Biofluorescent Worlds:

Biological fluorescence as a temporal biosignature for flare star worlds

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**ABSTRACT**

Habitability for planets orbiting active stars has been questioned. Especially, planets in the Habitable Zone (HZ) of M-stars, like our closest star Proxima Centauri, experience temporal high-ultraviolet (UV) radiation. The high fraction of M-stars (75%) within the solar neighborhood, the high occurrence rate of rocky planets around M-stars, and the favorable contrast ratio between the star and a potentially habitable rocky planet, makes such planets interesting targets for upcoming observations. During M-star flares, the UV flux on a HZ planet can increase by up to two orders of magnitude. High UV radiation is harmful to life and can cause cell and DNA damage. Common UV protection methods (e.g. living underground, or underwater) would make a biosphere harder to detect. However, photoprotective biofluorescence, “up-shifting” UV to longer, safer wavelengths (a proposed UV protection mechanism for some corals), would increase the detectability of biota and even uncover normally hidden biospheres during a flare. Such biofluorescence could be observable as a “temporal biosignature” for planets around UV-active stars. We model temporal biofluorescence as a biosignature for an exoplanet biosphere exposed to such conditions, based on planets in M-star HZs. We use fluorescing coral proteins to model biofluorescence, comparing observable spectra, and colors, to vegetation and fluorescent minerals. Our planetary models assume a present-day Earth atmosphere and explore the effect of varying cloud coverage and land/ocean fractions. UV flare-induced biofluorescence could be remotely detectable, comparable in strength to vegetation on Earth. On planets in the HZ of M-stars, biofluorescence could be a temporary biosignature, distinguishable from fluorescing minerals and vegetation.

*Keywords:* astrobiology — stars: activity — stars: flare

1. **INTRODUCTION**

M stars are the most common type of star in the galaxy and make up 75% of the stars in the solar neighborhood. They are also excellent candidates for habitable zone (HZ) terrestrial planet searches. Our closest star, Proxima Centauri, is an active M6 star that currently experiences intense flares every 10-31 hours (Cincunegui et al. 2007), with several teams searching for a planet in the HZ around it. Another nearby M star, the young M8 star TRAPPIST-1, has been shown to have three Earth-sized planets close to its HZ (Gillon et al. 2016). Recent observations suggest the inner planets, TRAPPIST-1 b and c, are likely to be terrestrial (de Wit et al., 2016). Some possible orbits for the outermost planet, TRAPPIST-1d, place it in the system’s HZ (Gillon et al. 2016). Estimates of the HZ occurrence rate of Earth-sized (0.4-1 R\(_{\oplus}\)) planets around cool dwarfs range between 15% and 66% (Traub 2011; Gaidos 2013; Dressing et al. 2013; Kopparapu 2013; Ari et al. 2015). The upcoming TESS mission, scheduled for launch in 2017, will survey nearby bright stars to identify transiting exoplanets, including terrestrial ones in the HZ. It will be sensitive enough to identify HZ planet candidates around nearby low mass stars (T\(_{\text{eff}}\) ≤ 4000K; late M and early K stars) for future ground and space-based characterization (Ricker et al. 2014; Sullivan et al. 2015). TESS is expected to find 100s of 1.25-2 R\(_{\oplus}\) planets and 10s of Earth-sized planets, with a handful (< 20) of these planets in the HZ of their cool host stars (Ricker et al. 2014; Sullivan et al. 2015; Barnes et al. 2015). This makes it likely that the first HZ planet that can be characterized will be orbiting a nearby M star.

Planets that receive high doses of UV radiation are generally considered to be less promising candidates in the search for life (see e.g. Buccino et al. 2006). However, several teams have made the case that planets in the HZ of M stars can remain habitable, despite periodic high UV fluxes (see e.g. Rugheimer et al. 2015b, Scalo...
et al. 2007; Buccino et al. 2007; Tarter et al. 2007; Heath et al. 1999).

