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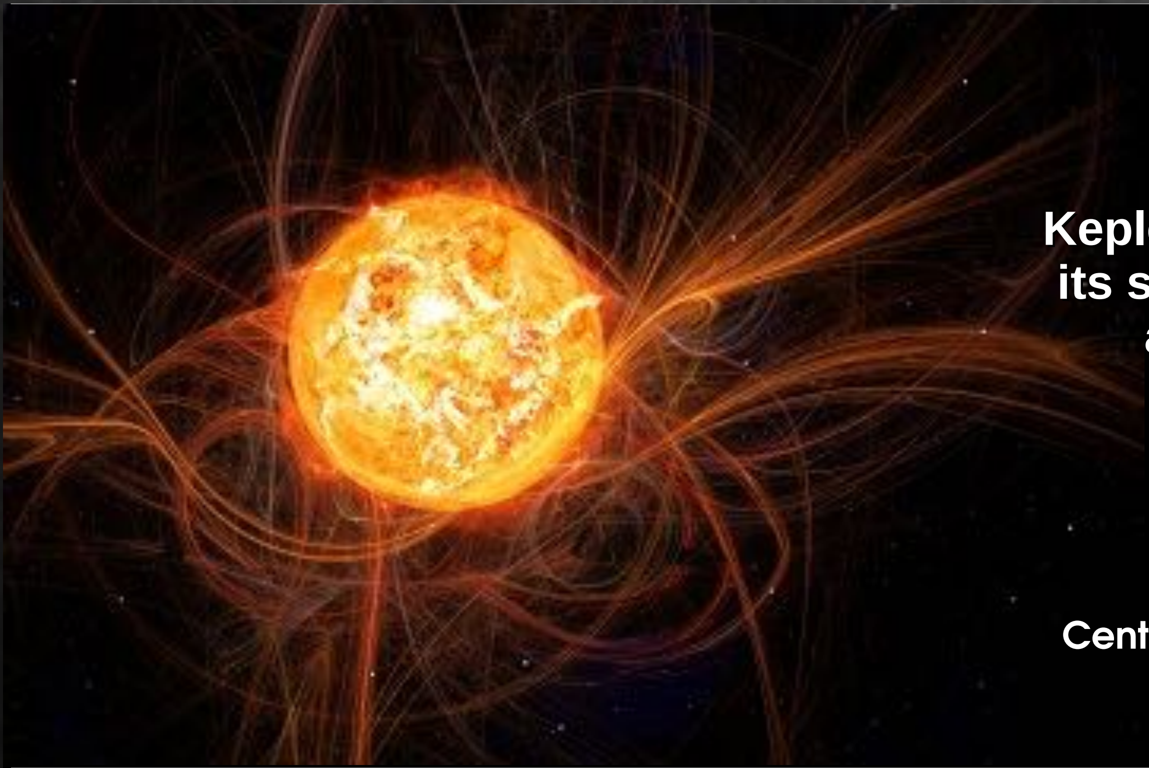

Kepler-96 system: exploring the habitability of its super-Earth and of a hypothetical Earth in an environment of strong superflares

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Center for Radioastronomy and Astrophysics Mackenzie
Sao Paulo, Brazil

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1. Kepler solar-type stars and their superflares

2 About Kepler-96

3. Modelling flares in planetary transits

4. Biological Impact

5. Summary+comments

Superflares in Kepler solar-type stars

Observations from the Kepler telescope have led to the discovery of stellar superflares → **more likely in young rapidly rotation stars**
stars with temperature and rotation close to the Sun

Superflares in solar-type stars in Kepler data:

- bolometric energy range of 2×10^{32} up to 8×10^{36} erg
- duration interval varying from 5 to 120 min
- average occurence: once in 500-600 years

Maehara et al (2012)
Maehara et al (2015)

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For comparison (in the **Sun**):

- larger solar flares detected have 10^{32} erg, with occurence frequency of one in 10 years

Superflares effects on habitability

- Superflares releases 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:

  - Atmospheric loss
  - Affects the chemical composition of the upper atmosphere

    Protons that arrive from the flare produce odd nitrogen and odd hydrogen in the upper stratosphere and mesosphere that destroy ozone. Segura et al. (2010)

