Photosynthesis on a Planet Orbiting an M Dwarf: Enhanced Effectiveness during Flares

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Abstract

On planets near M dwarfs, oxygenic photosynthesis (PS) will occur with an effectiveness that depends on the supply of visible photons with wavelengths between 400 and 700 nm. In this paper, we quantify the effectiveness of PS in two contexts that are relevant for M dwarfs. First, using photons from an M dwarf in its quiescent (nonflaring) state, we find that PS on an M dwarf planet in the habitable zone (HZ) of its parent star is less effective than on Earth by a factor of 10 for a flare star with mid-M spectral type. For a flare star with late-M spectral type, PS effectiveness (PSE) is smaller than on Earth by a factor of 100 or more. Second, using photons that are incident on the HZ planet during flares, we find that PSE can increase by factors of 5–20 above the quiescent values. In the case of a flare star with mid-M spectral type, we find that the PSE during a flare can increase up to as much as 50%–60% of the values on Earth. However, for a late-M flare star, even during flares, the PSE remains almost one order of magnitude smaller than on Earth. We suggest that for biological processes on M dwarf planets, the stellar activity cycle may replace the orbital period as the “year.”

Key words: astrobiology – stars: flare – stars: individual (YZ CMi, 2MASSW J0149090+295613)

1. Introduction

Planets in orbit in the habitable zone (HZ) around M dwarfs are of great interest as regards the search for life. For a recent discussion of some of the extensive literature on this topic, see, for example, Shields et al. (2016), Cui et al. (2017), and Ranjan et al. (2017). In this paper, we are interested in one particular aspect of exoplanetary life (photosynthesis, hereafter PS) and how this is affected by variations in the radiative output from the parent star when that star is an M dwarf.

A well-known aspect of M dwarfs is that most of them are subject to flares, that is, temporary events during which the star brightens by some (variable) amount and then, over the range of a finite time, returns to its quiescent level (e.g., Gershberg 2002). When we refer to the “brightness” of an M dwarf during a flare, we are referring to the intensity of stellar radiation integrated over the entire visible disk of the star. This integrated radiation includes the quiescent radiation from the undisturbed (nonflaring) portions of the surface, plus more intense, localized radiation from an individual active region in which the flare has actually occurred. A nearby planet will receive the combined spectrum of flare plus quiescent radiation. For the present purposes, the most salient aspect of the radiation received by a planet during flares is that the spectrum of the radiation extends over a broad range of wavelengths. In a recent paper, Ranjan et al. (2017) focused on flare spectra in the ultraviolet (UV) and demonstrated that the dose rates of flare UV photons in a certain range of wavelengths (200–300 nm) are useful in enhancing prebiotic chemistry.

In the present paper, we focus on a portion of the flare spectrum that was not discussed by Ranjan et al., namely, the visible range of wavelengths (400–700 nm). We are interested here in how the visible flare photons contribute to oxygenic PS. While it is well known that PS ultimately provides energy (either directly or indirectly) for most life on Earth, PS is also of interest as regards the search for life on exoplanets. The reason is that PS produces planetary-scale biosignatures, including distinctive reflectance spectra (the “red edge”) of the PS organisms, as well as identifiable biogenic gaseous products (including O₂, O₃, CO₂; e.g., Heath et al. 1999; Des Marais et al. 2002; Kiang et al. 2007; Seager 2014; Berdyugina et al. 2016).

A planet orbiting an M dwarf will find itself, during a flare, subject to fluxes of PS-driving photons that are larger than those emitted by the quiescent star. In this paper, we quantify the enhancement that is expected to occur in PS during a flare compared to that which occurs in the quiescent state. To do this, we convolve the wavelength distributions of the two factors that play a role in PS: (1) the photons that are emitted by the star, and (2) the absorbance of the material that gives rise to PS. In Section 2, we provide details of factor (1). In Section 3, we discuss the properties of chlorophyll that are pertinent to the present paper: in particular, we present in Section 3.3 in graphical format, the wavelength-dependent details of factor (2). Results of the convolution of the two factors are presented in Section 4 for two particular M dwarfs for which suitable spectra exist in the literature. Some further relevant properties of flares are summarized in Section 5. Discussion and conclusions are presented in Sections 6 and 7.

2. The Radiation Environment in the HZ

Planets in the HZ around stars of different spectral type are situated at different radial distances from the parent star. The definition of HZ we use here is that the mean surface temperature of the planet is 288 K; that is, the radiation that is incident at the top of the atmosphere has (more or less, ignoring differences in albedo and greenhouse trapping) the same energy flux as the Earth receives from the Sun when integrated over all wavelengths. Thus, the integrated energy flux incident on the top of the planetary atmospheres we consider here is about 1370 W m⁻².

Planets in the HZ around parent stars of different spectral types receive photon fluxes that are strongest at different wavelengths. For example, near an F star, more energy is incident at short wavelengths, while near an M dwarf, more
temperatures of 288 K, there will be a

As a result, when spectra of stars of different spectral types are

the wavelength-integrated

energy is incident at long wavelengths. And yet, by definition, the wavelength-integrated flux must be the same in all cases. As a result, when spectra of stars of different spectral types are plotted in a single graph such that all lead to planetary temperatures of 288 K, there will be a “crossover wavelength” for each spectral type (e.g., Kiang et al. 2007; Shields et al. 2016). By the term “crossover wavelength,” we mean the wavelength where two spectral distributions have the same flux. We shall use the measured flux at the crossover wavelength to normalize the spectra, thereby enabling a meaningful comparison between PS on Earth and PS on planets around M dwarfs.

In this paper, we focus on two particular flare stars for which spectra are available in the literature over appropriate wavelength ranges. One flare occurred on a star with mid-M spectral type (YZ CMi), and the second on a star with late-M spectral type (2MASSW J0149090+295613, hereafter J0149). A first step in our work is therefore to identify the crossover wavelengths for these two M dwarfs. To do that, we need to start with the radiation emitted by the Sun as a function of wavelength.

2.1. The Radiation Environment Incident on Earth

Neckel and Labs (1984, hereafter NL) reported measurements of the Sun’s mean intensity (in units of W cm\(^{-2}\) ster\(^{-1}\) Å\(^{-1}\)) that is incident on Earth’s atmosphere at wavelengths between 330 and 1250 nm. For the present purposes, we have extracted (from their Figures 4 and 5) values of the mean intensity at selected wavelengths throughout that range. Inserting an angular size of the Sun of 6.67 × 10\(^{-3}\) steradians, we convert the NL results to irradiances and plot the results in units of W cm\(^{-2}\) μm\(^{-1}\) in Figure 1 (short dashed line). Integrating the flux from 330 to 1250 nm, NL obtained a flux of 1059.7–1062.4 W m\(^{-2}\) depending on corrections to the continuum. According to NL, measurements made by other researchers at longer wavelengths add 271.3–276.8 W m\(^{-2}\) to the integrated flux, while the inclusion of UV wavelengths adds 37.0–38.4 W m\(^{-2}\). Combining these, NL reported a range of values for the “solar constant,” namely, 1369–1378 W m\(^{-2}\) at the top of Earth’s atmosphere.