Two recent studies (Rugheimer et al. 2015a, 2015b) model the amount of radiation reaching the surface of an Earth-like planet with a 1 bar surface pressure through its geological evolution (following Kaltenegger et al. 2007) for different star types. The study also assessed the biological impact of that radiation for atmospheres corresponding to different times in the geological history of a planet, modeled on Earth. Generally, an Earth analog planet orbiting an inactive M star would receive a lower UV flux than Earth. It’s biologically effective UV radiation dose is between 0.001-0.03 times that on the present Earth (Rugheimer et al., 2015a, 2015b). However, around active M stars, such planets would be subject to periodic bursts of UV radiation, because of the proximity of the HZ to the star. That increases the surface UV flux on a HZ planet by up to two orders of magnitude for up to several hours for the most active M stars (Segura et al., 2010). M stars also remain active for longer periods of time than the Sun (see West et al., 2011). Figure 2 shows the change in magnitude of the UV flux from AD Leo, an active M star, before and during a flare, compared to the UV flux at present-day Sun.

The close proximity of planets in the HZ of cool stars can cause the planet’s magnetic field to be compressed by stellar magnetic pressure, reducing the planet’s ability to resist atmospheric erosion by the stellar wind. X-ray and EUV flare activity can occur up to 10-15 times per day, and typically 2-10 times, for M dwarfs (Cuntz & Guinan, 2016), which increases atmospheric erosion on close-in planets. This results in higher fluxes of UV radiation reaching the planet’s surface (Lammer et al. 2007; See et al., 2014) and, potentially, a less dense atmosphere. In addition, planets in the HZs of M stars are subject to stellar particle fluxes orders of magnitude stronger than those in the solar HZ (Cohen et al. 2014) that could erode their protective ozone shield as well as some of the atmosphere. Note that currently we can not model the expected surface pressure on an exoplanet. A decrease in surface pressure or atmosphere mass increases the UV flux reaching the surface, assuming the same atmospheric composition of a planet.

When UV radiation is absorbed by biological molecules, especially nucleic acids, harmful effects, such as mutation or inactivation can result, with shorter UV wavelengths having the most damaging effects (see e.g. Voet et al. 1963; Diffey 1991; Matsunaga et al. 1991; Tevini 1993; Cockell 1998; Kerwin & Remmele 2007). On the present-day Earth, the ozone layer prevents the most damaging UV wavelengths, UV-C radiation (100 - 290 nm), from reaching the surface. However, on other HZ planets, a protective ozone layer may not be present; the early Earth, for example, lacked a significant ozone layer (see e.g., Kaltenegger et al. 2007).

In the absence of an ozone layer, depending on the atmospheric composition of a planet, other atmospheric gases, such as sulphur compounds and CO$_2$ can absorb UV radiation (see e.g., Cockell et al., 2000; Rugheimer et al. 2015a). The thinner the atmosphere of a planet is, the more of the damaging radiation would reach the planet’s surface. Hence, mechanisms that protect biota from such radiation are a crucial part of maintaining habitability, especially on planets with thin atmospheres that, for example, are less massive and can therefore not maintain a dense protective atmosphere.

On Earth, biological mechanisms such as protective pigments and DNA repair pathways can prevent, or mitigate, radiation damage (see e.g. Cockell 1998; Heath 1999; Neale & Thomas 2016). Additionally, subsurface environments can reduce the intensity of radiation reaching an organism (see e.g. Heath 1999; Wynn-Williams et al., 2002; Ranjan & Sasselov 2016). Some teams have suggested that life that is constrained to habitats underwater, or beneath a planet’s surface, may not be detectable remotely (see e.g. Cockell 2014), making an inhabited planet appear uninhabited. However, photoprotective biofluorescence, in which protective proteins absorb harmful UV wavelengths and re-emit them at longer, safer wavelengths, is a mechanism that has not yet been considered. It could be a strong temporal biosignature on planets orbiting active M stars. On Earth, evidence suggests that some coral species use such a mechanism to reduce the risk of damage to symbiotic algae, which provide the coral with energy (see e.g. Salih et al. 2000; Roth et al. 2010): fluorescent proteins in corals absorb blue and UV photons and re-emit them at longer wavelengths.