- could affect the origin and evolution of life

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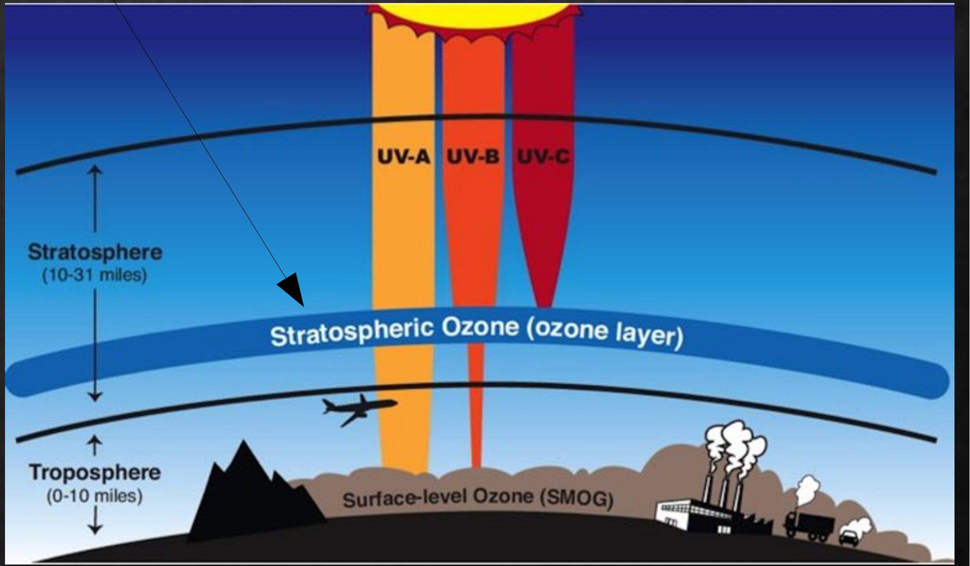

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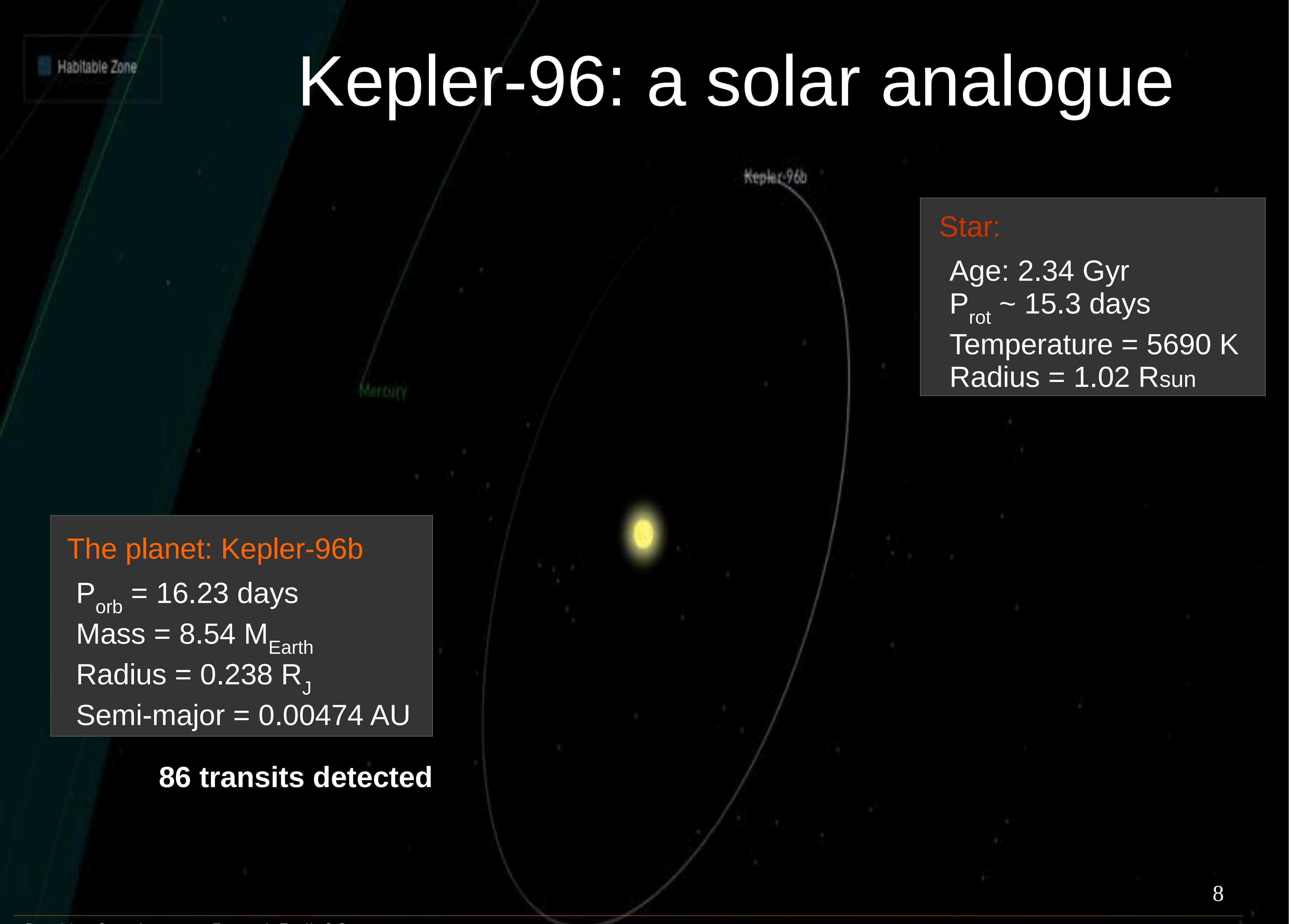
Kepler-96: a solar analogue



