Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.

doi:10.1017/S1743921319002035

The biological impact of superflares on planets in the Habitable Zone

Adriana Valio, Raissa Estrela, Luisa Cabral and Abel Grangeiro

Mackenzie Presbyterian Universtiy, CRAAM, São Paulo, Brazil
email: avalio@craam.mackenzie.br

Abstract. Younger and fully convective stars are much more active than our Sun, producing many superflares. Here we estimate the impact of the superflares UV radiation on living organisms on the surface of orbiting planets in the habitable zone of the star. For this we study two active stars, Kepler-96 (solar type) and TRAPPIST-1 (M dwarf). Kepler-96, with an age of 2.4 Gyr, is at the same stage of the Sun when the first multicellular organisms appeared on Earth. The biological impact of super flares are studied on a hypothetical Earth at 1AU of Kepler-96 and on planets TRAPPIST-1e, f, and g for three atmospheres scenarios: an Archean and Present-day atmospheres with and without ozone. We estimated the survival rates of two bacteria and concluded that life would only survive on the surface of these planets if their atmosphere had an ozone layer, or in shallow waters of an ocean.

Keywords. Astrobiology, Stars: flare, Planetary systems

---

1. Introduction

Living around an active star can be vary dangerous. Even though the Sun is considered mildly active among other stars, our technological society is frequently affected by its activity. An important manifestation of solar activity are solar flares. Among the disruptions caused by a flare is an increase in hazardous radiation such as ultraviolet (UV) and X-rays, beside energetic particles. This high energy radiation can be lethal to astronauts outside the protection of rockets or the Space Station. Fortunately, common humans on the ground are protected from this ionizing radiation by Earth's atmosphere. But it may not have been so in the past.

Young stars are known to produce much stronger flares, due to an increased dynamo action. Also fully convective stars, such as early M-type stars are very active generating flares sometimes 10,000 times stronger than those of the present Sun. Superflares release significant amount of XUV, EUV, FUV and UV radiation. Depending on the size of the flare, they can cause potential effects on the planetary atmosphere such as atmospheric loss and/or affect the chemical composition of the upper atmosphere. Moreover, protons accelerated in the flare produce odd nitrogen and odd hydrogen in the upper stratosphere and mesosphere that destroy ozone (Segura *et al.* 2010). Last but not least, the energetic radiation from superflares could affect the origin and evolution of life on a planet orbiting in the Habitable Zone of the star.

The goal of this work is to determine if superflares can be dangerous to life present in the surface or an ocean of a hypothetical planet in the habitable zone (HZ) of Kepler-96 and the three planets in the HZ of the TRAPPIST-1 system, planets e, f and g. The next section describes the two stars studied and their orbiting planets, the following Section 3 characterizes the observed flares and estimates the UV flux generated. Three types of planetary atmospheres are assumed for each planet (Section 4) to determine the amount of damaging UV flux that reaches the surface, and thus the biological impact on two

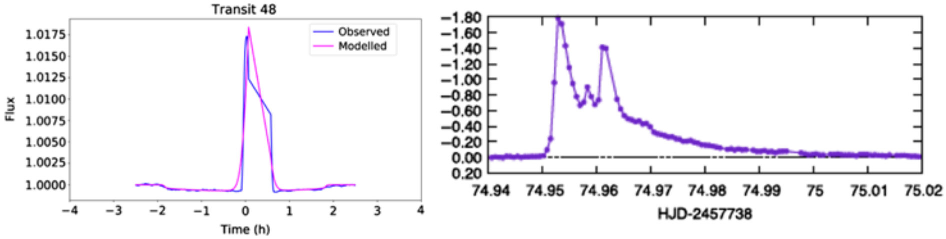

Figure 1. Left: Largest superflare observed in the light curve of Kepler-96 (Estrela & Valio 2018). Right: Largest superflare of TRAPPIST-1 (Segura *et al.* 2010).

bacteria (*D. Radiodurans* and *E. Coli*). A brief discussion of the results and the main conclusions are presented in the last section.

2. Stars and their planets

Kepler-96 is a solar type star, mass of $(1.0 \pm 0.06) M_{\odot}$ and radius of $(1.02 \pm 0.09) R_{\odot}$, with approximately half the age of the Sun, at 2.34 Gyr. It is orbited by a hot Super-Earth (Kepler-96b) of $8.6 M_{Earth}$ and $2.67 R_{Earth}$ with a period of 16.2385 days. Being a young star, Kepler-96 produced several flares that were observed during the transits of Kepler-96b.

