Chapter 10. Observations of solar eclipses and exoplanetary transits

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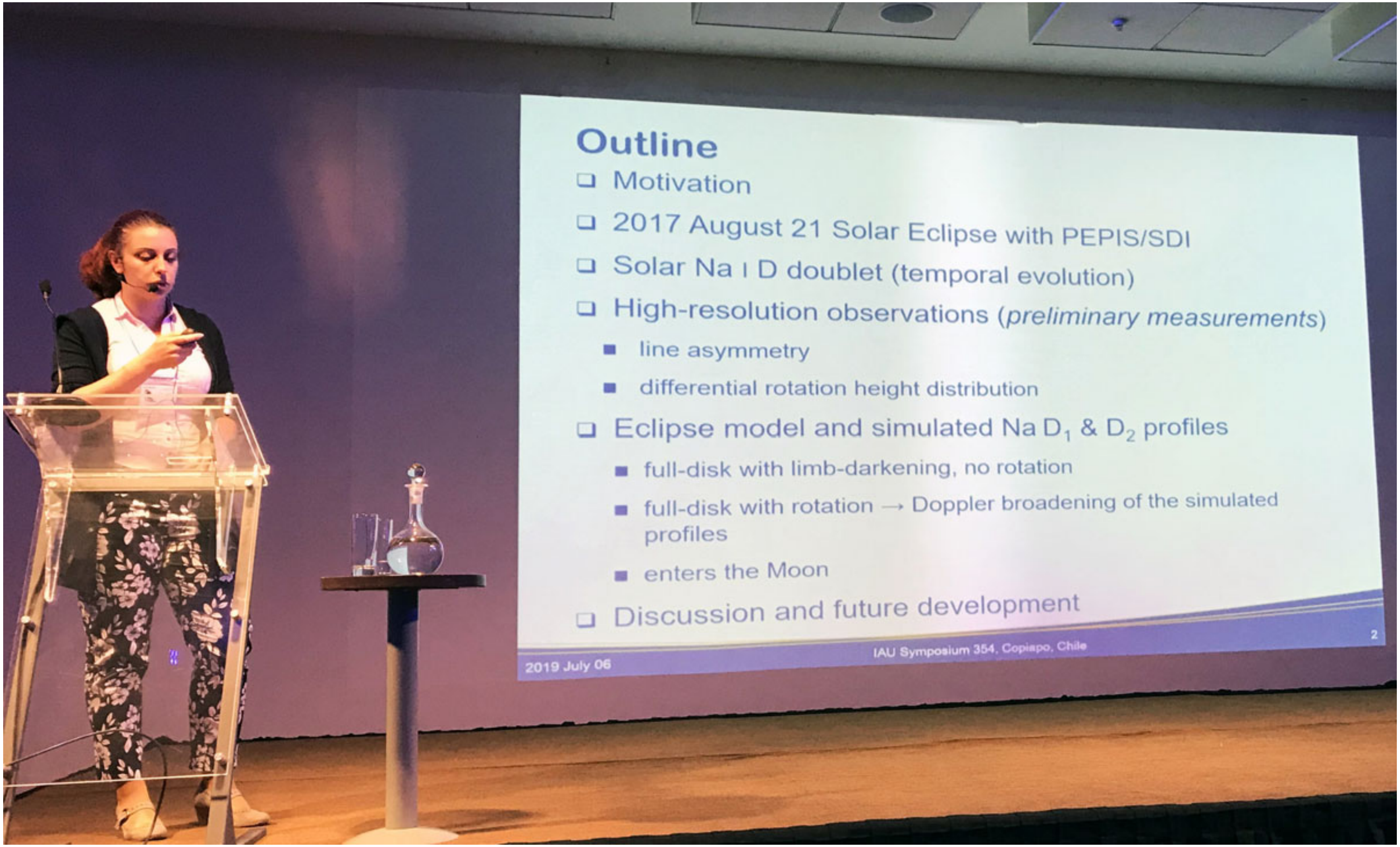