Star:

Age: 2.34 Gyr
P_{rot} ~ 15.3 days
Temperature = 5690 K
Radius = 1.02 Rsun

The planet: Kepler-96b

P_{orb} = 16.23 days
Mass = 8.54 M_{Earth}
Radius = 0.238 R_J
Semi-major = 0.00474 AU

86 transits detected

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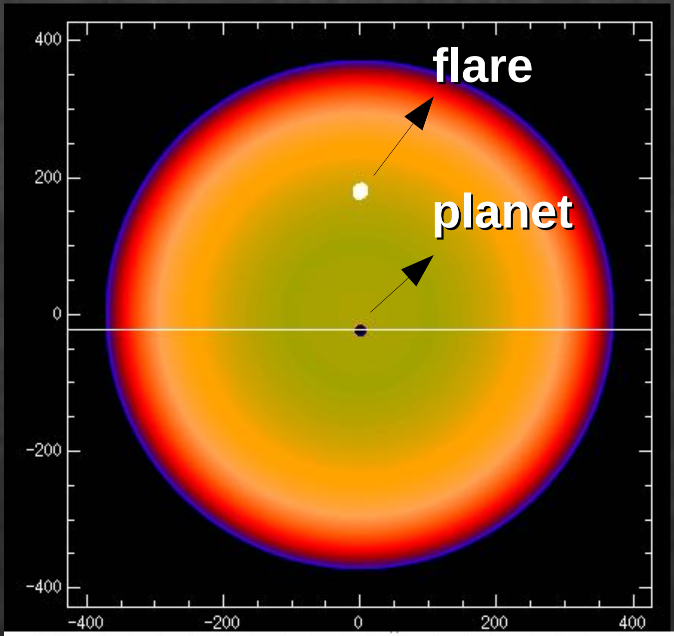
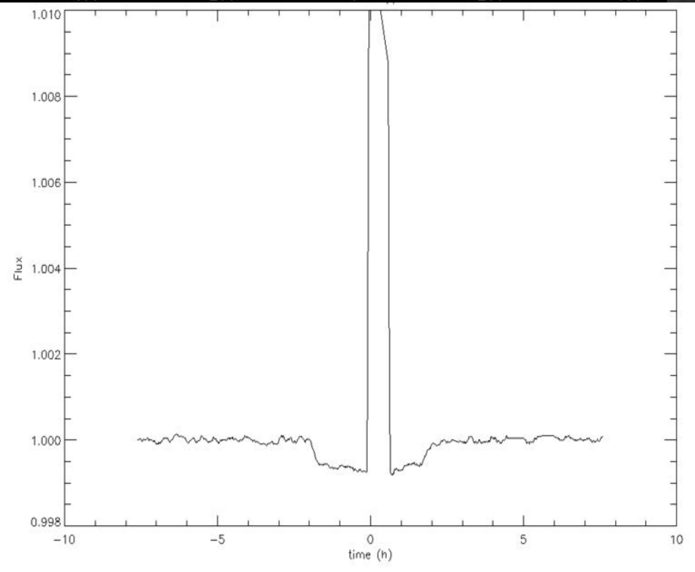
Modelling flares in planetary transits

Model that simulates planetary transit and allows the insertion of features in the stellar disc, such as spots and flares (Silva, 2003).