Kepler-96 has an age that corresponds to the end of the Archean Era on Earth, when life here underwent a major change with the emergence of the first multi-cellular organisms. This caused a boom of oxygen on our atmosphere, known as the Great Oxygenation Event, thus creating the ozone layer. Due to its close orbit, the surface temperature of Kepler-96b is estimated to be between 2000 to 3000K, thus it is interesting to evaluate the effect of the UV flux produced by the giant flares of Kepler-96 and the impact this would have on life on the surface of a hypothetical planet located at 1 AU of Kepler-96, within this solar-type star habitable zone.

The other interesting system worth studying under the same aspect is the TRAPPIST-1 planetary system with 7 terrestrial planets. TRAPPIST-1 is an M8 star ($(0.08 \pm 0.009) M_{\odot}$ and $(0.117 \pm 0.004) R_{\odot}$) of 0.5 Gyr age. Of the seven terrestrial planets in orbit, three of them are within the habitable zone of the star: planets e (0.0282 AU), f (0.0371 AU), and g (0.0451 AU).

3. Stellar flares and superflares

Many flares were observed in the Kepler-96 lightcurve, especially during the transits of the Super-Earth. The most intense flare is shown in Figure 1 (left panel). Estrela & Valio (2018) analyzed three of these events and estimated the total energy from each flare by modelling the time profile as a Gaussian. This strongest flare released a total of 1.8×10^{35} ergs. This energy range corresponds to superflares (Maehara *et al.* 2015)

To estimate the amount of UV flux produced by the flare of Kepler-96, a solar-type star, we took the strongest solar flare recorded in modern times, a GOES class X17 flare that occurred on the 28th October 2003. The total energy from this flare was $E = 4 \times 10^{32}$ ergs (Woods *et al.* 2004). During this flare, the solar MUV (200 – 300 nm) flux increased by 12%. Since the total thermal blackbody flux of Kepler-96 and that of the Sun are very similar, we considered that the superflare of Kepler-96 would increase the UV flux by the same amount. Thus applying this same percentage to the superflare of Kepler-96, yields an increase of 5400% in the MUV flux. The final flux was decreased by 75% of the present valued, due to the smaller flux of the young Sun with an age of 2.4 Gyr.

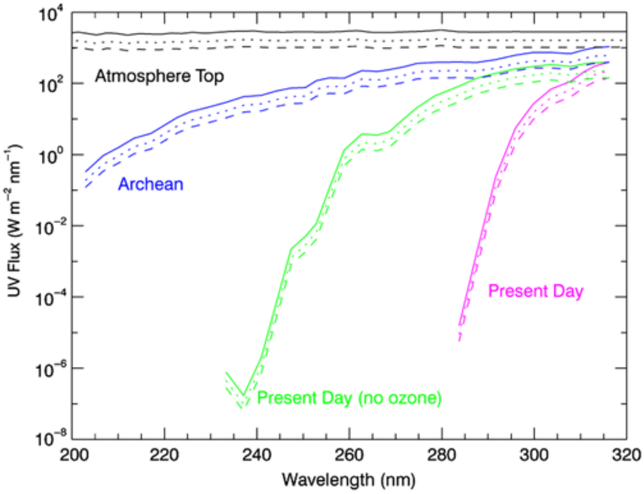

Figure 2. Ultraviolet flux at the top of the atmosphere of planets TRAPPIST-1e (solid), TRAPPIST-1f (dotted), TRAPPIST-1g (dashed) shown in black. The UV flux at the surface transmitted by three atmosphere models: Archean (blue), Present day without Ozone (green), and Present day atmosphere with Ozone (magenta).

The TRAPPIST-1 star is known to be very active, with 47 flares detected with energies between 10^{30} and 10^{33} ergs (Vida *et al.* 2017). The largest flare, depicted in the right panel of Figure 1, released a total energy of 1.24×10^{33} erg over 43 min.