More recently, due to recalibrations of space-borne detectors, the IAU has adopted a “nominal” solar constant of 1361 W m\(^{-2}\) (Prsa et al. 2016). In view of the 1%–2% ranges in the numerical values for the “solar constant,” and since the detailed NL data are especially useful in calculating PS effectiveness (PSE), we adopt a “mean solar constant” of 1370 W m\(^{-2}\) (i.e., lying within the NL range) when we calculate the integrated fluxes of our two M dwarfs.

It is noteworthy that some 25% of the Sun’s integrated flux occurs at wavelengths longer than 1.25 μm. For M dwarfs, the percentages of the integrated flux beyond 1.25 μm will be even larger than for the Sun. Therefore, in order to obtain reliable integrated fluxes for M dwarfs, we need to have access to flux measurements at wavelengths extending to many micrometers.

2.2. Determining the Crossover Wavelength for a Mid-M Star

In order to determine the crossover wavelength for our mid-M star (YZ CMi), it would ideally be necessary to have access to the spectrum of YZ CMi at wavelengths extending from the UV to far out into the infrared. However, the most extensive spectra we have been able to identify for YZ CMi span wavelengths only from 350 to 900 nm (Kowalski 2012). The wavelength range from 0.35 to 0.9 μm is too narrow to provide a reliable value for the integrated flux. However, a spectrum of another flare star (AD Leo) extending from 0.115 to 173 μm is available online (Cohen 2017). According to the Simbad database, the spectral type of AD Leo is M4Vae, while YZ CMi is listed as M4.0Ve: these spectral types are so similar to each other that we will adopt the extensive AD Leo spectrum as a proxy for YZ CMi.

Integrating over the entire AD Leo spectrum and applying a distance of 4.87 pc, we find that a planet at a distance of 1 au from AD Leo would receive an integrated input flux of 32 W m\(^{-2}\); therefore, if a planet in orbit around AD Leo is to receive 1370 W m\(^{-2}\) (and therefore lie in the HZ), the planet must be at a distance of \(\sqrt{32/1370} = 0.15\) au from AD Leo. (With a stellar radius of order 0.4R\(_{\text{Sun}}\), the HZ planet is at a distance of order 80 stellar radii from AD Leo.) The input irradiance spectrum to such a planet is illustrated by crosses in Figure 1: the units are the same as those used by NL for the case of sunlight arriving at Earth. Inspection of Figure 1 shows that the crossover for AD Leo and the Sun occurs at a wavelength of 0.8 μm.

In order to discuss PS on a planet in the HZ around YZ CMi, we shall assume that the crossover wavelength is 800 nm.

2.3. Determining the Crossover Wavelength for a Late-M Star

Liebert et al. (1999) have reported on J0149, which underwent a “spectacular flare.” The visible spectra reported by Liebert et al., in quiescence and during the flare, span the wavelength range from 630 to 1000 nm.

In order to obtain an integrated flux and thereby identify the crossover wavelength for this star, we need to supplement the data from Liebert et al. with data at both shorter and longer wavelengths. As regards extrapolations to wavelengths that are shorter than 630 nm, we could adopt a variety of approaches:
for example, scale the observed spectrum of an M dwarf, or use a Planck function.

As regards scaling the observed spectrum of an M dwarf in quiescence, we note that the quiescent spectrum of YZ CMi (see Figure 3) is observed to decrease almost monotonically toward shorter wavelengths, falling essentially to zero at 400 nm. In principle, we might consider adding supplemental spectral information for J0149 at wavelengths less than 630 nm by scaling the observed spectrum of the quiescent spectrum of YZ CMi. However, this is not reliable, because the spectral type of J0149 (M9.5-9.7) is so much later than the spectral type of YZ CMi (M4.0). As a result, the spectral features in YZ CMi between 400 and 630 nm may have little to do with the spectral features that occur in the J0149 spectrum in the same wavelength range. To illustrate this point, we may cite the results of Rajpurohit et al. (2013), who have illustrated the optical-to-red spectral energy distributions for M dwarfs from M0 to M9.5: this range of spectral types extends late enough to overlap with one of the spectral types assigned to J0149. In principle, we would like to examine the wavelength range from 630 to 400 nm. Unfortunately, this is not possible because the wavelength range shown by Rajpurohit et al. (in their Figure 2) extends only to 520 nm. But using the data that are available in their Figure 2, we see that in an M4 star the (quiescent) spectrum between 630 and 520 nm certainly contains spectral features that are plainly visible. On the other hand, in an M9.5 star, in the same wavelength range, the spectrum contains no visible features. Therefore, we consider that scaling the spectrum from an M4 star in the range 630–520 nm would not necessarily yield a reliable measure of the spectrum of an M9.5 star in the range 520–630 nm. A fortiori, we believe that it would not be helpful to scale the YZ CMi spectrum over the range 400–630 nm and apply the scaled results to J0149.

As regards using a Planck function in order to extrapolate from 630 to 400 nm, we note that, because of the presence of increasingly strong molecular absorptions at lower temperatures, the spectra of M dwarfs in the optical-to-red region depart more and more from a Planck spectrum as we examine later and later spectral types. This can be seen also in the paper by Rajpurohit et al. (2013, their Figure 3). In view of this, we consider that there would be little to gain by using a Planck function for the extrapolation of J0149 to wavelengths shorter than 630 nm.

In view of the difficulties associated with an extrapolation from 630 to 400 nm using either a scaling from the observed spectrum of a hotter M dwarf or a Planck function, we have chosen a less rigorous approach: we have added a linear ramp to the blue of the shortest wavelength (630 nm) reported by Liebert et al. We assume for simplicity that the blueward ramp decreases to zero flux at 400 nm.

At wavelengths longer than 1000 nm, we supplement the fluxes measured by Liebert et al. in two steps.

First, we note that Liebert et al. assign a spectral type of M9.5V to this star, but in a more recent paper (Gagliuffi et al. 2014), a spectral type of M9.7V is also listed. Gagliuffi et al. present infrared spectra for some of the stars in their sample. Unfortunately, J0149 is not included in the spectra they illustrate. However, in their Figure 4, they include the spectrum of an M9.9V star over a range of wavelengths extending from 0.9 to 2.4 μm. Among the sample of stars reported by Gagliuffi et al., this M9.9V star is the closest in spectral type to the M9.5V and M9.7V types listed for J0149. We therefore consider it plausible to use the 0.9–2.4 μm spectrum of the M9.9V star as a proxy for J0149. In the wavelength range from 0.9 to 1.0 μm, the Gagliuffi et al. spectrum overlaps with that of Liebert et al. (1999). Using this overlap, we merge the spectra to obtain a single empirical curve from 0.63 to 2.4 μm in the units used by Liebert et al., that is, 10⁻¹⁵ W m⁻² μm⁻¹.

Second, in order to estimate the contribution to the integrated flux of wavelengths longer than 2.4 μm, we assume a Rayleigh–Jeans irradiance \( I(\lambda) = K/\lambda^4 \), where \( K \) is chosen to match the observed irradiance \( I(2.4) \) at \( \lambda = 2.4 \) μm. With this choice, the contribution to the integrated flux at \( \lambda > 2.4 \) μm is equal to 0.8(2.4).