Modelling flares in planetary transits

A gaussian profile was chosen to model the flare:

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

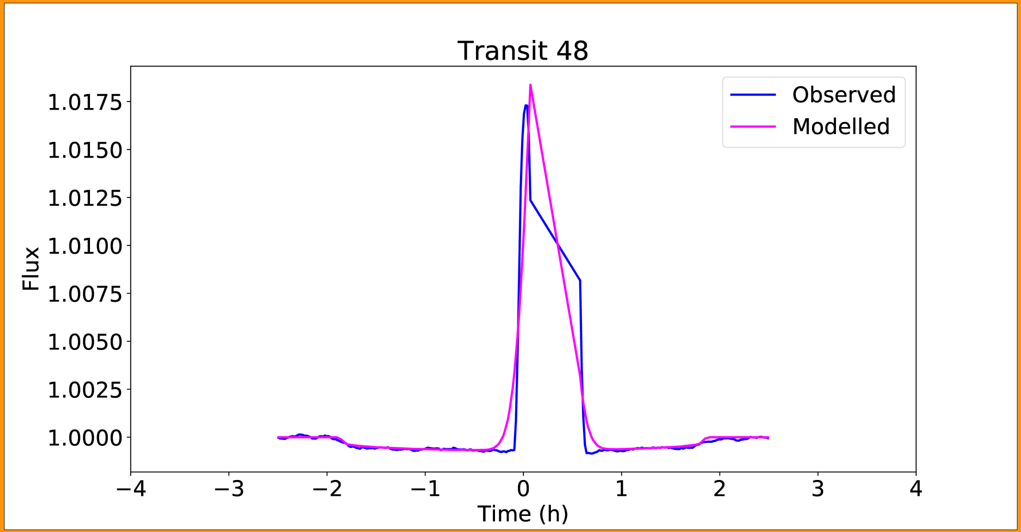
A (amplitude): measured with respect to stellar maximum intensity (center);