Here we outline the possibility of detecting a fluorescent biosphere responding to stellar UV flare events, such as in the HZ of an M star. Section 2 describes biofluorescence and modeled UV surface levels on exoplanets, section 3 describes our models, section 4 shows our results, and section 5 discusses open issues.

2. BIOFLUORESCENCE IN CORALS

Scleractinian (hard) coral reefs are comprised of colonies of identical animals called polyps (small sac-like animals with a set of tentacles surrounding a central mouth) that secrete calcium carbonate to form a hard exoskeleton. Excessive light can be harmful to corals, either by damaging the algal photosystem, or by increasing oxidative stress, via photochemical reactions (Bhagooli & Hidaka 2004; Takahashi & Murata 2008; Roth et al. 2010). Some species contain fluorescent proteins with excitation spectra in the UV-A (315-400 nm) and blue regions of the spectrum, which have emission
Coral fluorescent proteins absorb near-UV and blue light and re-emit it at longer wavelengths (see e.g. Mazel & Fuchs 2003). Image made available under Creative Commons CC0 1.0 Universal Public Domain Dedication.

The visible signature of a coral reef has two components: elastic scatter (reflected light) and inelastic scatter (fluorescent light). Fluorescence can be a significant factor in the appearance of coral reefs (Fuchs 2001). The magnitude of the increase in intensity at the emitting wavelengths of fluorescent proteins varies depending on the intensity of the radiation absorbed, the wavelengths a protein absorbs/emits and the spectral overlaps between proteins with different excitation spectra within a reef (Fuchs 2001). The four most commonly occurring fluorescent proteins in coral have emission peaks at 486 nm, 515 nm, 575 nm and 685 nm (the 685 nm pigment is associated with chlorophyll in symbiotic algae). The properties of these pigments are summarised in Table 1. All except the 515 nm protein are excited by UV-A radiation (Fuchs 2001).

Fluorescent efficiency is the ratio of the number of photons emitted to the number of photons absorbed. A material is considered to be quite fluorescent if it has an efficiency of approximately 10%. Coral fluorescence becomes more significant under artificial lighting conditions (see e.g. Mazel & Fuchs 2003; Hochberg et al. 2004), with increases in reflectance of up to an order of magnitude; the increase depending on the spectral distribution of the illuminating light source (Mazel & Fuchs 2003). For example, laser-induced fluorescence enables corals to be successfully identified and monitored from the ocean surface, rather than in-situ (Myers et al. 1999; Mumby et al. 2004). A more intense UV regime should result in a stronger fluorescence effect.

### Table 1. The four most common fluorescent proteins in coral species.
<table>
<thead>
<tr>
<th>Emission peak (nm)</th>
<th>Excitation range (nm)</th>
<th>Fluorescent efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>486</td>
<td>350-475</td>
<td>3-5</td>
</tr>
<tr>
<td>515</td>
<td>400-525</td>
<td>10-12</td>
</tr>
<tr>
<td>575</td>
<td>350-575</td>
<td>8-10</td>
</tr>
<tr>
<td>685</td>
<td>350-650</td>
<td>1-2</td>
</tr>
</tbody>
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Fluorescent efficiency is the ratio of the number of photons emitted to the number of photons absorbed. A material is considered to be quite fluorescent if it has an efficiency of approximately 10%.
(Segura et al. 2010), an order of magnitude higher than on present-day Earth. Note that the modeled UV surface values would increase when one accounts for the deformation of a planet’s compressed magnetic field due to stellar magnetic pressure (Lammer et al. 2007). Lower surface pressure would also increase the UV levels on a planet’s surface. For different atmospheric compositions - like a younger Earth (see Rugheimer et al. 2015a,b for details) - the UV surface flux also increases.