The integrated flux longward of 400 nm is then normalized to have a value of 1370 W m⁻² and is plotted in Figure 2 along with the solar data. Inspection of Figure 2 shows that the crossover for J0149 and the Sun occurs at a wavelength of 1.0 μm. We adopt this crossover wavelength in our study of PSE in a planet in the HZ of J0149.

2.4. Quiescent and Flaring Spectra for YZ CMi

In order to take advantage of the crossover wavelength at 800 nm, we need to have access to spectra of YZ CMi that extend to at least 800 nm. Moreover, to make comparisons between PSE during flares and in quiescent conditions, we need to have spectra extending to 800 nm for both the quiescent star and during a flare.

In an extensive study of flare spectra, Kowalski (2012) included some 60 spectra obtained at various phases during flares in a sample of six flare stars (including YZ CMi), with spectral types ranging from dM3e to dM4.5e. However, as regards the wavelength scale, among the 60 (or so) spectra, some 40 to 45 extend in wavelength only to (about) 550 nm, and four to five others extend to only 680 nm. As regards spectra that extend as far as 800 nm (or beyond), we find four
flare spectra (in Kowalski’s Figure 6.32) that extend from 350 to 920 nm. However, the calibrations of these four spectra are said to be suspect longward of 750 nm and also around 550 nm. Two reliable spectra are reported to extend from 340 to 920 nm, but they were obtained during the decay phase of two flares, rather than at the peak phase. Only one spectrum (in Kowalski’s Figure 6.31) obtained at a flare peak extends over the wavelength range we seek: this is for a flare labeled impulsive flare #3 (if3) on YZ CMi, and the spectra extend out to 920 nm.

As regards the star in quiescence, Kowalski (2012) provides (in his Figure 6.31) the irradiance \( I_q(\lambda) \) of YZ CMi in its quiescent state: this spectrum is suitable for our purposes because it also extends to wavelengths of 920 nm. We have scanned the Kowalski quiescent spectrum and plot the scan in Figure 3 (dotted curve labeled YZ-q). In the plot, the ordinate is in the units of irradiance used by Kowalski (2012), that is, \( 10^{-12} \) W m\(^{-2}\) m\(^{-1}\). (Note that these units are 1000 times larger than those used by Liebert et al. 1999: the difference arises in part from the fact that J0149 lies at a greater distance than YZ CMi, and in part from the later spectral type of J0149.)

The wavelength range that is plotted along the abscissa is chosen to be wide enough to allow the reader to see the crossover wavelength at 800 nm. However, when it is time for us to quantify the effectiveness of PS (in Section 3.3), we shall not actually make use of the spectrum longward of 700 nm.

Also in Figure 3, we show Kowalski’s data for the irradiance spectrum \( I_f(\lambda) \) at the time of flare peak (open squares connected by a dotted line and labeled YZ-f). The units along the ordinate are the same as those used for the quiescent spectrum. To avoid confusion in Figure 3 at the longest and shortest wavelengths, the wavelength range we use for flare radiation extends only from 400 to 700 nm. In Kowalski’s notation, the curve YZ-f refers to radiation emitted by the flare alone, that is, excluding the quiescent radiation.

It is important to recognize that, based on observations of solar flares, where imaging can be performed, only one active region is typically involved in any particular flare, while the remainder of the Sun’s surface remains in its nonflaring (quiescent) state. By analogy, it seems likely that an active region on a flare star also occupies only a fraction of the surface of the star at the time of flaring. Therefore, during a flare, the flaring star actually emits a spectrum with an irradiance \( I_{of}(\lambda) \), which is a combination of the irradiance from the quiescent surface \( I_q(\lambda) \) and the irradiance \( I_f(\lambda) \) from the portion of the stellar disk that is undergoing flaring. We already know what \( I_f(\lambda) \) is: it is provided in Kowalski’s Figure 6.31 in units of \( 10^{-12} \) W m\(^{-2}\) m\(^{-1}\). If we were interested in determining the irradiance of the flaring region in absolute terms, then we would need to know an extra piece of information, namely, the fractional area of the stellar disk that is occupied by the flaring region. This fractional area can be expressed as a filling factor, ff. The irradiance we measure on Earth during a flare is determined by integrating over the visible disk of the flaring star such that the value of \( I_{of}(\lambda) \) is given formally by the weighted sum \( I_{of}(\lambda) = ff I_q(\lambda) + (1-ff) I_f(\lambda) \). Typically, the value of ff for any particular flare on an M dwarf star (where no imaging of the surface is available) is unknown. Therefore, in general, although we can determine \( I_q(\lambda) \) reliably (by restricting observations to time intervals that include no flares), it is difficult (if not impossible) to determine \( I_f(\lambda) \) reliably in absolute units.

But what the observations do tell us reliably is that the intensity of the overall output of radiant energy from the M dwarf, as seen on Earth, increases during a flare by a certain amount X. Moreover, the observations indicate reliably that the value of X varies systematically with wavelength: \( X(\lambda) < 1 \) at long wavelengths, and \( X(\lambda) > 1 \) (sometimes by as much as 10–100) in the blue. A formula that represents the numerical value of \( X(\lambda) \) at any wavelength \( \lambda \) can be expressed formally as the weighted sum of \( ff I_f(\lambda) + (1-ff) I_q(\lambda) \) divided by \( I_f(\lambda) \). Thus, a measurement of \( X(\lambda) \) at any wavelength \( \lambda \) already incorporates the effects of the filling factor on the overall output of radiant energy from the flaring M dwarf even if we cannot separate out the value of ff. If, for example, \( X(\lambda) \) is observed in a particular flare to have a value of 3, this could be due to a flare that occupies 10% of the surface (i.e., \( ff = 0.1 \)) which has an enhancement \( I_f(\lambda)/I_q(\lambda) \) of order 30, or it could be due to a flare that occupies 1% of the surface (i.e., \( ff = 0.01 \)) which has an enhancement \( I_f(\lambda)/I_q(\lambda) \) of order 300. Or it could be due to any other combination of flare intensity and flare area such that the overall effect is to increase the brightness of the star by a factor of 3. We have in general no way of knowing which of these options are relevant to any particular flare. We do know that, during the flare, the radiant energy received by a PS plant located on any HZ planet around the M dwarf will increase by a factor of 3.

There is one case in which we would really need to know the value of \( I_f(\lambda) \) in order to proceed with the calculation in the present paper. Suppose we were dealing with a planet that belongs to the class known as “hot Jupiters.” Such a planet is in an orbit that lies very close to the parent star, within perhaps only a few stellar radii above the surface. If this planet were to pass over the flare site at a distance of close to one stellar radius, then the flare site, as viewed by the planet, could
essentially fill the entire field of view of the stellar surface all the way to the horizon. In such a case, PS plants on that planet could certainly be exposed to the full effects of the flare radiation; then the enhancement in radiant energy impacting the planet during a flare could indeed be as large as the (illustrative) factors of 30–300 mentioned above. However, in such cases, if the planet were really in such a close orbit, it would be too hot to lie in the HZ; such a planet would be of no interest as regards the study of living organisms (such as those that cause PS). Instead, we are interested in planets that lie in the actual HZ of the M dwarf. In such cases, the separations between star and planet in terms of stellar radii are large enough (several dozen radii) that the flare radiation will typically not fill the entire field of view all the way to the horizon. Instead, the field of view from the planet will include not merely the flare but also the portions of the star’s surface that are not flaring at all. Therefore, the radiant energy arriving at the planet will not consist of flare radiation alone, but of flare plus quiescent radiations. As a result, the radiation arriving at the planet will be enhanced during a flare by the integrated effects of quiescent radiation (covering most of the stellar surface) plus the effects of the flare (with enhancements of, say, 30–300) diminished by the filling factor. In effect, a planet in the HZ will see a relative enhancement in radiation during a flare similar to what an observer on Earth sees.

