THE PRODUCTIVITY OF OXYGENIC PHOTOSYNTHESIS AROUND COOL STARS.

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Introduction: In the near future, space and ground based telescopes will look for signs of life around M dwarf stars. One prominent biosignature is the presence of atmospheric oxygen, as it may be indicative of oxygenic photosynthesis on the planetary surface [1]. On Earth, the vast majority of oxygenic photosynthesizing organisms use photons between 400-750 nm, which have sufficient energy to drive the photosynthetic reaction and generate O_2 from H_2O and CO_2. Photosynthetic organisms around cool stars may evolve similar pigments and machinery capable of evolving oxygen. However, in the habitable zones (HZ) of the coolest M dwarf stars, photon fluxes in the visible wavelength range may be just a few percent that of Earth's. While the Earth's modern biosphere is growth limited by *nutrient availability* [2–4], Earth-like planets in the HZ of cool stars may be growth limited by *photon availability* given the low photon fluxes in the 400-750 nm range.

In this study, we examine how the photon availability, and thus the biosphere of the modern Earth would be impacted if the stellar type of the Sun and orbital distance of the planet were changed. In part, we look to answer the question: if the modern Earth were placed around a TRAPPIST-1-like star with a photospheric temperature of ~2500 K [5], could its biomass production be maintained and could that impact O_2 production?

Results and Discussion: Our model shows that an Earth-like planet around a cool star may be unable to support the Earth's extant biosphere. This is shown in Figure 1, where we assume that the modern Earth orbits stars of various temperatures at various orbital distances.

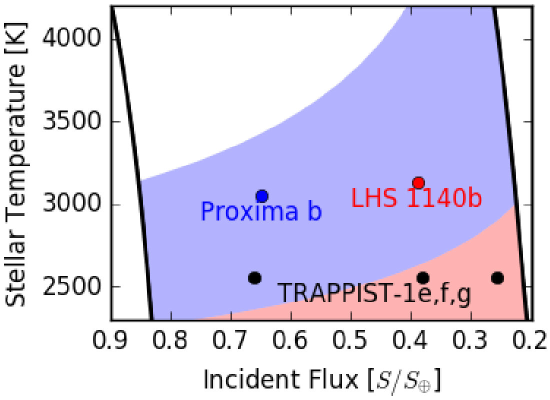

Figure 1. The photons available to drive photosynthesis around stars with photospheric temperatures between 2300 K and 4200 K. The horizontal axis shows the incident flux on the planet, scaled by the incident flux of the modern Earth, $S_\oplus = 1361$ W m^{-2}. The solid black lines show the inner and outer edges of the HZ from ref. [6]. The blue shaded region indicates the photon flux incident on the planet in the 400-750nm range is below the photon requirements of the terrestrial biosphere on the modern Earth. The red shaded region shows the flux of 400-750nm photons is below the photon requirements of the ocean biosphere on the modern Earth.

The small flux of 400-750nm photons around M dwarf stars could result in an Earth-like planet being growth limited by photon availability, as shown in Figure 1. A caveat is that we have assumed that the oxygenic photosynthesizing organisms on other planets will require the same photons (400-750nm) as on Earth. But it may be possible for organisms to synthesize oxygen using longer wavelength photons, which comprise a larger fraction of the total stellar flux as stellar temperature is decreased.

On the modern Earth, the photon flux per unit frequency from the sun peaks in the 400-750nm range, so it is not surprising that oxygenic photosynthesizing organisms absorb such photons. Indeed, if atmospheric attenuation of solar photons is accounted for, Earth's oxygenic photosynthesizing organisms are likely optimized when absorbing in that range [e.g., 7]. If organisms around other stars are similarly optimized, then decreasing stellar temperature will increase the optimal photon wavelength at which they absorb. Around the coolest M dwarf stars, we find that photosynthetic organisms producing oxygen are likely optimized if they absorb photons near 1.5µm, rather than in the 400-750nm range. If photosynthetic organisms can use photons up to 1.5µm, then an Earth-like biosphere may be sustainable around all but the coolest M dwarf stars, even when the reduced quantum yield from low-energy, long-wavelength photons is considered.

However, photons with wavelengths of 1.5µm may be unusable in oxygenic photosynthesis. For a photon to be used by the photosynthetic reaction, it must generate an electronic excitation in the absorbing pigment. At long wavelengths, incident photons induce rotational or vibrational transitions in the absorbing pigment, which are thermal in nature and thus cannot drive the photosynthetic reaction. The wavelength transition between electronic and thermal excitations for photosynthetic pigments is unknown, but it may fall well below 1.5µm. The best man-made detectors find that 1.1µm is the limit for electronic excitations [e.g., 8] and the longest wavelength photons used in photosynthesis (anoxygenic) by any organism fall closer to 1µm [e.g., 9].

Reducing the wavelength limit for photons useable by photosynthetic pigments increases the likelihood an Earth-like planet will be limited by *photon availability*. We explore potential wavelength limits, such as 1µm, 1.1µm, and 1.5µm, and how such limits alter the productivity of an Earth-like biosphere around cool stars.

From Figure 1, it may be likely that Earth-like biospheres around cool stars will be limited by photon availability (if they have nutrient fluxes comparable to the modern Earth and organisms use similar photon wavelengths). The biomass productivity of these biospheres will be restricted, potentially limiting the amount oxygen available to build up in the planetary atmosphere. The oxygen sinks from processes like metamorphism, volcanic outgassing, and serpentinization could overwhelm any oxygen produced by such a photon-limited biosphere. Thus, even if oxygenic photosynthesis is occurring on planets around stars like TRAPPIST-1, it may be undetectable to future missions looking for atmospheric oxygen as a biosignature.

References: [1] V.S. Meadows *et al.*, *arXiv preprintarXiv:1705.07560*, 2017. [2] G.I. Ågren, J.Å.M. Wetterstedt, M.F.K. Billberger, *New Phytologist*, 2012, 194, 953. [3] C.T. Reinhard *et al.*, *Nature*, 2016, 541, 386. [4] T. Tyrrell, *Nature*, 1999, 400, 525. [5] M. Gillon *et al.*, *Nature*, 2017, 542, 456. [6] R.K. Kopparapu *et al.*, *The Astrophysical Journal*, 2013, 765, 131. [7] N.Y. Kiang *et al.*, *Astrobiology*, 2007, 7, 222. [8] N.Y. Kiang *et al.*, *Astrobiology*, 2007, 7, 252. [9] L.O. Björn, H. Ghiradella, in *Photobiology*, (Björn, L. O.) Springer New York, 2015, 97.