Increased UV flux on a planet’s surface could occur due to associated proton events with the flare, in which charged particles from the star are accelerated in the direction of a flare. If the planet is in the line of sight of the charged particle stream, ionized particles can interact with the planet’s atmosphere, forming odd hydrogen species and breaking up N₂ to form NOₓ species, both of which can destroy ozone (see e.g. Segura et al. 2010; Grenfell et al. 2012). Accounting for a proton event associated with an M star flare, Segura et al. (2010) calculated that approximately 70 days after the flare, ozone depletion could cause surface UV fluxes to increase for up to 2 years. Frequent flares and proton events could thus permanently weaken, or erode, a planet’s ozone layer and overall atmosphere, allowing more UV radiation to reach the planet’s surface if the star’s activity cycle is shorter than the recovery time of the atmosphere.

3. MODELS

3.1. Planetary Models

Our model initially explores the surface signal strength if the surface is a global ocean inhabited by biofluorescent life, or a hypothetical fully vegetation covered planet. This constitutes the ideal case with the strongest signal. Next we add a clear atmosphere to the planet (assuming an M3V host star) using EXO-Prime (see e.g. Kaltenegger & Sasselov 2009); a coupled 1D radiative-convective atmosphere code developed for rocky exoplanets. The code is based on iterations of a 1D climate model (Kasting & Ackerman 1986; Pavlov et al. 2000; Haqq-Misra et al. 2008), a 1D photochemistry model (Pavlov & Kasting 2002; Segura et al. 2005, 2007), and a 1D radiative transfer model (Traub & Stier 1976; Kaltenegger & Traub 2009) that calculates the model spectrum of a rocky exoplanet in the HZ. EXO-Prime models exoplanet’s atmospheres and environment depending on the stellar and planetary conditions, including the UV radiation that reaches the surface and the planet’s reflection, emission and transmission spectrum.

We then reduce the fraction of biofluorescent life on the surface to test how long it can be detectable by adding ocean (from the USGS Spectral Library) as an additional surface to explore the effect of different fractions of inhabited versus uninhabited surface on the spectrum. We compare the biofluorescent signal to that of vegetation (from the USGS Spectral Library) for detectability.

Then we add clouds (from the USGS Spectral Library, following Kaltenegger et al. 2007) to the model. We assume clouds block our view of any surface feature. We model different cloud coverages up to 50% (an Earth-like cloud fraction). Any surface feature signature is reduced with increasing cloud cover because clouds are highly reflected and therefore strongly influence a planet’s spectrum (see e.g. Kaltenegger et al. 2007).

3.2. Biofluorescence Models

We use the efficiency limits of terrestrial fluorescent proteins as a guide to the exploration of the magnitude of our modeled biofluorescence. The first fluorescent proteins studied were green fluorescent proteins (GFPs), extracted from jellyfish (Shimomura et al. 1962; Johnson et al., 1962; Morin & Hastings 1971; Morise et al. 1974; Tsien 1998). Over time these have been adapted and engineered for use in a variety of applications, from fluorescent microscopy to transgenic pets (see e.g. Stewart (2006) and references therein). GFPs have been engineered in the lab to have a much higher fluorescence
efficiency by taking advantage of useful mutations. This has resulted in proteins with high efficiencies of up to 100% (Ilagan et al. 2010; Goedhart et al. 2012). Therefore, although this is not observed in nature on Earth, it is feasible that, given the right evolutionary conditions, highly efficient fluorescent proteins could evolve with up to 100% efficiency (C. Mazel, private communication). Furthermore, in a study on coral fluorescent proteins, Roth et al. (2010) found that rapid changes in protein concentrations occurred in response to changes in light intensity, and that pigment concentration strongly correlates with fluorescence intensity. Hence, we postulate the possible evolution of dense fluorescent pigment concentrations in a high-UV environment to explore the idea of a biofluorescent biosignature. We assume biofluorescence here that increases reflectance by 100%.