In view of this, and especially since we are interested in performing a differential study of PSE during flares on a particular star, we consider it reasonable to apply the empirical values of $\chi(\lambda)$ as measured on Earth during a flare to be applicable also to the increase in radiant energy experienced by a plant on a planet that is in HZ orbit around that particular star, that is, at a radial distance of 80 stellar radii in the case of AD Leo. We note also that in the case of the cool star Trappist 1 (with radius 0.121 $R_{\odot}$), the planet labeled planet f in the HZ occurs at a distance of 0.039 au, that is, at a distance of about 70 stellar radii. Thus, planets in the HZ around an M dwarf orbit at distances that are many tens of stellar radii. These distances are large enough that the plants on such a planet will receive radiation not merely from the flare site, but in fact mostly from the nonflaring regions of the star. Plants on such a planet will indeed be subject to radiant energy from the flare site, but (unlike the “hot Jupiter” case) the full effects of the flare site will be diluted by the factor $ff$.

As regards PSE, we note that a blackbody (BB) continuum rising strongly toward the blue is prominent in the flare spectrum. This BB radiation presumably arises from dense gas in the photosphere that is locally heated by transient energy input (either particles or photons) coming down from the site of the primary flare energy release. (In solar flares, primary energy release occurs in the corona at altitudes of tens of thousands of kilometers above the photosphere; see Aschwanden et al. 1996.) The temperature of the BB that provides the best fit to the BB during the sample of flares reported by Kowalski (2012) ranges from as low as 7,000 K to as large as 14,000 K; we shall use both of these limits on the BB temperature when we model the spectra of flares for which we have no direct observations over a range of wavelengths where BB radiation is known to dominate. Kowalski also reports that flares exhibit a Balmer continuum, but this is not pertinent in the present paper because the photons lie at wavelengths (<360 nm) that are outside the range (400–700 nm) which is relevant for PS.

Also prominent in flare spectra are four prominent lines of the Balmer series (H$\alpha$–H$\delta$) in emission at 656, 486, 434, and 410 nm; these emission lines also make a contribution to enhancing PSE during flares. According to Kowalski (2012, his Table 8), the H$\alpha$ line alone can contribute as much as 10% of the overall flare flux in certain gradual flares. (In impulsive flares, the contribution is closer to 1%.) Also according to Kowalski (his Table 8), the fluxes in each of the three higher Balmer lines are equal to the H$\alpha$ flux within a factor of 2, sometimes exceeding H$\alpha$, and in other flares being weaker.

Our goal in this paper is to quantitatively how flares can be beneficial for life (specifically, as regards PSE). But we also need to admit that not all flare phenomena are beneficial: in Section 6, we will discuss how UV photons and energetic particles generated by a flare may negatively impact life.

### 2.5. Normalizing the Sun and YZ CMi to Evaluate Relative PSE

In the units used by Kowalski (2012), that is, $10^{-12}$ W m$^{-2}$ $\mu$m$^{-1}$, our inspection of the YZ-q spectrum provided by Kowalski (2012) indicates that the flux at the crossover wavelength (800 nm) is 6.8. We therefore use this number to normalize the solar spectrum in order to perform a differential study between PS on Earth and on a planet located in the HZ of YZ CMi. That is, we change the solar irradiance at 800 nm from the value reported by Neckel and Labs (1140 W m$^{-2}$ $\mu$m$^{-1}$) to the value reported by Kowalski for YZ CMi ($6.8 \times 10^{-12}$ W m$^{-2}$ $\mu$m$^{-1}$). In Figure 3, the uppermost curve shows the solar spectrum scaled to the value $6.8 \times 10^{-12}$ W m$^{-2}$ $\mu$m$^{-1}$ at 800 nm.

### 2.6. The Quiescent and Flaring Spectrum of a Late-M Flare Star

Liebert et al. (1999) obtained spectra for J0149 in quiescence and during a flare spanning the wavelength range from 630 to
1000 nm. These spectra are useful for our purposes because they include the crossover wavelength (1000 nm) for an M9.5-M9.7 dwarf. This enables us to normalize the solar spectrum so that we can make meaningful comparisons of PSE.

For PS purposes, we need to extrapolate the J0149 spectra reported by Liebert et al. toward shorter wavelengths. In the case of the quiescent spectrum, Liebert et al. (1999) measured the fluxes down to wavelengths no shorter than 630 nm (see the bottom panel in their Figure 2). Our choice of linear ramp between 630 and 400 nm (see Section 2.3) means that we will miss some of the (small) features around 580 and 540 nm, as well as the higher Balmer lines (Hβ-Hδ). However, the latter lines are expected to be weak, especially since even the Hα line (expected to be the strongest in the series) can barely be identified in the quiescent spectrum reported by Liebert et al. In Figure 4, the resulting quiescent spectrum that we adopt for J0149 is shown as the lowest-lying curve: the ordinate is in units of $10^{-15}$ W m$^{-2}$ μm$^{-1}$.

In the case of the flare spectrum of J0149, we use the plot given by Liebert et al. (their Figure 3, top panel) for radiation at wavelengths >630 nm. Our scan of this spectrum appears in our Figure 4 (dashed curve with crosses). These data include an exceptionally strong Hα line, with an equivalent width of 300 Å: using a scaling between Hα and total flare output, Liebert et al. report that the flare output during the impulsive phase (lasting 1000 to 2000 seconds) may have exceeded the bolometric photospheric luminosity.

In order to fill in the remainder of the PS-effective flare photons at wavelengths <630 nm, we impose a BB continuum (see Section 2.4). In view of the results reported by Kowalski (2012), a temperature in the range $T = (0.7-1.4) \times 10^4$ K can be assigned to the BB in different flares. In reporting our results, we shall start with a model where we use $T = 10,000$ K. However, we shall also report on results for a flare in which the BB temperature is only 7000 K and for a flare where $T = 14,000$ K. We used the online tool SpectralCalc.com to calculate the spectral irradiance from a $10^4$ K BB at wavelengths between 400 and 700 nm, and we fitted the output to the shortest wavelength flare point (630 nm) reported by Liebert et al. The resulting flare spectrum is illustrated in Figure 4 (middle curve). As Figure 4 illustrates, in going from a wavelength of 630 nm to a wavelength of 400 nm, the BB curve increases from the measured irradiance at 630 nm (2.49 in the units of Figure 4) to a value of 5.97 (in the same units). This increase in irradiance at 400 nm relative to that at 630 nm (by a factor of $\rho = 2.4$) is the increase reported by SpectralCalc.com for $T = 10,000$ K. Although, to avoid confusion, we do not include in Figure 4 the BB continua that we will use for the cases $T = 7000$ and 14,000 K, we can report that at $T = 7000$ K, the irradiance at 400 nm is larger than at 630 nm by a factor $\rho = 1.44$. At $T = 14,000$ K, the corresponding factor is $\rho = 3.3$. Thus, in going from $T = 10,000$ to 14,000 K, the value of $\rho$ increases linearly with $T$. But at lower temperatures, from 10,000 to 7000 K, $\rho$ falls off more steeply, varying as $T^{1.4}$. Because of the different values of $\rho$, we expect that in flares where the BB temperature is 14,000 (or 7000) K, PS will be more (or less) effective than the results for $T = 10,000$ K. We shall report results for all three values of $T$ below.

