Photosynthesis on habitable planets around low-mass stars

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ABSTRACT
We show that planets around M-dwarfs with $M_\star \lesssim 0.2M_\odot$ may not receive enough photons in the photosynthetically active range of 400-750 nm to sustain Earth-like biospheres. As a result of the lower biological productivity, it is likely that biotic molecular oxygen would not build up to detectable levels in the atmospheres of habitable planets orbiting low-mass stars, consistent with prior work by Lehmer et al. (2018). We also estimate the minimum flaring rate for sustaining biospheres with Earth-like productivity and permitting the build-up of atmospheric oxygen, and find that the overwhelming majority of M-dwarfs are unlikely to exceed this threshold.

Key words: astrobiology – planets and satellites: terrestrial planets – stars: low-mass – extraterrestrial intelligence

1 INTRODUCTION
It is no exaggeration to claim that life on Earth is dominated by photosynthesis as far as its biomass is concerned (Bar-On et al. 2018). Photosynthesis arose relatively early in Earth’s evolutionary history, with the emergence of anoxygenic photosynthesis ostensibly serving as the precursor for oxygenic photosynthesis, which involves the splitting of water molecules to produce oxygen (Xiong & Bauer 2002; Hohmann-Marriott & Blankenship 2011; Fischer et al. 2016). In its simplified form, the net reaction can be expressed as

$$\text{CO}_2 + 2\text{H}_2\text{O} \xrightarrow{h\nu} \text{CH}_2\text{O} + \text{H}_2\text{O} + \text{O}_2,$$

with the presence of H$_2$O on both the left- and right-hand-sides signifying the fact that water serves as both reactant and product. Oxygenic photosynthesis dominates the net primary productivity (entailing the fixation of carbon) on modern-day Earth, and is often regarded as a major evolutionary development because of the dramatic changes that were subsequently engendered (Lane 2003; Knoll 2015).

Given the centrality of photosynthesis for the reasons outlined above, one may naturally ask as to whether other planets are capable of sustaining biospheres whose biomass is similar to that of Earth. One of the key points to note is that the rate of carbon fixation via photosynthesis on Earth is dependent on the flux of photons in the wavelength range of $\sim 400$-$700$ nm, collectively termed photosynthetically active radiation (PAR). In the habitable zone of cool stars (M-dwarfs in particular), it is well-known that the PAR flux is much smaller than the solar value on Earth, implying that biospheres on habitable planets orbiting these stars may be constrained by the availability of photons (Pollard 1979; Gale & Wandel 2017; Lehmer et al. 2018). Thus, in this paper, we investigate the characteristics of photosynthesis-based biospheres on planets situated in the habitable zone, especially around low-mass stars.

Earlier studies in this area include Kiang et al. (2007); Gale & Wandel (2017); Ritchie et al. (2018); Mullan & Bais (2018); Lehmer et al. (2018). Our analysis closely parallels the recent work by Lehmer et al. (2018) and is consistent with their results, but it differs in the following respects. First, we study the maximum biological potential of Earth-like planets and the capacity for accumulating molecular oxygen in the atmosphere not only for M-dwarfs, but also for A-, F-, G- and K-type stars. Second, we analyze the significance of stellar flares in detail and derive an explicit criterion that must be satisfied in order for flares to contribute significantly to the flux of PAR.

The outline of the paper is as follows. In Section 2, we compute the PAR flux received by Earth-analogs, assess the contribution from stellar flares, and consider the limits on biological productivity. We explore the ensuing ramifications for the build-up of atmospheric oxygen and the emergence of complex life in Section 3. Finally, we summarize our primary conclusions in Section 4.

2 PHOTON FLUXES AT EARTH-ANALOGS
We will examine the PAR photon fluxes received by Earth-analogs orbiting other stars and discuss the contribution of stellar flares to the fluxes of PAR.
expressible as

\[ \frac{\dot{N}}{N_\odot} = 4 \frac{R^2}{\alpha^2} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{2e}{\lambda^4} \left( \exp \left( \frac{h \bar{c}}{\chi k_B T} \right) - 1 \right)^{-1} d\lambda, \]

where the photon production rate \( \dot{N} \) is defined as

\[ \dot{N}_\star = 4\pi R^2 \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{2e}{\lambda^4} \left( \exp \left( \frac{h \bar{c}}{\chi k_B T} \right) - 1 \right)^{-1} d\lambda, \]
average wavelength of a photon in the PAR range. Since the wavelength spans \( \sim 400-750 \) nm, note that the energy of a photon only varies by a factor of less than 2. We will use the arithmetic mean of the two energies, thus yielding \( hc/\lambda = 3.8 \times 10^{-19} \) J. In order for an Earth-like NPP to be sustained, the criterion \( F_I > F_o \) must be fulfilled. In order to compute \( \epsilon_{\text{PAR}} \), we use the approximation that the flare can be modeled as a blackbody with temperature 9000 K, which yields \( \epsilon_{\text{PAR}} \approx 0.4 \). From this data, we obtain:

\[
N_I \gtrsim 9.4 \times 10^3 \text{day}^{-1} \left( \frac{E_I}{10^{27} \text{J}} \right)^{-1} \left( \frac{R_\star}{R_\odot} \right)^2 \left( \frac{T_\star}{T_\odot} \right)^4,
\]

and this can be further simplified using the mass-radius and mass-luminosity scalings introduced earlier to yield

\[
N_I \gtrsim 9.4 \times 10^3 \text{day}^{-1} \left( \frac{E_I}{10^{27} \text{J}} \right)^{-1} \left( \frac{M_\star}{M_\odot} \right)^3.
\]

Note that (7) has the same functional dependence as Eq. (10) from Günther et al. (2019), except that the prefactor of \( 9.4 \times 10^3 \) in the former must be replaced with \( 3.4 \times 10^2 \). Using the data from the TESS mission presented in Figure 10 of Günther et al. (2019), it is easy to verify that < 1% of all M-dwarf flaring stars satisfy the condition (7), implying that flares might not suffice to deliver enough PAR to enable the sustenance of biospheres with Earth-like NPP around the majority of low-mass M-dwarfs. Next, let us apply (8) to Proxima Centauri. We find that the cumulative flare frequency must be \( \sim 160/\text{day} \) for flares with \( \gtrsim 10^{25} \) J. Using the cumulative flare frequency distribution for Proxima Centauri deduced from MOST observations (Davenport et al. 2016), we find that this criterion is not fulfilled. Likewise, repeating the same analysis for TRAPPIST-1 using (8), the frequency must be \( \sim 70/\text{day} \) for flares with \( \gtrsim 10^{25} \) J. Employing the flare frequency distribution formulated from the analysis of the K2 mission (Vida et al. 2017), this condition is not met. Hence, at least insofar as Proxima Centauri and TRAPPIST-1 are concerned, it seems unlikely that their flares deliver enough PAR fluxes to permit the sustenance of Earth-like NPP on planets orbiting these stars.

Moreover, there are additional caveats that deserve to be highlighted here. Unlike standard photosynthesis that can function continuously during the day, flare-driven photosynthesis would necessitate a very different mode of operation. Hence, in the absence of comprehensive laboratory experiments, it is not clear as to whether intermittent photosynthetic activity is possible. In particular, it is not clear as to whether densely ionizing radiation emitted during solar proton events associated with flares could induce damage and thereby inhibit photosynthesis (De Micco et al. 2011). Finally, we note that flares give rise to a number of other positive and negative effects. In the former category, they are capable of supplying ultraviolet photons and stellar energetic particles for prebiotic chemistry (Buccino et al. 2007; Ranjan et al. 2017; Lingam & Loeb 2018b; Rimmer et al. 2018; Lingam et al. 2018). On the other hand, flares contribute, either directly or indirectly, to a number of detrimental phenomena including atmospheric erosion (Lammer et al. 2007; Dong et al. 2017a,b, 2018) and ozone depletion (Segura et al. 2010; Lingam & Loeb 2017, 2019a).

**Figure 2.** The maximum possible oxygen source-to-sink ratio \( (\Delta \lambda_{\text{O}_2}) \) as a function of the stellar mass \( (M_\star) \) assuming that the PAR flux constitutes the sole limitation. In the case of Earth-analogs around stars whose values lie below that of the red line (where the source and sink are balanced), oxygen depletion is dominant.

### 3 IMPLICATIONS FOR ATMOSPHERIC OXYGEN

Hitherto, we have concentrated on assessing the potential biomass sustainable on Earth-analogs by taking only energetic constraints into account. However, it should be recognized that oxygentic photosynthesis not only entails the fixation of carbon but also the release of oxygen as a product, as seen from (1). Thus, the photon flux also dictates the amount of oxygen released into the atmosphere provided that all the sinks are held fixed. This consideration implicitly presumes that other limitations (e.g. nutrients) do not come into play; we will return to this issue later.