We simulated coral fluorescence by using models of the fluorescence response of the four common fluorescent proteins in corals (shown in Tab. 1), which have fluorescence peaks at 486 nm, 515 nm, 575 nm and 685 nm. The change in the reflectance spectrum caused by simulated fluorescence is illustrated in Fig. 4 (left column).

3.3. Color-color diagrams as a diagnostic tool

We explore how to use a standard astronomy tool to characterize stellar objects, a color-color diagram, to distinguish planets with and without biofluorescent biosignatures (following Hegde & Kaltenegger 2013). To determine the difference between the reflectance, r, of two different color bands, we use equation (1):

$$C_{AB} = A - B = -2.5 \log_{10} \left( \frac{r_A}{r_B} \right)$$

where $C_{AB}$ is the difference between two arbitrary colour bands, A and B.

We use standard Johnson-Cousins BVI broadband filters to define the color bands (0.4 μm < B < 0.5 μm; 0.5 μm < V < 0.7 μm; 0.7 μm < I < 0.9 μm). We used color-color plots (Figs. 6 to 10) to explore color change on model planets caused by flare-induced fluorescence compared to vegetation for clear atmospheres, cloudy conditions and different ocean fractions.

3.4. Investigating false positives

It is also possible for fluorescence to occur abiotically. Some minerals (e.g. calcite, fluorite, opal, zircon) and polycyclic aromatic hydrocarbons (PAHs; e.g. fluoroanthene, perylene, pyrene) are fluorescent at similar wavelengths to those of fluorescent corals; a result of metal cation impurities in the case of minerals, and delocalized electrons in aromatic molecule groups for the case of PAHs (see e.g. McDougall 1952; Modreski 1987; Beltrán et al. 1998). Therefore, we explore how to distinguish biofluorescence from fluorescent minerals.

Hydrocarbons and the metal inclusions within fluorescent minerals would not be subject to Darwinian evolution, so we assume here that their fluorescent levels would be comparable to those on Earth’s or slightly increased, or decreased, scaled to the UV surface flux at the exoplanet’s surface compared to Earth’s.

4. RESULTS

Figure 4 compares biofluorescent models with fluorescent mineral surfaces. The left column of Fig. 4 shows reflectance spectra for simulated coral fluorescence for four wavelengths compared to minerals that fluoresce at similar wavelengths in the right-hand column for a clear atmosphere. The spectra show that both have different responses to UV flux. The signal of fluorescent minerals has a different shape than the biofluorescent signal and, under the assumption that biofluorescence evolves, the mineral signature is also much weaker. The four mineral species were chosen for their abilities to fluoresce at similar wavelengths to corals and represent the strongest fluorescent minerals (see e.g. Modreski 1987; fluorescence information from: Luminescent Mineral Database).

Figure 5 compares biofluorescent signal strength (left column) to a commonly used biological surface feature, vegetation (right column). We use a fluorescent coral spectrum (coral B) and the 515 nm modeled biofluorescence as an example to compare them. All panels include a clear present-day atmosphere. In the top panel of Fig.5 we model a planet that is completely covered by the respective surface: biofluorescence (left) and vegetation (right). The middle panel of Fig.5 shows how an increasing ocean fraction of 30% and 70% decreases the detectable surface feature from either surface. The panels on the bottom of Fig.5 show how cloud cover, assuming fractions of 10% and 50%, decreases the detectable biological surface features even more strongly than reducing the surface cover of the biosignature, even for a planet that is completely covered by the biological surface. We call these two effects out separately, but they of course combine, depending on surface fraction coverage as well as cloud coverage (see discussion). Note that the aim of Fig.5 is not to give a specific value but to compare the strength and detectability of a biofluorescent biosphere to the commonly used vegetation red edge feature that is proposed as one of the biological surface features for upcoming visible direct imaging missions (see e.g. Seager et al. 2005; Tinetti et al. 2006; Schneider et al. 2010; Hu et al. 2012). Fig. 5 shows that the proposed biofluorescence signature can be stronger

