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The Biological Impact of Kepler-96 Superflares in a planet in the habitable zone

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Abstract. We present the analysis of superflares seen on the lightcurve of the active star Kepler-96. Its age of 2.4 Gyr is the same as the Sun when there was a sudden increase in the oxygen level on Earth atmosphere. Our analysis is based on the four years of continuous short cadence observation of the star by the Kepler telescope. The model used here simulates a planetary transit and allows the insertion of a flare in the stellar disk with different size, amplitude, and position. By fitting the observational data with this model, it is possible to infer the physical properties of the superflares, such as its duration (few minutes) and energy released. In addition, we analyze the biological impact of these superflares in an hypothetical Earth in the habitable zone of the star assuming it has protection via various atmospheres scenarios (an Archean and Present-day atmospheres) and an ocean. We estimated the UV flux increase produced by the strongest superflare and concluded that life would only survive on the surface if there was already an ozone layer present on the planet atmosphere or at ocean depths higher than 10m.

Resumo. Nós apresentamos o estudo de superexplosões magnéticas observadas na curva de luz da estrela Kepler-96. Esta estrela tem uma idade de 2,4 Ga, a mesma idade que o Sol tinha quando a Terra teve um aumento repentino no nível de oxigênio em sua atmosfera. Nossa análise é baseada em quatro anos de observação contínua desta estrela pelo telescópio Kepler. O modelo utilizado neste trabalho simula trânsitos planetários e permite a inserção de explosões com diferentes tamanhos, amplitudes e posições no disco da estrela. Ao realizar o ajuste entre o dado observacional e o modelo, é possível inferir propriedades físicas das superexplosões, como a duração (alguns minutos) e a energia liberada. Além disso, nós também analisamos o impacto biológico destas superexplosões em uma planeta hipotético tipo Terra localizado na zona habitável da estrela, supondo que a vida no planeta tem proteção através de uma atmosfera (Archeana ou atual com ozônio) ou de um oceano. Nós estimamos o aumento do fluxo de UV devido à superexplosão mais forte e concluímos que a vida só seria possível na superfície se tivesse ozônio presente na atmosfera do planeta ou em profundidades maiores que 10m no oceano.

Keywords. Astrobiology, Planets and satellites: atmospheres, Stars: solar-type, Sun: flares, Sun: UV radiation

1. Introduction

Kepler-96 is a solar analogue star harbouring a Super-Earth planet in close orbit. Its age of 2.3 Gyr is the same as the Sun when there was a considerable increase of oxygen in Earth's atmosphere in the end of the Archean era due to micro-organisms living under the sea. This star is still very active and has several superflares on its lightcurve. Some authors (Airapetian et al. (2016), Lingam & Loeb (2017)) discussed about the possibility of such superflares occurring in the young Sun and their impact on the primitive Earth. Thus, Kepler-96 is an interesting target to study because (i) the Archean Earth conditions if the Sun had such superflares at that time and (ii) a planet in the habitable zone with Archean conditions, considering that this planet had already enough time for life to evolve.

Here, we analyze the superflares of Kepler-96 using the transit model developed by Silva (2003). Properties of the superflares, such as duration, size, amplitude, and position will be intrinsically studied with this model. From these parameters it is possible to estimate the power released by the superflare. The increase in the UV flux due to superflares is also inferred. Then, we study how different atmospheres from the primitive and present-day Earth and an ocean could attenuate the increased UV flux arriving at a planet in the habitable zone (HZ, at 1AU) of Kepler-96. Finally, we estimate the biological impact of the superflares on two very resistant microorganisms, *Deinococcus radiodurans* and *Escherichia coli*, living in the surface or in the ocean of this planet.