Referring to Figure 4, we see that there are no emission lines of Hβ-Hδ on the curve between 630 and 400 nm: only a continuum is included, although the Balmer lines can be prominent in flares. Therefore, the PSE we will derive for the “flare” in Figure 4 will provide only a lower limit on the actual value. To avoid confusion with the quiescent spectrum in Figure 4, we plot the flare spectrum only over the range of wavelengths from 400 to 700 nm.

2.7. Normalizing the Sun and J0149 to Evaluate Relative PSE

In units of $10^{-15}$ W m$^{-2}$ μm$^{-1}$, our inspection of the quiescent spectrum in Liebert et al. (1999) indicates that the flux at the crossover wavelength (1000 nm) is 10.8. As we did for YZ CMi, we can set the stage to perform a differential study of PSE between the Sun and J0149 by changing the solar radiative flux at 1000 nm from the units used by Neckel and Labs (760 W m$^{-2}$ μm$^{-1}$) to the units used for the J0149 radiation ($10.8 \times 10^{-15}$ W m$^{-2}$ μm$^{-1}$).

In Figure 4, the uppermost curve shows the solar spectrum scaled to J0149 at 1000 nm.

3. Oxygenic Photosynthesis

The only chemical compound that we consider in this paper as responsible for PS is chlorophyll. We recognize that this sets a limit on the processes we are considering. Nature has developed various organisms (phototrophs) that can capture photons in order to perform certain functions. For example, retinal is the basis for animal vision and may assist in certain organisms to convert light into metabolic energy. Moreover, some phototrophs, for example, haloarchaea, can absorb photon energy in order to create adenosine triphosphate (ATP) and can move chloride ions in order to generate a voltage gradient to energize reactions. Another subset of phototrophs, those involved in anoxygenic PS (e.g., purple bacteria), cause the release of sulfur from H$_2$S. However, none of these photosensitive reactions involve fixing carbon from its inorganic form (CO$_2$).

In the one biosphere where we know that life has been successful, the most common phototrophs participate in oxygenic PS. This participation involves the use of photons absorbed by chlorophyll to perform a number of tasks: (1) convert CO$_2$ into organic material, (2) split water so as to donate electrons to an electron transport chain, and (3) cause O$_2$ to be released into the environment. The combination of these tasks is what makes us decide to concentrate in the present paper on oxygenic PS in the context of extraterrestrial life.

In order to quantify the effectiveness of oxygenic PS in the presence of various radiation environments, we need to have specific information about the wavelength dependencies of the absorbance of various kinds of chlorophyll. We now turn to a consideration of this information.

3.1. Chlorophyll Components in Plants

Chl occurs in various forms. Chl-a and Chl-b are the commonest chemical variants that occur in wild plants on Earth, with varying ratios depending on the species. Chl-a/b ratios range from 3.3 to 4.2 in species that grow in sunlight, but the ratio falls to 2.2 in plants that grow in shade (Munns et al. 2016). Shade-adapted plants adapt to the lower light levels by containing a larger fraction of Chl-b: this allows the plants to extend the range of wavelengths over which light is effectively absorbed toward the blue. Organisms on Earth cannot simultaneously maintain an effective ability to harvest light when the level of light intensity is high and when the light
3.2. Chlorophyll Absorbances as a Function of Wavelength

As regards empirical studies of Chl absorbances, we note that the wavelength behavior depends on the solvent and on how the solution was prepared. The initial Chl absorption curve reported by Zscheile & Comar (1941) was obtained by using ether as the solvent; the results identified peaks in absorption at 429 and 659 nm for Chl-a, and at 455 and 642 nm for Chl-b. The peaks were rather sharp, with FWHM of 20–30 nm. Thus, both variants of Chl show two absorption peaks, one in the red and one in the blue, with a broad range of low absorptions from (roughly) 490 to 630 nm. In a living organism, where the Chl exists in a medium containing a mixture of proteins and pigments, the peaks in absorption are still present, but they are shifted and broadened.

In order to proceed with a quantitative discussion, we note that the wavelength-dependent absorbances of Chl exhibit a slightly different behavior depending on the environment in which the Chl is located. In the present paper, two different environments are considered (see Munns et al. 2016, their Section 1.2.2). The first is light-harvesting Chl (LHC) protein complexes. In these, light is collected by many pigment molecules located in the photosynthetic membrane. The second is the reaction centers (RC): these are situated at the center of the LHC, and they act as antennas for the initial (PS II) stage of the PS process. Because there are (at least) two variants of Chl that are used in plants, we need to consider in what ratios they are present in order to evaluate PS efficiency.

In this regard, we note that both Chl-a and Chl-b are bound to the LHCs. The availability of Chl-b is important for assembly of proteins in the LHC complexes in plants (Bellemare et al. 1982; Peter & Thornber 1991). The presence of Chl-b in plants plays an important role in stabilizing the LHC complex. If Chl-b is absent, the LHC complex becomes unstable, leading to formation of proteases and protein degradation. Thus, although Chl-b is in the minority in plants, we cannot assume an abundance of zero. In the context of stellar flares, it is important to note that the amount of Chl-b depends on the intensity of the incoming light; plants use lesser amounts of Chl-b when the light intensity is high, but they use more when the light intensity is low. This suggests that, when an M dwarf has a flare in progress, plants on a nearby planet might in principle reduce their Chl-b content. However, this principle should not be pushed too far: the LHC will still need some Chl-b in order to stabilize the complex under varying light intensity. (For example, in a laboratory study of extinction coefficients (Evans & Anderson 1987), the ratio of Chl-b to Chl-a was allowed to fall to 10%–12%, but no lower.) Moreover, plants are known to acclimatize chloroplast movement during varying light intensity: in the stronger light intensity that arrives during a flare, for example, the chloroplasts will have a tendency to move farther into the interior of the plant. It is also important to recognize that other pigments such as flavonoids and betalains may also play a role in light harvesting under varying light intensity. Therefore, it is expected that plants on a planet that is illuminated by an M dwarf will have the capability to undergo certain trade-offs as the plants strive to adjust to conditions of varying light intensity. In view of these various effects, we speculate that plants might in favorable circumstances develop somewhat different PS absorbance spectra during high-intensity flares; that is, the absorbance spectra of photosynthetic organisms may not be the same in planets around other stars. The absorbances may become adapted and may even become time-dependent, in order to adapt to both the spectrum and intensity of...
the parent star. However, if we wished to treat this problem in full detail, we would need to know the timescales $T_i$ on which the various adjustments occur. Such a task is beyond the scope of the present paper, where we are interested in a proof of principle.