Ekaterina Dineva

Solar and Stellar Magnetic Fields: Origins and Manifestations
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Characterization of stellar activity using transits and its impact on habitability

Raissa Estrela[1,2], **Adriana Valio**[2] and **Sourav Palit**[3]

[1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109
email: rlf.estrela@gmail.com

[2]Center for Radioastronomy and Astrophysics Mackenzie, Mackenzie Presbyterian University Rua da Consolacao 896, Sao Paulo, SP 01302-907, Brazil
email: adrivalio@gmail.com

[3]Department of Physics, Indian Institute of Technology, Bombay, Powai, Mumbai 400076

Abstract. Stellar magnetic field is the driver of activity in stars and can trigger spots, energetic flares, coronal plasma ejections and ionized winds. These phenomena play a crucial role in understanding the internal mechanisms of the star, but can also have potential effects in orbiting planets. During the transit of a planet, spots can be occulted producing features imprinted in the transit light curve. Here, we modelled these features to characterize the physical properties of the spots (radius, intensity, and location). In addition, we monitor spots signatures on multiple transits to estimate magnetic cycles length of Kepler stars. Flares have also been observed during transits in active stars. We derive the properties of the flares and analyse their UV impact on possible living organisms in planets orbiting in the habitable zone.

Keywords. stars: flare, stars: activity, astrobiology, ultraviolet: stars

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1. Introduction

In the Sun, the sunspot number is used as an estimator of its 11 year solar cycle. Similarly, the number of spots that appears at the surface of a star varies in accordance with the stellar magnetic cycle. Estrela & Valio (2016) uses the passage of a planet in front of its host star to find evidence of starspots. During the transit, the planet can occult spots present in the stellar disk producing small "bumps" as signatures (increase in stellar luminosity) in the planetary transit lightcurves. Hence, the variation of the number of spots per transit can give an estimate of the magnetic cycle of the star.

Also, during the maxima of a cycle there is a higher frequency of flares, coronal mass ejections (CMEs) and protons events (McIntosh *et al.* (2015)). These space weather pheonomena can drive the emission of ultraviolet and X-ray radiation as well as energetic particles causing potential effects on the planetary atmosphere. For example, Carrington-class solar flares are usually associated with fast and dense CME events that can erode and compress Earth's magnetosphere and ionosphere (Airapetian *et al.* (2017)). Other stars can be more active and show flares that are 1000 times more energetic than solar flares. Studies show that these flares when associated with energetic particles can indirectly destroy the ozone in Earth-like planets due to the formation of nitrogen oxides (Segura *et al.* (2010); Venot *et al.* (2016)).

The solar-type star analysed here, Kepler-96, has several flares in its lightcurve, and also during the transits of planet Kepler-96 b that orbits this star every 16.23 days. The strongest flare, visible in the middle of the 48th transit (966.70 BJD – 2.454.833

days), released a total of 1.8×10^{35} ergs, within the range of superflares (Maehara *et al.* (2015)). A study by Vida *et al.* (2017) using the data from the Kepler spacecraft in the K2 program found frequent flaring activity during the 80 days of observations of TRAPPIST-1. A total of 42 flares were detected and the strongest eruption emitted energy of roughly 10^{33} ergs in white light, which is more energetic than the largest flare ever recorded from the Sun. These energetic events could threaten the habitability of the planets in the system as they orbit much closer to their host star (0.029, 0.037, and 0.0451 AU, respectively) than Earth.