1 http://flomin.org
Figure 4. Reflectance spectra in the visible for coral (left column) and fluorescent minerals (right column). Fluorescence at each of the common coral fluorescent protein emission wavelengths was simulated for increases in reflectance from 10% to 100%. The four mineral species shown were chosen for their abilities to fluoresce at similar wavelengths to corals and represent the strongest fluorescent minerals. (Non-fluorescent coral spectra from Roelfsema & Phinn 2006. Mineral spectra sources: Sources: USGS Digital Spectral Library (Clark 2007), ASTER spectral library, California Institute of Technology. Fluorescence was simulated using data from C. Mazel.)
than the surface biosignature of vegetation covering the same surface area.

A standard astronomy tool that characterizes stellar objects, a color-color diagram, can be used to distinguish planets with and without biofluorescent biosignatures (following Hegde & Kaltenegger 2013). We used these planet model spectra with and without clouds, and with varying surface fractions of biological versus ocean surface, to create standard Johnson colors from their fluorescent and non-fluorescent spectra for biofluorescence and minerals. We add vegetation for comparison as well.

The minerals and coral fluorescence occupy separate regions of the color-color diagram (Fig. 6), in both the non-fluorescing and fluorescing cases. The curved shape of the zircon reflectance spectrum in the visible region causes it to occupy a slightly separate region in the color space than the other minerals, which tend to have very flat reflectance profiles in the visible spectrum. Fluorescence at 515 nm, 575 nm and 685 nm, moves the color of the biofluorescent planet further away from fluorescent minerals and vegetation. However fluorescence at 486 nm moves the biofluorescent color closer to the color of minerals and vegetation. Coral D is closest in the color space to vegetation. Mineral fluorescence causes a much smaller change in color position, that is too small to show on the scale in Fig. 6.

Figure 7 shows the color-color diagram for a planet with different fractions of uninhabited ocean versus biofluorescent surface (see Fig. 5 for the corresponding spectra) for two examples, 30% and 70%, the latter corresponding to the Earth’s ocean fraction, for each of the four modeled biofluorescent pigments. The decrease in overall biological surface area reduces the influence of the biological surface on the overall planetary spectrum and color and therefore also the shift in colors due to fluorescence. Still, biofluorescent signatures are well distinguishable from minerals or vegetation in the color-color diagram in both cases.

Figure 8 shows the effect of cloud coverage on the colors of a planet (see Fig. 5 for the corresponding spectra) comparing a clear atmosphere to 10% and 50% cloud coverage, the latter corresponding to Earth’s cloud coverage. Increasing cloud cover moves the colors of all planetary models closer together - whether the planet is completely covered by minerals, vegetation or biofluorescent corals. Note that a planet model with 100% cloud coverage would not show any surface feature and appear the same in spectra and color, no matter what the underlying surface were covered in. The increase in cloud coverage also reduces the magnitude of the observable shift in position during biofluorescence, because only part of the surface is visible; the rest is blocked from our view by clouds (see discussion).

Figures 9 and 10 compare the colors of biofluorescence for the clear-sky case and partial cloud cover case, respectively, with the colors of solar systems bodies (using spectra from Irvine et al. (1968) and Karkoschka (1994)). Fluorescent coral colors are distinct from other solar system bodies (with the exception of 515 nm fluorescence of coral B, which moves close to the color position of Mars), as well as abiotic mineral fluorescence (as shown before). Figures 6 to 10 show that all four of the considered pigments produce notable changes in position on the color-color diagram.

