may, for instance, impose upper limits on the kinetic energy of CMEs (Alvarado-Gómez *et al.*, 2018).

Bearing these caveats in mind, we note that the mass-loss rates due to CMEs from magnetically active stars may be 1–3 orders of magnitude higher than the current mass carried away by the steady-state solar wind today (Drake *et al.*, 2013; Cranmer, 2017). Hence, from Eq. (6), it also follows that the atmospheric escape rates will be enhanced by the same degree for active (usually young) stars. In other words, the time scale for the total depletion of the atmosphere computed in Sec. II.B could represent an upper bound. The magnetospheres will also be compressed by a factor of a few owing to the enhanced value of the ram pressure in Eq. (2).

Thus, when viewed cumulatively, it seems plausible that CMEs exacerbate the issues discussed in the context of stellar winds in Sec. II.

C. Stellar proton events

The majority of large stellar flares are accompanied by the production of stellar or solar energetic particles (SEPs), and

these phenomena are known as stellar or solar proton events (SPEs). The mechanisms behind their production are complex, but can be divided into two broad categories: "impulsive" events involving magnetic reconnection and "gradual" events involving fast shock waves propelled by CMEs (Reames, 2013). Of the two, it is the latter that produce higher fluences of SEPs (Desai and Giacalone, 2016) and are therefore expected to be more prominent. The kinetic energies of SEPs (mostly protons or electrons) are usually in the keV and MeV ranges, but the maximum values can reach several GeV (Mewaldt, 2006). As direct measurements of extrasolar SEP fluences are not currently feasible, most models rely on extrapolations from empirical scalings (Takahashi, Mizuno, and Shibata, 2016; Youngblood *et al.*, 2017). It must, however, be appreciated that these predictions may break down at high SEP fluences (Hudson, 2015; Usoskin, 2017).

It has been duly recognized, since nearly half a century ago, that SEPs lead to the formation of hydrogen and nitrogen oxides (Crutzen, 1979; López-Puertas *et al.*, 2005). The latter, in particular, have been shown to facilitate the depletion of ozone (Solomon, 1999) through catalytic reactions, of which one of them is

$$NO + O_3 \rightarrow NO_2 + O_2, \tag{20}$$

where NO and NO_2 are nitric oxide and nitrogen dioxide, respectively (Crutzen, Isaksen, and Reid, 1975). Hence, high-fluence SPEs can lead to the destruction of the ozone layer (Tilley *et al.*, 2019), which in turn results in high doses of UV radiation reaching the surface. In principle, this might be offset by the presence of high concentrations of N_2O (which absorb UV radiation) (Rugheimer *et al.*, 2013; Rugheimer, Kaltenegger *et al.*, 2015). As noted previously, high-UV radiation fluxes do not preclude the existence of life under a layer of water or in subsurface environments, but they may impose constraints on surface habitability.

Segura *et al.* (2010) analyzed how a putative SPE associated with the AD Leonis flare, discussed earlier in Sec. IV.A, affected the ozone layer. It was found that the ozone depletion reached a maximum of 94% provided that the Earth analog was unmagnetized. Recently, a superflare with energy $\sim 10^{26.5}$ J was detected from Proxima Centauri (Howard *et al.*, 2018). In the presence of an ozone layer, the effects on habitability were not significant. However, when the effects of SPEs were taken into account, it was found that 90% of the ozone layer could be lost within five years. In this scenario, the amount of UV-C radiation (< 280 nm) that reached the surface was almost 2 orders of magnitude higher than the critical flux that would kill 90% of a given population of the radiation-resistant microbe *D. radiodurans*.

A similar study was undertaken to assess the impact of repeated SPEs on a hypothetical Earth analog around the star GJ1243, and it was found that ozone depletion of 94% could occur in as little as 10 yr (Tilley *et al.*, 2019). The net result of all these studies appears to be that complete ozone depletion might take place within $\mathcal{O}(10^5)$ yr, although it must be recognized that this time scale depends on the flaring frequency, planetary magnetic field, and atmospheric composition; see also Tabataba-Vakili *et al.* (2016) for a discussion

of how SPEs impact M-dwarf exoplanets. Consequently, it would result in a quiescent UV-C flux that may lie above the tolerance threshold of *D. radiodurans*, and this issue will probably be exacerbated by subsequent flares that increase the UV-C flux by 2–3 orders of magnitude.