2. Stellar magnetic cycles

By monitoring the number of spots during the approximate 4 years of observation of the Kepler stars it is possible to estimate stellar cycles. Estrela & Valio (2016) applied two new methods to investigate the existence of a magnetic cycle: spot modelling and transit residuals excess. They found agreement between the results of the two methods for the solar-type stars Kepler-63 and Kepler-17. With the first method, they obtained $P_{cycle} = 1.12 \pm 0.16$ yr (Kepler-17) and $P_{cycle} = 1.27 \pm 0.16$ yr (Kepler-63), and for the second approach: $P_{cycle} = 1.35 \pm 0.27$ yr (Kepler-17) and $P_{cycle} = 1.27$. The second method is much faster to determine magnetic cycles because it only requires to integrate the area of the residuals due to the activity (spots) in the transit light curve. We used this method to estimate the magnetic cycle of two more active stars observed by Kepler: HAT-P-11 (Kepler-3) and Kepler-96. For the former, we obtained a cycle of 0.83 ± 0.16 yr and for the latter, 1.50 ± 0.35 yr.

3. UV radiation from flares on Kepler-96 and Trappist-1 systems

During a flare, the solar flux in XUV (20–300Å) band increases by a factor of 1000 and in the EUV (300–1215Å) band by up to a factor of 20 (Woods & Rottman (2005); Airapetian *et al.* (2017)). Longer UV wavelenghts also have an increase, Woods *et al.* (2004) reported that one of the most intense solar flare detected, a X17 GOES class observed in 2003, increased by 12% the Mg II h and k emissions (279.58–279.70 nm), which is within the MUV range.

Here we compute the UV contribution due to the energetic flares observed in Kepler-96 and Trappist-1. We focus on the MUV region of the spectra (200–300) because at short wavelengths (0.1–200 nm) the UV is attenuated in the top of the atmosphere, considering an Earth-like atmosphere with strong absorbers like N_2, CO_2 or O_2. Radiation at wavelengths between 200–320 nm can partially reach the surface of the planet depending if the planet has or not an ozone layer, and are very harmful to life.

On Earth, the ozone layer is responsible for absorbing most of the solar ultraviolet radiation arriving at our planet. In particular, the radiation that is the most threatening for life, like UVC (100–280 nm), is completely absorbed by the ozone layer, while UVB (280–315 nm) has an absorption of 95% and UVA (315–400 nm) can reach the Earth‘s surface. Therefore, the ozone layer acts as a shield that protects lifeforms living on the surface of our planet from the harmful ultraviolet radiation.

Estrela & Valio (2018) estimated the UV flux contribution of Kepler-96 flares using the MUV flux measured from the most intense solar flares, that was observed in 2003. For Trappist-1, along with the flux values of the flare observed by Vida *et al.* (2017), we use spectral and lightcurve information of a similar observed superflare of the M dwarf star AD Leo presented by Hawley & Pettersen (1991) to find the approximate spectra of the Trappist-1 flare, obtained by systematic extrapolation following the methods of Segura *et al.* (2010). The estimated UV (180–400 nm) spectra of the Trappist-1 flare are shown in Fig. 1.