### 3.3. The Essential Calculation in This Paper: Convolution

To quantify and compare PSE in different environments, our approach will be to convolve the wavelength-dependent photon spectra (in Figures 3 and 4) with the wavelength-dependent absorbance (in Figure 5).

In the present calculation, we will use the wavelength dependencies of the absorbances in LHC and RC environments as shown in Figure 5 over the range of wavelengths from 400 to 700 nm. The curves in the figure are taken from Munns et al. (2016): the figure shows in situ absorption spectra (eluted from gel slices) for pigment–protein complexes corresponding to photosystem II reaction centers (PSII RC) and light-harvesting Chl-(a,b) protein complexes (LHC). A secondary peak at 472 nm and a shoulder at 653 nm indicate contributions from Chl-b to the absorption spectra. The units along the ordinate axis are dimensionless, but they can be converted to the absolute extinction coefficients for pigment–protein complexes corresponding to photosystem II reaction centers, ARC(i). In the convolution study that follows, we scan the absorbance figure shows in situ absorption spectra with the wavelength-dependent photon flux of radiant energy, $E(\phi)$, by multiplying $R(i)$ at each wavelength by the corresponding $E(\phi)$. Equivalently, we can obtain a quantity that is proportional to the photon energy required for oxygenic PS to occur. The energy dependencies of the absorbances in LHC and RC environments are shown in Figure 5. The units along the ordinate axis are dimensionless, but they can be converted to the absolute extinction coefficients for pigment–protein complexes corresponding to photosystem II reaction centers, ARC(i). In the present paper, we con

### Table 1

| Star    | PSE(LHC) | PSE(RC) | PSE(Earth/star) |
|---------|----------|---------|-----------------|
| Sun/YZ (Section 2.5) | 391 | 389 | 1
| YZ CMi (quiescent) | 43 | 43 | 0.11
| YZ CMi (flare) | 173 | 179 | 0.45
| YZ CMi (f+q) | 216 | 222 | 0.56
| Sun/J0149 (Section 2.7) | 944 | 940 | 1
| J0149 (quiescent) | 7.3 | 7.7 | 0.008
| J0149 (flare) | 151 | 156 | 0.16
| J0149 (f+q) | 138 | 164 | 0.17

Although we have selected for definitiveness the absorbances in Figure 5 to illustrate quantitative details, this is not meant to imply that other possible forms of PS are excluded from occurring on planets around other stars. For example, in a hydrogen-dominated atmosphere, where the principal carbon species may be CH$_4$, PS based on methane might be the main source of energy for life (Bains et al. 2014). The effect of flare photons on methane-based PS is not discussed in this paper. Or sulfur-based PS might be the dominant energy source in the vicinity of deep-sea thermal vents (black smokers), where the photons are associated with the thermal vent, where the temperature is only 600 K (Raven & Donnelly 2013). It is unlikely that photons from flares (such as we discuss here) would have any significant effect on processes at the bottom of the ocean.

In the present paper, we confine attention to oxygenic PS and to the wavelength range 400–700 nm.

### 4. Quantitative Comparison of PSE on Earth with PSE on Planets in the HZ of Flare Stars

Now that we have similar arrays for the various spectra, we can make meaningful comparisons of PSE by convolving an $R(i)$ array with $\lambda(i)$ and also with either the LHC array or the ARC array, in accordance with Equation (1) or (2).
4.1. Comparing PSE on Earth and on a Planet of YZ CMi

To start the comparisons, we use the YZ-q normalization of the solar spectrum as described in Section 2.5. In combination with Equation (1), we can obtain the convolution of \( R(i) \lambda(i) \) with Equation \( \lambda(i) \) that is appropriate for conditions on planet Earth. We find that the numerical value of PSE(HLC) is 391 (in units of \( 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1} \)). For RC absorbance, the convolution in Equation (2) leads to a numerical value of PSE(RC) of 389 (in the same units). These numerical values are a measure of the effectiveness of PS on Earth in units that allow us to make a meaningful comparison with conditions on a planet that is in the HZ of YZ CMi. The numerical values are listed in the first row of Table 1, with the notation (Section 2.5) referring to the normalization of the solar spectrum described in Section 2.5.

Next, we use the \( R(i) \) spectrum for YZ CMi in its quiescent state and calculate the PSE for this spectrum. Results for the same measure of PSE under these conditions are listed in row 2 of Table 1. We see that, when YZ CMi is in its quiescent state, the PSE on a planet in the HZ of YZ CMi is about one order of magnitude smaller than on Earth. Then we use the \( R(i) \) spectrum of YZ CMi in its flaring state. Results for the same measure of PSE under these conditions are listed in row 3 of Table 1. Actually, during a flare, the light from the star is the sum of the flare spectrum plus quiescent. Therefore, in row 4 of Table 1, we give the PSE values in the presence of the combined \( f+q \) photons. We see that during a flare, the PSE is some five times larger than in quiescence. When YZ CMi is in a flaring state, the PSE on a planet in its HZ reaches values of 50%–60% of the value of PSE on Earth. Thus, on a planet in the HZ of YZ CMi, flares on the parent star lead to PSEs on the planet that are within a factor of 2 of PSEs on Earth.

4.2. Comparing PSE on Earth and on a Planet of J0149

To start the comparisons, we use the J0149 normalization of the solar spectrum as described in Section 2.7. Then we repeat the steps described in Section 4.1. For the J0149 normalization, we find that the numerical value of PSE(HLC) on Earth is 944 (in units of \( 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1} \)). For RC absorbance, the convolution in Equation (2) leads to a numerical value of PSE (RC) on Earth of 940 (in the same units). These numerical values are a measure of the effectiveness of PS on Earth in units that allow us to make a meaningful comparison with conditions on a planet that is in the HZ of J0149. The numerical values for the Earth are listed in row 5 in Table 1, with the notation referring to the normalization of the solar spectrum described in Section 2.7.

Next, we use the \( R(i) \) spectrum for J0149 in its quiescent state and calculate the PSE for this spectrum. Results for the same measure of PSE under these conditions are listed in row 6 of Table 1. We see that PSE is more than two orders of magnitude lower than on Earth.

Lastly, we use the \( R(i) \) spectrum of J0149 in its flaring state. In the first instance, we assume that the flare radiation contains a BB component with a temperature of \( T = 10,000 \text{ K} \). Results for our measure of PSE under these conditions are listed in row 7 of Table 1: the numerical results are 151 and 156, that is, some 20 times larger than in quiescence. However, as was noted in Section 2.6, in a flare where the BB temperature is 14,000 K, the PSE effectiveness is expected to be larger. In fact, we find the values to be 179–186, that is, larger by some 19% than the results for \( T = 10,000 \text{ K} \). On the other hand, in a flare where the BB temperature is only 7000 K, the PSE effectiveness is found to be 118–120, that is, reduced by some 30% relative to the results for \( T = 10,000 \text{ K} \). Thus, when we allow for the known range of BB temperatures in flares, photons from flares in J0149 are more effective than quiescent photons as regards PS by factors of 16–24. When J0149 is in a flaring state, including the contribution of quiescent photons (see row 8 in Table 1), the PSE is found to lie in the range of 13%–20% of the value of PSE on Earth. Thus, although flares do cause an increase in PSE in this case, the PSE on a planet in the HZ of J0149 remains, even during a “spectacular flare” such as that reported by Liebert et al. (1999), almost one order of magnitude smaller than on Earth.