2. Methods

2.1. Modelling superflares

Kepler-96 has a Super-Earth planet orbiting very close to this star, with $P_{\mathrm{orb}} = 16.23$ days. By analyzing the 86 transits detected of Kepler-96b, three of them (30th, 48th, and 67th) show flares signatures, and in particular transit 48th has a high intensity flare that causes an increase of 4% in the total luminosity flux of the star. We have modelled the flares using the transit model described in Silva (2003), in which a stellar flare is added to the disk of the star outside the planet transit band. This model was already applied to model starspots in Kepler and CoRoT stars (Silva-Valio & Lanza 2011; Estrela & Valio 2016; Valio et al. 2017). A Gaussian profile was chosen to model the flare in time, t, as described below:

$$I_{\mathrm{flare}} = A \exp\left[\frac{(t-t_0)^2}{2\sigma_t^2}\right] \quad (1)$$

where A is the amplitude of the flare, t_0 represents the peak time as measured from midtransit time and σ_t is the temporal duration of the flare.

The three parameters that characterize the flare (A, t_0, and σ_t) were obtained by minimizing the χ^2 between the modelled transit lightcurve and the observed data.The results are summarized in Table 1.

In addition, we computed the total energy released by the flare using the following formula:

$$E_{\mathrm{flare}} = A L_{\mathrm{star}} \int_{-\infty}^{+\infty} \exp(t - t0^2/2\sigma_t^2)\mathrm{dt} \quad (2)$$

Table 1. Characteristics of the Kepler-96 superflares

Flare	Transit	Midtransit [BJD - 2.454.833 days]	Time position [hours]	Time duration [hours]	Time duration [min]	Amplitude [I_c]	Energy [ergs]
A	30th	674.41007	-0.0714 ± 0.006	0.118 ± 0.006	7.1 ± 0.4	39627 ± 0.00002	2.0×10^{33}
B	48th	966.70310	0.2402 ± 0.006	0.161 ± 0.003	9.7 ± 0.2	2986143 ± 0.002	1.8×10^{35}
C	67th	1275.2347	-0.108 ± 0.016	0.088 ± 0.017	5.3 ± 1.0	32885 ± 0.00006	1.2×10^{33}

Table 2. Biological effective irradiance from Kepler-96, $E_{\rm eff}$ [J/m^2]

	No atmosphere	Archean atmosphere	Present atmosphere with O_3
	Contribution of 5400% to the UV flux (Flare A)		
E. coli	$8 \times 10^4 \pm 0.020$	$1.3 \times 10^4 \pm 0.019$	$22 \pm 6.96 \times 10^{-8}$
D. radiodurans	$8.2 \times 10^4 \pm 0.15$	$1.3 \times 10^3 \pm 0.019$	$7.5 \pm 8.4 \times 10^{-8}$
	Contribution of 60% to the UV flux (Flare B)		
E. coli	$3 \times 10^3 \pm 10^{-4}$	$338 \pm 4 \times 10^{-4}$	$5 \pm 1.2 \pm 10^{-8}$
D. radiodurans	$2 \times 10^3 \pm 4 \times 10^{-4}$	$282 \pm 5 \times 10^{-4}$	$1.5 \pm 9.18 \times 10^{-8}$

2.2. Superflares contribution to the UV flux

To estimate the UV flux contribution of the Kepler-96 flares, we used the UV flux measured on the most intense solar flares observed. Woods et al (2004) reported one of the largest flares found in the Sun, a X17 GOES class flare with total energy of $E = 4 \times 10^{32}$ ergs, that increased by 12% the solar MUV flux. As the total thermal blackbody flux of Kepler-96 and the Sun are very similar, we considered that the superflares found in Kepler-96 would increase the UV flux proportionally. Therefore, a superflare found in Kepler-96 with $E = 1.8 \times 10^{35}$ ergs would increase by about 5400% the solar MUV flux.

3. Biological Impact

Stellar flares can give a significant contribution to the total UV flux of the star. For this reason, we analyzed here the possible impact that the superflares produced by Kepler-96 could have in life present in a planet on its habitable zone (1 AU).

Fortunately, this incident stellar UV flux ($F_{\rm inc}$) can be attenuated by a planetary atmosphere depending on its composition. Here we used different atmospheric scenarios found in Earth adopted from Cnossen et al. (2007): an Archean atmosphere composed of 80% N_2 and 20% CO_2, with concentrations of 2.09 $\times 10^{19}$cm^{-3} and 5.24×10^{18}cm^{-3} respectively, and a Present day atmosphere with ozone with concentrations of 2.09×10^{19}cm^{-3} for N_2, 5.62×10^{18}cm^{-3} for O_2, and 1.35×10^{12}cm^{-3} for O_3. These atmospheres contain molecules, such as N_2, CO_2 and O_2, that can absorb short wavelengths.