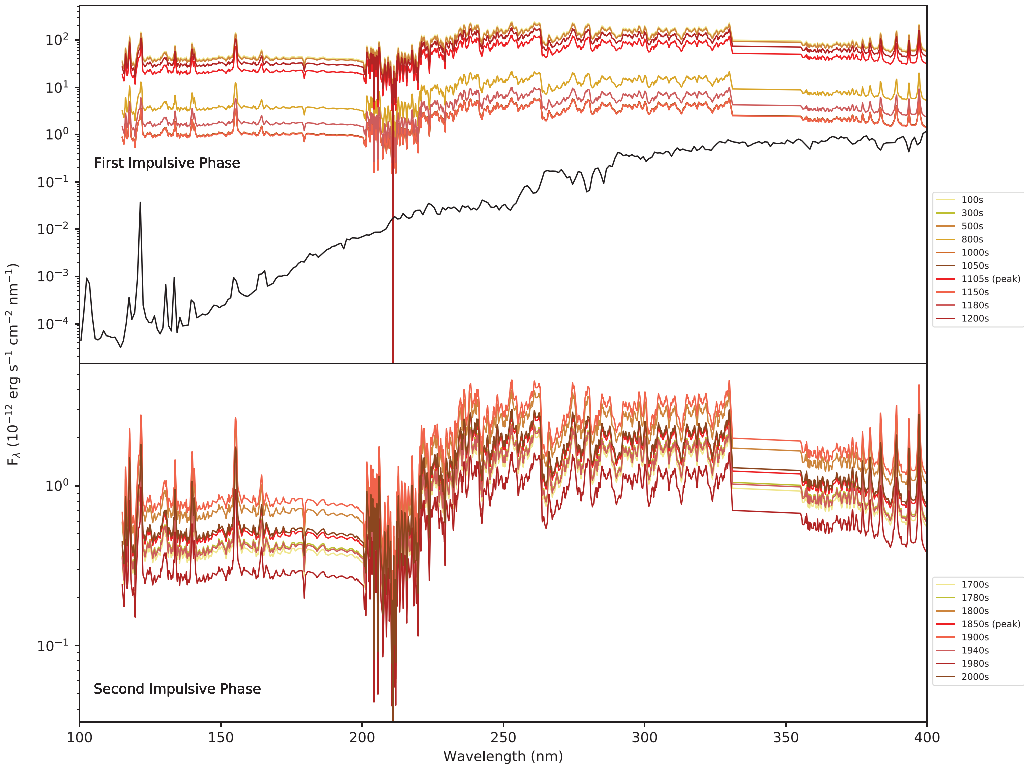

Figure 1. Estimated UV spectra of the strongest flare of Trappist-1 from Vida *et al.* (2017) for every 5 minutes during the evolution of the flare.

To compute the UV radiation (180–300 nm) through the atmospheres of the Trappist-1 planets, we use a two stream radiative transfer code from Ranjan *et al.* (2017). This code computes the UV fluxes and intensities at the top of the atmosphere and at the surface of the planets orbiting M-dwarfs, under a specified atmosphere and surface conditions. As input, the code requires the stellar spectrum, and the temperature, pressure and composition (gas molar concentration) as a function of altitude. We partitioned the atmosphere into 55 layers, each having thickness of 1km, and two atmospheric scenarios were used as an input to the code: (i) a 1 bar CO_2 dominated atmosphere (0.9 bar N_2, 0.1 bar CO_2), similar to the Archean Earth at 3.9 Gyr and (ii) a modern atmosphere with ozone. For the former, we adopted a pre-biotic model already provided by the code. While for the latter, we consider an atmosphere composed of N_2, O_2, CO_2, H_2O, CH_4, O_3, and SO_2.

3.1. *Results*

The net UV flux at the top of the atmosphere (dashed lines) and on the surface (solid lines) of the three TRAPPIST-1's HZ planets are shown in Fig 2. The fluxes reach the highest values during the first impulsive phase ($\sim 10^2$ $Wm^{-2}nm^{-1}$), but has a considerable increase during the second peak of the flare. These values are in accordance with the UV surface flux from Segura *et al.* (2010) for an Earth-like planet during the energetic flare (10^{33} erg) of the M dwarf star AD Leo. In the presence of ozone, the UV radiation shortwards of 280 nm, which are the most dangerous to life, is absorbed. Just a small amount of UVB radiation arrives at the surface. However, the UVB and