The UV flux contribution from TRAPPIST-1 was taken as the same UV flux fraction measured from a flare of Ad Leo, also an M red dwarf (Segura *et al.* 2010). Hawley & Pettersen (1991) observed a strong flare from the red dwarf Ad Leonis in the visible and ultraviolet. From their Table 6, we calculated the percentage of UV flux with respect to the visible from this flare as 59%. Taking into account the distance of the planets from the star, the total UV flux reaching the top of the atmosphere of the planets are: $3.275 \times 10^{12} erg/m^2$, $1.888 \times 10^{12} erg/m^2$, and $1.278 \times 10^{12} erg/m^2$ for planets e, f, and g, respectively. These fluxes as a function of wavelength are depicted in Figure 2 as black lines for the three planets following O'Malley & Kaltenegger (2017).

4. Planetary atmospheres

Three types of atmosphere were considered: an archean atmosphere and a present day one with and without Ozone. The present day atmosphere is composed of 80% of N_2 and 20% O_2, whereas the Archean atmosphere (3.9 Gyr – 2.5 Gyr) consists of 80% of N_2 and 20% CO_2 (Cnossen *et al.* 2007). Moreover, for Kepler-96, the flux was assumed to be 75% of the present-day solar irradiation.

To analyze the biological impact, we used the UV flux $(180 - 300\text{nm})$ passing through the different atmospheres. Estimates of the UV flux reaching the planetary surface were made using the curves shown in Figure 6 of Cnossen *et al.* (2007) for these three model atmospheres. This figure was adapted to determine the transmitted flux for each model atmosphere. In the case of TRAPPIST-1, a red dwarf star, we did not use the irradiation from the Sun (top curve of the Cnossen *et al.* figure), but rather the spectra proposed by O'Malley & Kaltenegger (2017) (black curves in Figure 2). The net UV flux that reaches the surface of the three TRAPPIST-1 planets in the HZ are shown for the different atmosphere types in Figure 2.

Table 1. Biological effective irradiance, E_{eff} (J/m^2), due to the strongest superflare

Planet	Bacteria	Archean	Present day - no ozone	Present day
Kepler-96 (1 AU)	*E. coli*	1.4×10^4	2.4×10^3	21.5
	D. radiodurans	8.0×10^3	1.3×10^3	7.5
TRAPPIST-1e	*E. coli*	9.0×10^3	962	8.2
	D. radiodurans	5.1×10^3	580	2.5
TRAPPIST-1f	*E. coli*	5.2×10^3	555	4.7
	D. radiodurans	2.9×10^3	334.4	1.5
TRAPPIST-1g	*E. coli*	3.3×10^3	353	3.0
	D. radiodurans	1.9×10^3	212	0.9

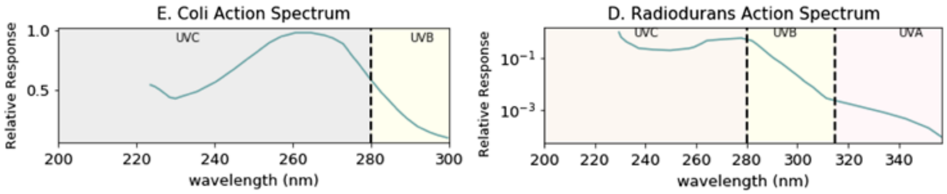

Figure 3. Action spectra, or biological response, for *E. coli* (left) and *D. radiodurans* (right).

5. Biological impact

Superflares will increase the UV flux of the star by a significant fraction. If a planet has an atmosphere with absorbers such as N_2, CO_2, or O_2, the short wavelengths radiation (0.1 – 200 nm) will be attenuated through the atmosphere. UVB and UVC, the most hazardous radiation, will be partially or totally absorbed by an Ozone layer. The DNA molecule of living beings is mainly damaged in the UVC and UVB range (MUV $\sim$ $200 - 300$ nm).

For this study, we chose two bacteria, a very resistant one, *Deinococcus radiodurans*, and a more common one, *Escherichia coli*. Since the response of a biological body varies as function of the wavelength, the biological response effectiveness at different wavelengths has to be estimated. For that, the incident UV flux, $F_{UV}(\lambda)$, is weighted by the action spectrum, $S(\lambda)$, which gives the biological response of different organisms.

$$E_{eff} = \int_{180}^{300} F_{UV}(\lambda)\ S(\lambda)\ d\lambda \tag{1}$$

The action spectra of the two bacteria are shown in Figure 3. The UV dosage for 10% survival of the two bacteria are 22.6 (Gascon *et al.* 1995) and 553 J/m^2 (Ghosal *et al.* 2005) for *E. coli* and *D. radiodurans*, respectively.