On Earth, it is known that oxygentic photosynthesis indirectly serves as the source of atmospheric oxygen via the burial of organic matter. A second major source of \( O_2 \) requires the burial of pyrite (FeS2). There are two major sinks, but only one of them is expected to be dominant in worlds where \( O_2 \) has not built up to sufficiently high levels. This sink corresponds to \( O_2 \) consumption by reactions with reducing gases arising from volcanism and submarine weathering (Catling & Kasting 2017). Lehmer et al. (2018) recently suggested that a potentially sufficient condition for ensuring oxygen buildup in the atmosphere is that the input rate must exceed the depletion rate. The influx rate of \( O_2 \) is computed by multiplying the maximum amount of carbon that can be fixed with the efficiency of burial of organic carbon (Holland 2002). The former factor in turn is directly proportional to the PAR flux. Following Lehmer et al. (2018), we hold the depletion rate to be constant, and adopt the value of \( \sim 5.7 \times 10^{12} \text{mol/yr} \) presented in Catling & Kasting (2017). Further details regarding this procedure can be found in Lingam & Loeb (2019c). In actuality, the oxygen depletion rate is time-dependent and is also likely to vary.
across different planets depending on their geological properties (e.g. internal heat budget).

In Figure 2, we have depicted the ratio of the oxygen source and sink fluxes, denoted henceforth by $\Delta_{O_2}$. This quantity only represents the maximum possible value (but not the actual value), since it presupposes that all of the PAR is utilized by photosynthesis in the absence of any other limitations. It is found that $\Delta_{O_2} < 1$ holds true when $M_\star \lesssim 0.13 M_\odot$. In other words, M-dwarfs with masses below this threshold, which constitute a sizable fraction of all stars including the local examples of Proxima Centauri and TRAPPIST-1, have a low probability of accumulating oxygen in the atmosphere via oxygenic photosynthesis. This result has two important consequences for biosignatures and technosignatures as discussed below.

First, if oxygen levels are not sufficiently high in the atmosphere, it is likely that searches for oxygen - for example, by means of transit spectroscopy (Meadows et al. 2018) - would give rise to “false negatives” (Reinhard et al. 2017). In other words, it is conceivable that planets host life but are not detectable by seeking signatures of $O_2$ and $O_3$ because of the simple fact that the concentrations of these gases in the atmosphere would be too low.\(^1\) The Earth, for instance, possessed a largely anoxic atmosphere until $\sim 2.4$ Ga with near-modern $O_2$ levels having been achieved only $\lesssim 0.5$ Ga (Lyons et al. 2014; Knoll & Nowak 2017; Catling & Kasting 2017; Lingam & Loeb 2018a). Hence, Figure 2 can assist in the identification of suitable target planets based on the stars that they orbit (Lingam & Loeb 2018c).

Second, the rise in atmospheric and oceanic oxygen levels has been proposed to constitute a necessary requirement for the origin of “complex” life endowed with high motility (Catling et al. 2005; Bains & Schulze-Makuch 2016). Although it cannot be naively said that the rise in $O_2$ levels served as the trigger for the diversification of animals (Mills & Canfield 2014), there are sufficient grounds for concluding that the former was responsible at least in part for the latter (Knoll 2017). Hence, if oxygen is truly a prerequisite for complex life, it will also be required for technological intelligence to evolve. In turn, the emergence of the latter opens up the possibility of finding life via technosignatures such as electromagnetic signals and artifacts (Lingam & Loeb 2019b).

Hitherto, we have not discussed the role of stellar flares in delivering sufficient PAR fluxes to enable the build-up of atmospheric $O_2$ indirectly via oxygenic photosynthesis. The procedure for calculating the desired occurrence rate is identical to that described in Sec. 2.2. The only difference is that the critical threshold that must be exceeded for permitting biotic $O_2$ accumulation is $\sim 0.57 F_\odot$. Thus, we find that the analog of (8) for the flaring rate is given by

$$N_f \gtrsim 5.4 \times 10^3 \text{ day}^{-1} \left( \frac{E_f}{10^{39} J} \right)^{-1} \left( \frac{M_\star}{M_\odot} \right)^3.$$

As noted in Sec. 2.2, the overwhelming majority of M-dwarf flaring stars do not meet this condition. Hence, it appears unlikely that flares are capable of providing sufficient PAR fluxes to permit the build-up of atmospheric $O_2$ around M-dwarf exoplanets.

In closing, there is an important point that must be mentioned here. Although our model predicts that the rise in $O_2$ levels may be suppressed or delayed on planets around low-mass M-dwarfs, this refers to biotic oxygen. In contrast, there are plenty of abiotic mechanisms for the accumulation of $O_2$ in atmospheres of M-dwarf exoplanets, the most common of which involves the photolysis of water and subsequent escape of hydrogen to space (Lingam & Loeb 2019a). Thus, even if $O_2$ is detected, it is important to apply suitable diagnostics to distinguish between abiotically and biotically produced oxygen (Meadows et al. 2018). While the buildup of $O_2$ through abiotic channels may come across as being positive from the standpoint of complex life, it is important to recognize that there are potential downsides as well. For example, it could be accompanied by the loss of water or result in extremely thick atmospheres with pressures of hundreds of bars (Luger & Barnes 2015).