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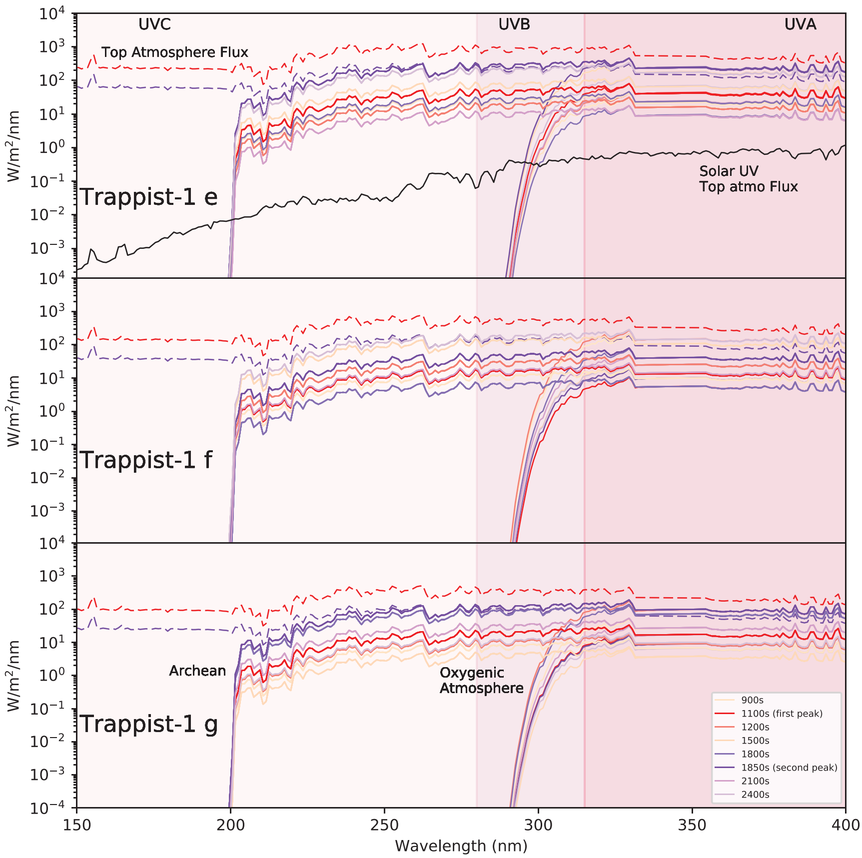

Figure 2. Ultraviolet flux at the top of the atmosphere (dashed line) and at the surface (solid line) of planets Trappist-1 e (top), Trappist-1 g (middle) and Trappist-1 f (bottom) during the evolution of the flare. The UV flux arriving at the surface is transmitted by two atmosphere models: 1 bar CO_2 dominated atmosphere (Archean) and a present day Earth-like atmosphere with ozone. The quiescent solar UV flux received at the top of the atmosphere of Earth is shown in the top panel for comparison (black solid line).

UVA flux during the impulsive phase of the flare can still be ∼100 times higher than the flux received by Earth (solid black line in Fig. 2). For an Archean atmosphere, only UV wavelengths smaller than 200 nm are absorbed, which means that the planetary surfaces receive UVB and UVC fluxes that are ∼5 times more biologically harmful than those on the present-day Earth.

4. Biological Impact

4.1. *On the surface*

To determine the survival of two bacteria on the surface of the Trappist-1's HZ planets we calculate the overall effective UV flux (E_{eff}) that falls in a biological body, considering the strongest observed flare of Trappist-1 and Kepler-96. Details of this calculation are presented in Estrela & Valio (2018). The threshold for the E_{eff} was chosen using the maximum UV flux for 10% survival of these bacteria.

Table 1 and 2 summarizes the results found for the E_{eff} considering the UV increase during the two impulsive phases of the flares in Trappist-1 and for a hypothetical planet at 1AU of Kepler-96. Thus, it is possible to observe that for a sudden increase of 5400%

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Table 1. Biological effective irradiance, E_{eff} (J/m^2), due to the strongest superflare on Kepler-96.

Planet	Bacteria	Archean	Present day
Kepler-96 (1 AU)	*E. coli*	1.4×10^4	21.5
	D. radiodurans	8.0×10^3	7.5

Table 2. Biological effective irradiance, $E_{\rm eff}$ (J/m^2), due to the two impulsive phases of the superflare. To obtain the values in Joules, we multiplied the values in Watts by the total duration of the each peak (146s and 158s, respectively).