5. Factors Contributing to PSE: Flare Durations, Intensities, and Frequencies

Although a flare involves a significant increase in photon output from a flare star, the overall PSE on a planet in orbit around the flare stars is also going to depend on other factors. Here, we discuss three of these: (1) how long does a flare last?, (2) how intense is the radiation?, and (3) how often do the flares occur?

(1) As regards flare durations, Gershberg (2002) includes an extensive discussion of data that were collected by observers over a time period of several decades. These data indicate that the duration of a flare \( T_1 \) (defined as the time interval during which the star’s brightness is greater than the quiescent level) spans a range of several orders of magnitude. At the long end of the distribution, the longest recorded flare (on the active flare star AU Mic) lasted 30–40 hr, as observed in the far-ultraviolet. A flare on an Orion flare star (T177) lasted about 20 hr, as recorded photographically. The star AZ Cnc was observed by the ROSAT X-ray satellite to have a duration of at least 8 hr. ROSAT also observed a flare on the star BY Dra that lasted about 4.5 hr. The star EV Lac was observed in visible light to have flares lasting 5 and 4.5 hr; the same star had an X-ray flare that lasted more than 4 hr. Coordinated ground-based observations of the star YZ CMi across a wide range of longitudes discovered an optical flare lasting more than 4 hr. A flare on the star EQ Peg was observed to have a duration in X-rays of more than 2.5 hr. Thus, the data indicate that flares on M dwarf stars can and do last as long as one hour and more. The longest flares also are associated with the largest flare energies, so they have the best opportunity to have an effect on the PSE.

Further data on flare durations have been reported by Kowalski et al. (2013, their Figure 18): in their sample of flares, which by no means includes the largest flares ever recorded, the maximum duration extends to timescales of order 1 hr. In particular, the emission in H\( \alpha \) lasts longer than at any other visible wavelength: the half-life for H\( \alpha \) in some of their flares is of order 1 hr. Thus, the H\( \alpha \) radiation from a flare as a whole can last for at least 2 hr. This longevity of H\( \alpha \) photons from a flare is important for flare-related PSE, since the H\( \alpha \) line lies close to the red peak of the PS absorbance (see Figure 5).

As regards the flare on J0149, Liebert et al. (1999) remark that their data spanned a time of only 42 minutes, but they could not determine “what fraction of the total flare event was detected, or whether the observations included the strongest part of the flare.” But their data certainly indicated that the flare lasted at least 42 minutes. And the data they did have suggested that for a period of 1000 to 2000 s, the flare output exceeded the total output power from the star as a whole.
At the extreme short end of the distribution of flare durations, Gershberg (2002) reports that some flares last for no more than 1 s.

As was mentioned in Section 3.1, the duration of a flare $T_f$ has a bearing on PSE. Specifically, if $T_f < T_s$ (the ramping-up timescale for PS to adapt to higher light levels), then a plant will not be able to adapt to the higher light level in the flare. Certainly the shortest flares mentioned above (lasting only seconds or a few minutes) will fall into this category and are of little relevance in the present context. On the other hand, the longest-lasting flares on M dwarfs (with durations of 1 hr or more) may well last long enough to allow the terrestrial light-harvesting apparatus to acclimatize to the higher light levels. If $T_f$ is about (say) 1 hr, we speculate that the enhancements in PSE calculated above (see Table 1) pertain preferentially to longer-lasting flares, unless planets near M dwarfs have developed a method for their light-harvesting apparatus to adapt to changes in light conditions that are more rapid than terrestrial organisms have to deal with.

(2) As regards the intensity of radiation that is emitted by flares, we have already quantified this in Figures 3 and 4, where one can make a direct comparison between the intensity of radiation from a star in its quiescent state and the intensity at the same wavelength in the flaring state. In Figures 3 and 4, we see that at the longest wavelengths of PS sensitivity, the ratio of flare radiation to quiescent radiation is close to unity. But at the shortest wavelengths of PS sensitivity (400 nm), the ratio is several dozen.

(3) As regards the frequency of flares, Shakhovskaya (1989) has compiled data on how frequently flares of a given energy occur on each star. The energies plotted by Shakhovskaya are given in terms of $E_R$, the energy contained in the Johnson B band (spanning wavelengths from 360 to 550 nm): to convert these to total energies in visible photons, we need to multiply by $3.8$ (Gershberg 2002). Inspection of Shakhovskaya’s Figure 2 suggests that in flare stars such as YY Gem or GT Peg, flares with $E_R$ of order $10^{20}$ J occur roughly once every 10 hr. The optical luminosity in the form of such flares is expected to be of order $3.8 \times 10^{26}/36,000 = 10^{22}$ W. Adding in flares of other energies from as much as $10^{28}$ J (occurring rarely, once per 1000 hr) to as little as $10^{24}$ J (occurring once every hour or so), the integrated flare luminosity may be of order $L(f) = 3 \times 10^{22}$ J. How does this compare with the quiescent luminosity $L_{bol}$ of these stars? In the Gershberg (2002) list of 463 flare stars, $L_{bol}$ is listed for only 20% of the sample: these are the brightest or nearest stars, and their listed $L_{bol}$ (in J) values range from 22.39 to 26.55, with a mean value of about 25.0 and an rms deviation of $\sigma = \pm 0.9$. For the remaining >80% of the stars in Gershberg’s list for which no value of $L_{bol}$ is given, it is expected that these flare stars have $\log L_{bol} < 25$ by a finite amount. There is no indication as to what the finite amount may be, but as a rough guide, we estimate 1–2$\sigma$. If this is correct, then the great majority (>80%) of flare stars in Gershberg’s list have a mean $\log L_{bol}$ in the range 23–24, that is, a mean $L_{bol}$ of order $3 \times 10^{24}$ J.

In view of this, the fraction of output power from flare stars in the form of flares, $L(f)/L_{bol}$, may rise to values as large as 10% (see Mullan 1989). Although the fractional flare output will be less than this limit in some flare stars, we suggest that there may be a selection effect in favor of life in the following sense: the effectiveness of flare-enhanced PS on a planet around a flare star will be greater in cases where the star (1) has longer flares and (2) outputs a larger fraction of its total power in the form of flares. In the context of the present paper, we suggest that such stars could be optimal candidates in a search for life around M dwarfs.

6. Discussion

Visual inspection of the flare spectra in Figures 3 and 4 suggests why flares contribute to an increase in PSE: the light intensity increases across essentially all of the visible spectrum where the photons are maximally effective in driving PS. Especially important during a flare in this regard is the presence of a BB continuum at temperatures of order $10^5$ K: this continuum provides an enhanced supply of photons that overlaps favorably with the absorbances of Chl (LHC) and Chl(RC). In addition to the continuum, the presence of enhanced emission lines during a flare also contributes to enhancing PS. The most prominent line feature of a flare spectrum at longer wavelengths (>600 nm) is the H$\alpha$ line, which is strongly in emission at 656 nm. Compared with the Chl absorbances in Figure 5, it is clear that H$\alpha$ has overlap with the red peak of Chl absorbance, especially with the LHC “shoulder.” And at the shorter wavelengths (<500 nm), the higher members of the Balmer series (at 486, 434, and 410 nm), all of which are also strongly in emission, overlap with the blue peak of Chl absorbance, especially with the LHC data. It is almost as if the optical spectra of M dwarf flares are (in a sense) “tuned” to exploit optimally the wavelength-dependent absorbances of Chl.