The UV radiation can also be attenuated by the water. Therefore, the UV flux in the ocean varies considerably with depth, and can be determined by the equation:

$$I(\lambda, z) = I_0(\lambda)e^{-K(\lambda),z} \quad (3)$$

where I(λ, z) is the UV spectral irradiance at a depth z, $I_0(\lambda)$ is the UV spectral irradiance with the superflare contribution passing through an Archean atmosphere and K(λ) is the diffuse attenuation coefficient for water adopted by Smyth (2011).

We used the attenuated UV flux with the superflares contribution to estimate the biological impacts in a hypothetical Earth in the HZ either for life on the planet surface or under the ocean surface. In both cases, we weighted the increased UV flux with the action spectrum of the microorganisms to get information about the total flux in the UV band that falls onto unit area of these biological bodies, known as biological effectiveness irradiance ($E_{\rm eff}$):

$$E_{\rm eff} = \int F_{inc}(\lambda)S(\lambda)d(\lambda) \quad (4)$$

Table 3. UV Irradiation at Ocean depths

	Ocean Depth [m] (increase of 5400%)	Ocean Depth [m] (increase of 60%)
E. coli	28	10
D. radiodurans	12	surface

where F_{inc} is the total incident MUV flux with the superflare contribution arriving at the planet surface/ocean depth, S is the action spectra of a biological body and λ is the MUV wavelengths. Here we used the action spectra of two microorganisms that define the surviving zone for life: *Deinococcus radiodurans* (Setlow & Boling (1965); Calkins & Barcelo (1982); O'Malley-James & Kaltenegger (2017)) and *Escherichia coli* (Giller (2000)).

Then, we verified if the estimated $E_{\rm eff}$ can be tolerated by *D. radiodurans* and *E. coli*.

4. Results

We estimated the biological effective irradiance ($E_{\rm eff}$) for two resistant microorganisms (*D. radiodurans* and *E. coli*) present in an Earth-like planet in the HZ of Kepler-96. The threshold for the $E_{\rm eff}$ is defined using the maximum UV flux for 10% survival of these microorganisms, which is $F_{10}^{UV} = 5.53 \times 10^2$ J/m^2 for *D. radiodurans* (Ghosal et al. 2005) and $F_{10}^{UV} = 22.6$ J/m^2 for *E. coli* (Gascón et al. 1995). These results are shown in Table 2, note that to obtain the values in Joules, we multiplied the values in Watts by the total duration of the superflare.

For the contribution of the strongest superflare (increase of 5430% in the MUV flux), the $E_{\rm eff}$ shows that *D. radiodurans* would only survive in the surface of a hypothetical Earth at 1AU if there is an ozone layer present on the planet atmosphere (see Table 2). Considering the effects of a smaller superflare (increase of 60% in the MUV flux), *D. radiodurans* could survive in the surface even if the planet has an Archean atmosphere.

Moreover, we also analyzed the ocean depths that could harbour extremophile life in this planet without being damaged by the strongest superflare of Kepler-96 (see Table 3). Thus, considering the effects of this superflare (flare B) in a planet in the HZ, an ocean depth of 28m would be necessary to absorb the UV irradiation such that *E. coli* could survive and 12m for *D. radiodurans*.

5. Conclusion

We detected and modelled flares present in the transits of Kepler-96b. All of them showed an energy range that corresponds to superflares.

The study of the biological impact suggests that the stellar UV Flux (increased by the contribution of the strongest superflare) received by a biological body would allow the presence of life in the surface only for a planet with ozone. An ocean in this planet can also attenuate the UV radiation and protect the microorganisms from the increased UV radiation due to the superflares. Thus, although a hypothetical Earth-like planet orbiting Kepler-96 receives an increased UV radiation due to the superflares, life could still survive in depths inside the photic zone (up to 200m) of an Archean ocean present in these planets.

In a future work we will consider the cumulative effects of all superflares from the star.

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