To determine the survival of the two bacteria on the surface of planets in the habitable zone of their stars, we have calculated the integral in Eq. 1 for the hypothetical planet in orbit at 1 AU of Kepler-96 and the three TRAPPIST-1 planets in the HZ, e, f, and g, considering the strongest observed flare of both stars (see Figure 1). The results are listed in Table 1.

6. Discussion and conclusions

We analyzed the strongest flare detected in planetary transits of Kepler-96b (Estrela & Valio 2018), with total energy of 1.8×10^{35} ergs, and of TRAPPIST-1 (Vida *et al.* 2017), with 1.24×10^{33} ergs. Both these flares had energies in the range of superflares. We used the strongest recorded solar flare (Woods *et al.* 2004) to model the UV radiation of Kepler-96 flare, whereas the UV contribution of the TRAPPIST-1 flare was taken from a well observed flare of Ad Leo (Hawley & Pettersen 1991), a star of same spectral type.

Next, to determine the amount of UV flux that reaches the surface of the planets, three atmospheric models were considered: an Archean atmosphere and present-day atmospheres with and without Ozone (Cnossen *et al.* 2007). Two bacteria, *E. coli* and the hard X-ray resistant *D. radiodurans*, were chosen to determine their survival rate under the heavy UV bombardment due to the flares. For this study, we calculated the effectiveness response of each bacteria due to the UV flaring flux (see Table 1).

The results of the biological impact suggests that the UV flux from the strongest superflare received by a biological body would only allow the presence of life on the surface of a hypothetical planet at 1 AU of Kepler-96 if there was an atmosphere with Ozone. The same is true for TRAPPIST-1e, the planet in the HZ closer to the star. However, for the two other planets, f and g, *D. radiodurans* could survive even if there was no ozone in the atmosphere. Neither bacteria could survive in any planet with an Archean atmosphere.

Estrela & Valio (2018) showed that an ocean in the hypothetical Kepler-96 planet in the HZ could protect organisms from the increased UV radiation, allowing life in depths within the photic zone (up to 200m). Maybe this scenario is also applicable to the TRAPPIST-1 planets, that is, an ocean is a necessary condition to protect primitive organisms from the increased UV flux due to superflares, until an ozone layer is formed. In a future work, we will consider the cumulative effects of all superflares from the star.

References

Cnossen, I., Sanz-Forcada, J., Favata, F., Witasse, O., Zegers, T., & Arnold, N. F. 2007, *JGR*, 112, E02008

Estrela, R. & Valio, A. 2018, *Astrobiology*, 18, 1414-1424

Gascon, J., Oubina, A., Perez-Lezaun, A., & Urmeneta, J. 1995, *Curr. Microbiol.*, 30, 177182

Ghosal, D., Omelchenko, M. V., Gaidamakova, E. K., Matrosova, V. Y., Vasilenko, A., Venkateswaran, A., Zhai, M., Kostandarithes, H. M., Brim, H., Makarova, K. S., Wackett, L. P., Fredrickson, J. K., & Daly, M. J. 2005, *FEMS Microbiol. Rev.*, 29, 361375

Hawley, S. L., & Pettersen, B. R. 1991, *ApJ*, 378, 725

Maehara, H., Shibayama, T., Notsu, Y., Notsu, S., Honda, S., Nogami, D., & Shibata, K. 2015, *Earth Planets Space*, 67, 59

OMalley-James, J. T. & Kaltenegger, L. 2017, *MNRAS*, 469, L26L30

Segura, A., Walkowicz, L. M., Meadows, V., Kasting, J., & Hawley, S. 2010, *Astrobiology*, 10, 751771

Vida, K, Kovari, Zs., Pal, A., K. Olah, K, & Kriskovics, L. 2017, *ApJ*, 841, 124-129

Woods, T. N., Eparvier, F. G., Fontenla, J., Harder, J., Kopp, G., McClintock, W. E., Rottman, G., Smiley, B., & Snow, M. 2004, *Geophys. Res. Lett*, 31, L10802

Discussion

GUENTHER: You study the impact of super-flares on the organism, but there are many small flares for each large one. What effect would these small but frequent flares have?

VALIO: Definitely the cumulative effects of smaller super-flares are important. Moreover, the recurrence of super-flares during the recovering phase of mico-organisms can also be damaging. We plan to investigate these issues in the near future.