By examining the available empirical evidence for the correlations between flare energy, the fluence of SEPs, and the degree of ozone depletion, Lingam and Loeb (2017b) presented a phenomenological relation between the ozone depletion ($\mathcal{D}_{O_3}$) and the flare energy:

$$\mathcal{D}_{O_3} \sim 2.8\% \left(\frac{E}{10^{25} \text{ J}}\right)^{9/25} \left(\frac{a_p}{1 \text{ AU}}\right)^{-18/25}. \tag{21}$$

Hence, it can be verified that a flare with $E \sim 2 \times 10^{29}$ J would lead to complete ozone depletion ($\mathcal{D}_{O_3} \approx 100\%$) for a terrestrial planet at 1 AU, whereas the corresponding value at 0.1 AU is $E \sim 2 \times 10^{27}$ J. If we make use of the relations $a_p \propto L_\star^{1/2} \propto M_\star^{7/4}$ (Böhm-Vitense, 1992) for Earth analogs, we obtain $\mathcal{D}_{O_3} \propto E^{0.36} M_\star^{-1.26}$.

Setting aside the issue of ozone depletion, another problematic issue arising from SEPs is that their impact with atmospheres induces the formation of secondary particle cascades that increase the radiation dose received at the surface (Melott and Thomas, 2011; Atri and Melott, 2014). This topic was recently studied by Atri (2017) for a wide range of planetary parameters. In general, it was found that the radiation dose at the surface increased when (a) the atmospheric column density was lowered, (b) the flare energy was increased, (c) the planetary magnetic moment was reduced, and (d) the star-planet distance was lowered. In the case of exoplanets around M dwarfs, it is conceivable that one or more of (a)–(d) are applicable. While this does not rule out the prospects for life, the critical radiation doses for macroscopic multicellular organisms on Earth (e.g., mammals) are exceeded under certain circumstances.

However, there are potential benefits associated with SPEs as well. To begin with, the abiotic synthesis of the building blocks of life requires suitable energy sources and pathways (Miller and Urey, 1959; Chyba and Sagan, 1992; Deamer and Weber, 2010). One of the most important feedstock molecules for prebiotic synthesis is hydrogen cyanide (Sutherland, 2016). Detailed numerical simulations carried out by Airapetian *et al.* (2016) demonstrate that hydrogen cyanide (HCN) can be synthesized at concentrations of tens of parts per million by volume in the lower atmosphere during SPEs. The production of the aforementioned nitrogen oxides via SEPs can also be associated with a positive component: these compounds are attractive electron acceptors that may facilitate the emergence of metabolic pathways and life at alkaline hydrothermal vents (Wong *et al.*, 2017) or shallow ponds and lakes (Ranjan *et al.*, 2019).

Looking beyond feedstock molecules like HCN and formaldehyde (CH_2O), laboratory experiments have demonstrated that a wide array of biomolecular building blocks such as amino acids and nucleobases, which are essential components of nucleotides (i.e., monomers of nucleic acids), are synthesized with relatively high efficiency when gaseous mixtures are irradiated by high-energy protons (Kobayashi *et al.*,

1998; Miyakawa *et al.*, 2002; Dartnell, 2011). The averaged energy flux (Φ_{SEP}) delivered to the surface of a planet with a 1-bar atmosphere via SEPs is (Lingam *et al.*, 2018)

$$\Phi_{SEP} \sim 50 \, \mathrm{J m^{-2} \, yr^{-1}} \left(\frac{\dot{N}}{1 \, \mathrm{day^{-1}}}\right) \left(\frac{a_p}{1 \, \mathrm{AU}}\right)^{-2}, \quad (22)$$

where $\dot{N}$ denotes the number of "large" SPEs expected to impact the planet per day, which could reach a maximum of order unity for young Sun-like stars as well as M dwarfs (Kay, Opher, and Kornbleuth, 2016). It is evident from Eq. (22) that M-dwarf exoplanets will receive higher SEP fluxes due to the smaller values of a_p (Fraschetti *et al.*, 2019). In turn, this could result in the enhanced synthesis of prebiotic compounds (Nava-Sedeño *et al.*, 2016), thereby partially offsetting the deficiency of UV light delineated in Sec. III.B. By drawing upon laboratory experiments, which are admittedly idealized, Lingam *et al.* (2018) suggested that the production rates of organics were given by

$$\dot{\mathcal{M}}_A \sim 10^7 \, \mathrm{kg/yr} \left(\frac{\Phi_{SEP}}{100 \, \mathrm{J m^{-2} \, yr^{-1}}}\right) \left(\frac{R_p}{R_\oplus}\right)^2, \quad (23)$$

$$\dot{\mathcal{M}}_N \sim 10^4 \, \mathrm{kg/yr} \left(\frac{\Phi_{SEP}}{100 \, \mathrm{J m^{-2} \, yr^{-1}}}\right) \left(\frac{R_p}{R_\oplus}\right)^2, \quad (24)$$

where $\dot{\mathcal{M}}_A$ and $\dot{\mathcal{M}}_N$ denote the rate of production of amino acids and nucleobases, respectively. On early Earth, it was found that $\dot{\mathcal{M}}_A$ was comparable to the production rate of amino acids from electrical discharges (lightning), and 3–4 orders of magnitude higher than the delivery rate of these compounds through meteorites.