5. DISCUSSION

To produce a strong fluorescence effect during an M star flare, the best fluorescent proteins will be those that absorb most strongly in the UV part of the spectrum. Alternatively to higher UV flux, an increased quantum efficiency of fluorescent proteins could also enable detectable biofluorescence, even for a lower UV surface flux. A fluorescence quantum yield of 1 is possible, based on lab-based improvements on the yield of the green fluorescent protein, discussed earlier, which would increase the detectability of a biofluorescent signal. Additionally, a denser concentration of fluorescent proteins may be selected for under high UV conditions, enhancing the strength of the fluorescent signal.

During a flare, models show that a planet in the HZ of AD Leo would receive a UV-B surface flux 80% higher than Earth’s (Segura et al. 2010), while the UV-C surface flux would be several orders of magnitude higher than Earth’s, if an ionized particle stream aligns with the flare and depletes the planet’s ozone layer (Segura et al. 2010). Hence, fluorescent proteins that downshift the full UV flux (UV-A to -C) to benign visible wavelengths (perhaps via a cascading chain of fluorescent proteins with different excitation wavelengths; see, for example, Gilmore et al. 2003) may be selected for under high UV conditions, further strengthening a biofluorescent signal.

Most corals gain energy, carbohydrates and oxygen via symbiotic relationships with algae, which in return feed on CO2 and waste products from the coral. To maintain this symbiosis, coral habitats are limited to the euphotic zone of the oceans (to a maximum depth of up to 165 m on Earth; Kahng & Maragos 2006) to allow access to photosynthetically active radiation (PAR). Water attenuation would reduce coral fluorescent flux. Here we make the simplifying assumption of shallow, transparent oceans. This is consistent with shallow-water coral reef habitats on Earth, which are typically warm, clear seawater environments, at depths as shallow as 0-3 m (Kleypas et al. 1999; Nagelkerken et al. 2000). Furthermore, the lower flux of Earth-like PAR on an M star planet would make shallow water habitats more preferable for any aquatic photosynthesisers.

We do not argue for the evolution of an exact replica.
of coral reefs on other worlds. In this hypothesis we use corals as an example of an organism that exhibits fluorescence and contains convergent evolutionary features (i.e. features that have evolved independently in different species that are not closely related). We argue for the evolution of an organism that shares some of these convergent traits with corals; specifically the ability to form simple, collaborative colonies and the ability to fluoresce.

Corals were one of the the earliest forms of animal life to evolve on Earth, with an evolutionary history spanning 500 Myr. Initially existing as simple, solitary organisms, they later evolved into collective reefs. Reef-building is an ancient trait for life on Earth. Many marine species have independently evolved reef-building abilities, but the trait can be traced back to colo-

nial groups of bacteria building stromatolites 3.5 Gya (Kiessling 2009).

The fluorescent proteins in corals are descended from green fluorescent proteins (Field et al. 2006). Green fluorescent proteins are present in a variety of phyla, suggesting an origin within an ancient common ancestor in the very early metazoan (animal) life, over 500 Myr ago (Chudakov et al. 2010).

Biofluorescence is widespread in life on Earth and is thought to have evolved independently, multiple times (Sparks et al., 2014; Gruber et al. 2015; Gruber & Sparks, 2015), which strengthens a case for the evolution of biofluorescence on other inhabited worlds, following convergent evolution arguments.

M star HZs are subject to stellar particle fluxes orders of magnitude stronger than those in the solar HZ.
Figure 6. Color-color diagrams for four fluorescent corals and four fluorescent minerals, before (grey - labelled A, B, C, D) and during (black - labelled A’, B’, C’, D’) fluorescence at each of the four common emission wavelengths. We assume 100% increase in reflectance over the wavelength range of the emission spectra for each coral fluorescent pigment during fluorescence. Note that the change in position before and during mineral fluorescence is too small to plot on this scale.