### 4 CONCLUSIONS

We have explored the prospects for sustaining Earth-like biospheres (in terms of biological productivity) via photosynthesis on habitable planets around other stars. We modeled the stellar emission spectrum as a blackbody and computed the photon flux incident at the surface of an Earth-analog in the wavelength range of 400-750 nm. The photon flux received in this range sets limits on the biological potential of these worlds, provided that other desiderata such as nutrients and electron donors are fulfilled.

We found that the following broad conclusions arise. First, quiescent stars with $M_\star \lesssim 0.13 M_\odot$ are more likely to possess habitable planets with anoxic atmospheres due to the fact that the build-up of $O_2$ in the atmosphere via oxygenic photosynthesis is suppressed. This has two important consequences. The absence of sufficiently high oxygen levels might preclude complex multicellular life as well as technological intelligence from arising on such planets. However, even in the absence of oxygenic biosignatures, it would be feasible to detect anoxic biosignatures (e.g., methane) in the atmospheres of worlds where $O_2$ has not built up (Krissansen-Totton et al. 2018a,b). Interestingly, the above criterion is satisfied by both TRAPPIST-1 and Proxima Centauri, thereby potentially indicating that planets in the habitable zone of these stars may not accumulate biotic oxygen in the atmosphere.

Second, stars with $0.13 M_\odot \lesssim M_\star \lesssim 0.21 M_\odot$ are expected to possess habitable planets where the build-up of atmospheric oxygen is feasible, but the associated timescale for reaching modern Earth levels could be much longer (possibly exceeding the age of the Universe) and the overall NPP is predicted to be smaller than that of the Earth. Third, habitable planets around stars with $M_\star \gtrsim 0.21 M_\odot$ are theoretically capable of sustaining biospheres with the same productivity as the Earth, provided that photon limitation constitutes the only determining factor. Lastly, we calculate the minimum flaring rates necessary for the sustenance of biospheres with Earth-like productivity and the build-up of atmospheric oxygen via oxygenic photosynthesis as a function of stellar mass and flare energy. We concluded that a potentially negligible fraction ($\lesssim 1\%$) of M-dwarfs are likely to exceed the critical flaring frequency.

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\(^1\) In the case of tidally locked planets around M-dwarfs, it should also be noted that the day-to-nightside contrasts in the concentration of $O_2$ and $O_3$ could be appreciable (Chen et al. 2018).
Thus, our analysis suggests, in agreement with previous studies, that the likelihood of finding Earth-like biospheres around low-mass stars is comparatively low. In particular, these conclusions are consistent with those of Lehmer et al. (2018) who expressed their results in terms of a lower bound on stellar irradiation. Here, we have employed mass-luminosity and radius-luminosity relationships to determine a lower limit on stellar mass, since the latter could be more readily useful for astronomers. Replacing our mass-luminosity relation with the broken power-law scalings presented in Salaris & Cassisi (2005) and Loeb et al. (2016) will result in the aforementioned cutoffs \(0.13 M_{\odot}\) and \(0.21 M_{\odot}\) being replaced by \(0.21 M_{\odot}\) and \(0.39 M_{\odot}\). Hence, our estimates of \(0.13 M_{\odot}\) and \(0.21 M_{\odot}\) may serve as fairly robust lower bounds for permitting the build-up of atmospheric \(O_2\) and sustenance of Earth-like biological productivity, respectively. If the build-up of atmospheric oxygen and the evolution of complex life is indeed suppressed on low-mass M-dwarfs, this might provide a partial explanation as to why \textit{Homo sapiens} (i.e., intelligent and conscious observers) find themselves around a Sun-like star in the present epoch instead of orbiting an M-dwarf in the cosmic future (Loeb et al. 2016; Haqq-Misra et al. 2018).

Throughout our treatment, we have implicitly assumed that the properties of extraterrestrial biospheres (e.g. photosynthetic pathways) are akin to that of our planet, and we have not taken planetary factors such as the land-water fraction into account (Lingam & Loeb 2019c). Moreover, our analysis accounts for stellar mass, but not for other stellar parameters such as age and rotation rate. Despite these caveats, the advantage of this simple model is that it provides predictions for the detectability of biosignatures and technosignatures that will be testable in the coming decades.

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