We note that Ranjan et al. (2017) have already demonstrated that photons emitted by stellar flares could be beneficial for prebiotic chemistry. The difference between our work and that of Ranjan et al. is that we focus on visible photons, whereas Ranjan et al. focused on UV photons. But our overall conclusions have an interesting overlap, specifically, that some flare photons may be beneficial for life.

Unfortunately, other aspects of flare activity may be detrimental to life. For example, extreme UV photons can be hazardous to biomolecules (Sagan 1973). Moreover, coronal mass ejections (CMEs) may strip away some of the atmosphere of an orbiting planet if the latter does not possess a significant magnetic field (Kay et al. 2016). In the case of the Sun, CMEs are known to be associated with certain flares: during the years from 1996 to 2010, the GOES spacecraft recorded 22,688 solar flares, while during the same period, the SOHO spacecraft recorded 12,433 solar CMEs (Youssif 2012). That is, a CME occurs on average in about 50% of solar flares; however, the percentage of flares with CMEs increases to essentially 100% in the largest flares (those that are classified as X flares; see Andrews 2003). Stellar flares are known to have total energies that exceed the largest solar X-flare energies by several orders of magnitude (Shakhovskaya 1989). An advantage of the largest stellar flares would be that they may have photon fluxes which enhance the PSE results by factors that are even larger than the factors we have presented. On the other hand, CMEs may also be more common in association with the largest stellar flares. Whether flares as a whole lead to a net benefit or a net deficit as regards biology remains to be seen.

7. Conclusion

We have found that a quantitative measure of the effectiveness of oxygenic PS in planets that are in orbit in
the HZ around M dwarfs is smaller than on Earth by one to two orders of magnitude when the M dwarf is in quiescence. But, during flares, the PSE increases by factors of $\sim 5$–20. These increases bring the PSE on planets in the HZ around mid-M dwarfs up to values that approach within factors of 2–3 those on Earth. But in late-M dwarfs, even during flares, the PSE remains almost one order of magnitude smaller than on Earth. This suggests that biology on a planet in the HZ of a mid-M dwarf could benefit from flares, at least as far as PSE is concerned. However, flares also lead to certain negative effects (Sagan 1973), so despite the results presented here, it might be argued that, when all of the relevant effects are quantified, flares might turn out not to have a net benefit for life. On the other hand, given the propensity for life to adapt to a variety of conditions, it is possible that life on a planet around an M dwarf, where UV and optical photon excesses are more or less continuous hazards, may develop some way to protect itself against the negative effects of flares.

In the event that flares turn out to have a net benefit for life on a planet that is in orbit within the HZ of an M dwarf, we consider that it could be worthwhile to pay attention to two different timescales. For brevity, we refer to these as the “daily” timescale and the “yearly” timescale. In the “daily” timescale, the axial rotations of HZ planets around M dwarfs are possibly tidally locked to the orbital period. In view of this locking, an anonymous referee has suggested that “a continuous illumination of one planetary hemisphere can be advantageous for PS-based life.”

As regards the “yearly” timescale, if the occurrence of flares turns out to have a net benefit for life, then we would like to suggest the following possibility: the “yearly” cycle of growth and dormancy that is characteristic of many plants on Earth might be replaced by a different type of cycle. On Earth, the tilt of the rotational axis relative to the orbital axis results in a modulation of photon fluxes at a given latitude on the Earth that has a timescale determined by the orbital period (1 year). However, the orbital periods of HZ planets around M dwarfs are much shorter than the orbital period of Earth: for example, in the Trappist 1 system, the planets in the HZ (e, f, g) have periods of 6–12 days. Given the finite timescales required for chemical reactions to occur at temperatures of 288 K (the mean global temperature; we do not examine here the possibilities of higher or lower temperatures at different latitudes), it is difficult to imagine how plants on planets in the HZ of Trappist 1 (where the temperatures are also about 288 K) could go through complete cycles of growth and dormancy in periods of only a few days. On the other hand, if PS (and by extension, perhaps other biological processes) is enhanced by radiation from flares on the parent star, then the period $P_a$ of an activity cycle of that star could provide a natural process of waxing and waning of PS activity on timescales of order $P_a$.

What sort of values of $P_a$ might stellar activity cycles exhibit? A report referring to an F5 star that was observed asteroseismically by COROT suggested a cycle with a period of about 120 days (Garcia et al. 2010). In another F star (KIC 3733735), Mathur et al. (2014) reported a cycle period of at least 1400 days. However, in a subsequent paper (Regulo et al. 2016), the same F star was reported to exhibit a seemingly cyclic behavior in the frequency of its asteroseismic modes: inspection of Figure 10 in Regulo et al. (2016) suggests a period of about 400–500 days. The largest survey of activity cycle periods to date is based on *Kepler* photometry:

Reinhold et al. (2017) have found long-term variations in more than 3000 *Kepler* stars that suggest the occurrence of activity cycles. They identify cycle periods in the range 0.5–6 years. Such values of $P_a$ augur well for the possibility that photochemical reactions that are effective on timescales of a few months on Earth (i.e., during the growing season in the northern hemisphere) will also have time to complete their functions in the HZ environment around a flaring M dwarf.

To consider this more quantitatively, suppose that (as was mentioned in Section 5(3)) 10% of a flare star’s energy is emitted in the form of flares. Consider a planet in the HZ of such a star: by definition, the total incoming energy flux to that planet (integrated over all wavelengths) is comparable to what the Earth receives from the Sun (the solar “constant” $\approx 1370$ W m$^{-2}$). However, in the case of the flare star’s planet, most of the incoming radiative energy occurs at wavelengths around 1000 nm, with greatly reduced fluxes at the wavelengths relevant for PS (400–700 nm). As a result, in the quiescent state, we have found that the PSE is 10–100 times less than the Earth’s value (see Section 4). But in the course of a flare, the PSE increases to as much as 50%–60% of the Earth’s value, that is, to a flux of about 700 W m$^{-2}$. With flares contributing 10% of the star’s output, this means that for 10% of the time, the flare star’s planet could receive roughly 700 W m$^{-2}$ of input power that is PS effective. Averaging over time, this planet can expect to receive a flux of roughly 70 W m$^{-2}$ of PS-effective photons: this is less than Earth receives by a factor of about 20. As a result, a growing season that on Earth receives enough PS-effective photons to be complete in (say) 3 months would require about 5 years on a flare-star planet. We consider it noteworthy that a 5 year interval falls within the range of activity cycle periods that have been reported among low-mass stars by Reinhold et al. (2017).

In contrast to the pessimistic conclusion of Sagan (1973) regarding the negative effects of stellar flares on life, the present paper suggests that the opposite conclusion may be worth exploring: flares may turn out to play an essential role in driving PS on a planet in the HZ around an M dwarf.

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