(Cohen et al., 2014), which could trigger aurorae up to $10^3$ times more intense than on Earth. For planets with weaker magnetic fields than Earth, the auroral oval (the amount of planetary area with open magnetic field lines) could cover all latitudes on the planet (Vidotto et al., 2013), changing the colors of planets during a flare, potentially adding other absorption and emission features in the atmosphere that were not taken into account in our models. However, aurorae fluoresce at known wavelengths depending on the composition of the atmosphere and therefore would be distinguishable from biofluorescence.

A planet will most likely have both clouds as well as different surfaces, depending on how dense their atmosphere is. With decreasing surface pressure, cloud coverage should also decrease, therefore we showed the effects separately in Fig.5 to Fig.8, which allows insight into the individual effects on detectability and characterization of a planet in a spectrum, or in a color-color diagram.

For planets with non-complete cloud coverage, the effect of clouds can be distinguished from surface features with many short, high signal-to-noise observations, because clouds should occupy all areas of the planet given enough time. Thus one can separate them from surface features that are bound to the rotation of a planet, if the observations can be limited to about 1/20 of the planet’s rotation period, or for the Earth, about an hour (see Pallé et al. 2008), requiring big future telescopes.

Even though removing the effect of clouds on planetary spectra is not feasible for near-term observation with telescopes like the E-ELT, it should be possible with even more ambitious space and ground-based telescopes that are being designed.

6. CONCLUSIONS

In this work, we explored the hypothesis and detectability of exoplanets dominated by a biofluorescent biosphere, which uses fluorescence as a UV damage mitigation strategy. Especially planets in the Habitable Zone (HZ) of M-stars would experience temporal high ultraviolet (UV) radiation. During an M-star flare, the UV radiation flux on a HZ planet can increase by up to two orders of magnitude. Photoprotective biofluorescence (the “up-shifting” of UV light to longer, safer wavelengths, via absorption by fluorescent proteins), a proposed UV protection mechanism of some coral species, would increase the detectability of biota, both in a spectrum, as well as in a color-color diagram. Such biofluorescence could be observable as a “temporal biosignature” for planets around stars with changing UV environments, like active flaring M stars, in both their spectra as well as their color.

Using a standard astronomy tool to characterize stellar objects, a color-color diagram, one can distinguish planets with and without biofluorescent biosignatures. The change in color caused by biofluorescence differs, in position and magnitude, from that caused by abiotic
fluorescence, distinguishing both.

The TESS mission will be sensitive enough to identify rocky planets in the HZ of nearby M stars, providing targets for testing this hypothesis with follow up observations. A planet in the HZ of Proxima Centauri will be the best target to look for biofluorescence. Watching a star during a flare event could uncover a biofluorescent biosphere on a planet orbiting it. This suggests that exoplanets in the HZ of active M stars are also interesting targets in the search for signs of life beyond Earth. Hence, high UV fluxes could actually make certain hidden biospheres detectable.

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Figure 8. Color-color diagrams for planets with surfaces completely covered by biofluorescent corals, vegetation or minerals, for a clear atmosphere and for 10% and 50% cloud coverage. Non-fluorescing corals are marked with grey points, labelled A to D. Fluorescing corals are marked with black points labelled A’ to D’.

tral Library for reflectance spectral data for minerals, vegetation and ocean water. We would also like to acknowledge funding from the Simons Foundation (290357, Kaltenegger).

REFERENCES

Figure 9. Color-color diagrams of planet models with clear atmospheres, and a surface that is completely covered by biofluorescent corals, fluorescent minerals, or vegetation compared to the colors of planets in our own Solar System, before (grey - labelled A, B, C, D) and during (black - labelled A’, B’, C’, D’) fluorescence at each of the four common emission wavelengths.

Figure 10. Color-color diagrams of planet models with an atmosphere and 50% cloud cover, and a surface that is completely covered by biofluorescent corals, fluorescent minerals, or vegetation compared to the colors of planets in our own Solar System, before (grey - labelled A, B, C, D) and during fluorescence at each of the four common emission wavelengths.