First Impulsive Phase			
Planet	**Bacteria**	**Archean**	**Present day**
TRAPPIST-1e	*E. coli*	1.3×10^6	59.4
	D. radiodurans	6.6×10^6	19
TRAPPIST-1f	*E. coli*	8.2×10^5	14
	D. radiodurans	4×10^5	4.4
TRAPPIST-1g	*E. coli*	5.5×10^5	12
	D. radiodurans	2.7×10^5	3.8
Second Impulsive Phase			
Planet	**Bacteria**	**Archean**	**Present day**
TRAPPIST-1e	*E. coli*	3.8×10^5	17
	D. radiodurans	2×10^5	5.4
TRAPPIST-1f	*E. coli*	2.3×10^5	4
	D. radiodurans	1.2×10^5	1.3
TRAPPIST-1g	*E. coli*	1.6×10^5	3.5
	D. radiodurans	7.8×10^4	1.1

from the strongest flare in Kepler-96, both micro-organisms can live in the surface if the planet has an atmosphere like the one we find on the present-day Earth with ozone. The same is true for the Trappist-1 planets. The UV flux received by the bacteria in a planet with a primitive atmosphere is very high ($\sim 10^5$ J/m^2) compared to the one with ozone. For a planet with a present-day atmosphere (with ozone), *E. Coli* could not survive in Trappist-1 e only during the first impulsive phase of the flare. However, both bacteria could survive in the other HZ planets under the presence of ozone.

4.2. *On the ocean*

The exposure to the high UV irradiation of flares imposes difficulties to the survival of microorganisms on the surface of the planet. A deep ocean could provide a safe refuge for micro-organisms against this extreme environment, by attenuating the effects of this radiation. Therefore, depending on the absorption of the UV radiation by the water, which varies with the ocean depth, the aquatic environment is more likely to host life. The UV spectral irradiance as a function of ocean depth can be calculated using the following equation:

$$I(\lambda, z) = I_0(\lambda) e^{-K(\lambda) z} \tag{4.1}$$

where $I(\lambda, z)$ is the UV spectral irradiance at depth z, $I_0(\lambda)$ is the UV spectral irradiance with the superflare contribution passing through a Primitive/Present-day atmosphere, and reaching the water surface and $K(\lambda)$ is the diffuse attenuation coefficient for water given by the sum of the absorption coefficient of water and the scattering coefficient.

Then, to quantify the effects on a micro-organism living in the ocean, we compute the biological effective irradiance. For that, we convolve the UV irradiation at a certain

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ocean depth z with the action spectrum of the bacteria to estimate at which depth the micro-organisms would receive an UV radiation dosage that they can tolerate.

Estrela & Valio (2018) assumed that an hypothetical Earth at 1 AU orbiting the star Kepler-96 has a calm and flat Archean ocean and found that *D. Radiodurans* and *E. Coli* would need to live at a depth of 12m and 28m, respectively. In the case of the Trappist-1 planets, during the first impulsive phase, E. Coli and D. Radiodurans could survive approximately at 40 and 20m, respectively, below the ocean surface of the three HZ planets. While for the second impulsive phase, they could survive at lower ocean depths: ∼38 and 21m, respectively.

5. Conclusions

In this work we estimated short magnetic cycles using planetary transits for the stars HAT-P-11 and Kepler-96, and we obtained cycles of 0.83 ± 0.16 yr and 1.50 ± 0.35 yr, respectively. Moreover, we estimated the impact that the UV increase due to high energetic flares from Kepler-96 would have if there was a hypothetical planet orbiting this star in the habitable zone (1 AU). We also applied similar analysis for the Trappist-1 system. We find that to survive the impacts from the strongest flare observed in Kepler-96 and in Trappist-1 microorganisms would need the protection from the ozone. An ocean in these planets could also provide a safe refuge for the lifeforms under the high UV irradiation of the flares. For the bacteria analysed in this work, *E. Coli* and *D. Radiodurans* they could escape from the hazardous UV effects of Kepler-96 flare at a depth of 28m and 12m below the ocean surface,respectively. In the three Trappist-1 HZ planets, they could survive at approximately 40m and 20m, respectively, below the ocean surface during the first impulsive phase of the superflare.

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