From a geological standpoint, the primordial Earth possibly required a high concentration of greenhouse gases to prevent its oceans from freezing due to the lower luminosity of the Sun (70% of the present-day value) during this epoch (Sagan and Mullen, 1972). This has led to many proposals to explain how temperatures above freezing were achieved (Feulner, 2012). Nitrous oxide (N_2O) is efficiently formed during SPEs (Airapetian *et al.*, 2016),[12] and has a greenhouse potential that is ~ 300 times higher than CO_2 over a 100-yr period (Voigt *et al.*, 2017). The latter feature lends credence to the idea that it may have contributed to the greenhouse warming of early Earth (Canfield, Glazer, and Falkowski, 2010) and possibly other habitable planets. Signatures of N_2O and biosignature gases like O_2 could be "highlighted" during episodes of magnetic activity, thereby making them more detectable (Airapetian, Jackman *et al.*, 2017).

V. DISCUSSION

M dwarfs like Proxima Centauri and TRAPPIST-1 are $\lesssim 10$ times more abundant than the Sun (Chabrier, 2003; Robles *et al.*, 2008) and have stellar lifetimes that are ~ 100–1000 times greater (Adams and Laughlin, 1997; Loeb, Batista, and Sloan, 2016; Tarter *et al.*, 2007). Furthermore, exoplanets

around these stars are easier to detect and their atmospheres can be analyzed via transit spectroscopy (Winn, 2010; Fujii *et al.*, 2018), thus enabling the ready detection of biomarkers. Hence, in light of these facts, we are confronted with the following question: how is exoplanetary habitability influenced by the properties of the host star? One possible answer is that physical mechanisms could act in concert to suppress the likelihood of life's emergence on M-dwarf exoplanets relative to their counterparts around solar-type stars.

In this Colloquium, we have encountered a number of potential reasons as to why the habitability of M-dwarf exoplanets might be reduced. These include atmospheric erosion due to intense stellar winds, coronal mass ejections and UV radiation, paucity of photons for the origin of life and photosynthesis, and an inhospitable surface environment due to radiation from stellar flares and solar proton events. Yet, it is equally vital to appreciate that numerous nonlinear feedback mechanisms are at play, and that none of the aforementioned factors rule out the prospects for life altogether.

For instance, exoplanets around M dwarfs could have started out with massive hydrogen-helium atmospheres and lost them via atmospheric erosion involving UV radiation, stellar winds, or active phases of supermassive black holes to yield potentially habitable worlds (Luger *et al.*, 2015; Chen, Forbes, and Loeb, 2018). It is also possible that planets started with high water inventories that were depleted through UV photolysis and hydrogen escape to yield worlds with a mixture of land and oceans on the surface. In addition, planets may have formed outside the HZ and escaped the brunt of the long and intense pre-main-sequence phase of M dwarfs, before eventually migrating inward into the HZ at a later stage; see Tamayo *et al.* (2017) and Ormel, Liu, and Schoonenberg (2017). Finally, M-dwarf planetary systems might possess inherent advantages such as the enhanced transport of life between planets via lithopanspermia by several orders of magnitude compared to the Earth-Mars system (Steffen and Li, 2016; Krijt *et al.*, 2017; Lingam and Loeb, 2017c). However, in each of these instances, either a high degree of fine-tuning might be required or the feasibility of the proposed mechanisms remains indeterminate.

The question posed earlier is important from a practical standpoint because of the fact that resources such as the observation time, technological capabilities of current facilities, and funding are all limited. Hence, the selection of the most optimal target stars and planets when searching for biosignatures will be of the utmost importance in the future, when we are confronted with a diverse array of planetary systems around different stars (Horner and Jones, 2010; Kaltenegger *et al.*, 2010; Lingam and Loeb, 2018a). In this respect, the importance of theoretical modeling as a tool for identifying which targets merit the highest consideration becomes manifest. Moreover, theoretical models can also help us figure out what kind of hypothetical biospheres may exist and what to potentially expect when searching for signatures of life.

The ultimate answer to this question will, of course, necessitate detailed observations that are free of preconceived biases. With the upcoming launch of the James Webb Space Telescope, the ongoing development of ground-based extremely large telescopes, and mission concepts for future

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[12]Moreover, it may also build up on planets with low-UV fluxes as the latter would otherwise destroy N_2O (Rugheimer *et al.*, 2013).

space telescopes, the characterization of terrestrial planets and searching for biosignatures is expected to become feasible in the upcoming decades (Rodler and López-Morales, 2014; Snellen *et al.*, 2015; Barstow and Irwin, 2016; Morley *et al.*, 2017; Fujii *et al.*, 2018; Kiang *et al.*, 2018). These developments might not only help us answer the age-old question of whether we are alone but also assess the rarity or commonality of life in the Universe.

ACKNOWLEDGMENTS

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