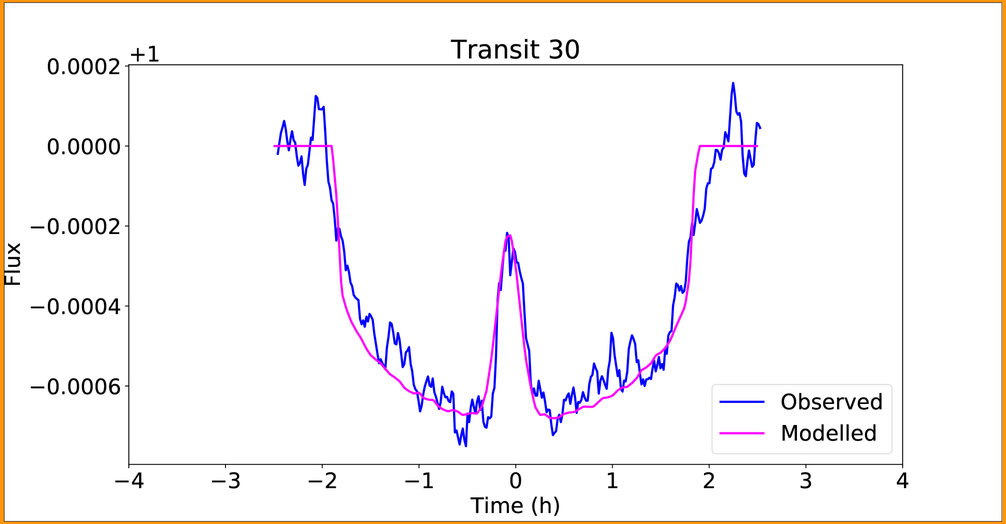
T_0: Time of maximum in the transit

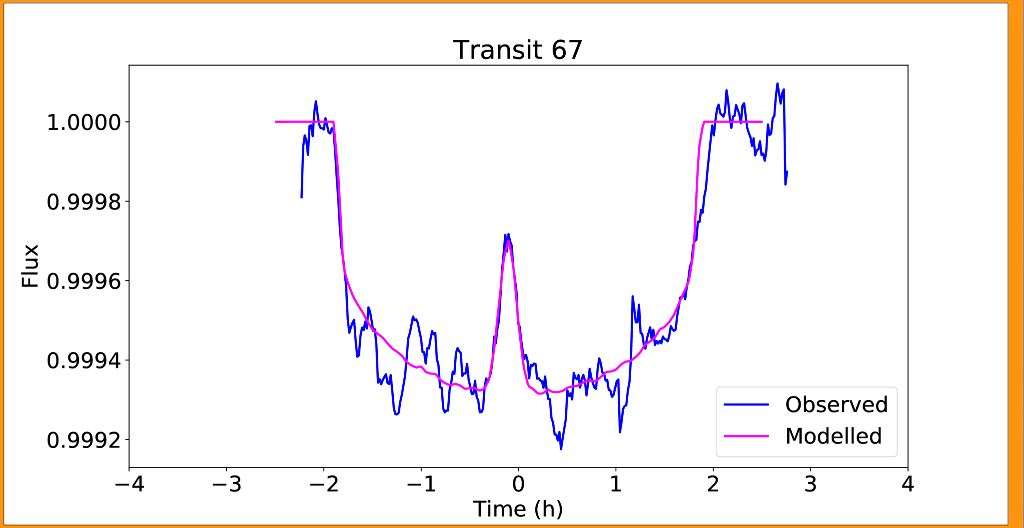
σ_t :Duration

Energy released by the flare: $E_{flare} = \sigma_t \sqrt{2\pi}$

Modelling flares in planetary transits







Modelling flares in planetary transits

Characteristics of the superflares

Transit	Amplitude [I_c]	Energy [ergs]
30th	39627 ± 0.00002	2.0×10^{33}
48th	2986143 ± 0.002	1.8×10^{35}
67th	32885 ± 0.00006	1.2×10^{33}

Energy range that corresponds to superflares

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Kepler-96 has an age that corresponds to the end of the Archean Era on Earth

→ **Great Oxygenation Event**

can be a proxy to understand the primitive Earth environment

- Quantify the total flux in the UV band that falls onto unit area of the biological body → **Biological Effectiveness of UV radiation (E_{eff})**

To analyse E_{eff}, we used the UV flux passing through atmospheres at different epochs in Earth:

- Archean (3.9 Gyr – 2.5 Gyr): 80% N_2, 20% CO_2
- Present day without ozone: 80% N_2, 20% O_2
- Present day with ozone

Cnossen et al. (2007)

UV Irradiance at Earth`s surface 4-3.5 Gyrs ago

Emission from the solar atmosphere:
75% of the present-day solar irradiation

Stellar superflares can give a significant contribution to the total UV flux of the star

Solar Flare X17
28 October 2003

One of the largest flare in the Sun
Total energy $E = 4\times\ 10^{32}$ ergs — Woods et al. (2006)
Increased by 12% the solar **MUV flux (200–300 nm)**

Superflare
In Kepler-96

Total energy $E = 1.8\times 10^{35}$ergs
Increase by 5400% the **MUV flux**

The total thermal blackbody flux of Kepler-96 and the Sun are very similar, we considered that the superflare found in Kepler-96 would increase the UV flux in the same amount.

Biological Impact: surface

Biological effective irradiance from Kepler-96, E_{eff} [J/m^2] †

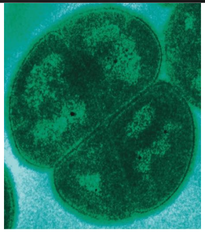
Contribution of 5400% to the UV flux (strongest superflare)

	No atmosphere	Archean atmosphere	Present atmosphere without O_3	Present atmosphere with O_3
Kepler-96b	3.2×10^8	3.4×10^7	5×10^6	178
Planet at 1AU	1.5×10^5	1.6×10^4	2401.2	0.0084

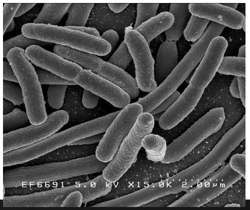
Only with ozone

Microorganisms that define survival zone for life:

Flux (dosage) for 10% survival: $F_{10}^{UV} = 5.53\times\ 10^2 J/m^2$ → Deinococcus radiodurans



$F_{10}^{UV} = 22.5 J/m^2$ → Escherichia coli



Ghosal et al (2015)
Gascón et al (1995)

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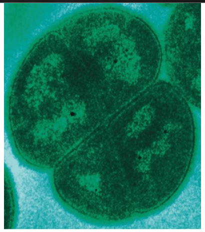

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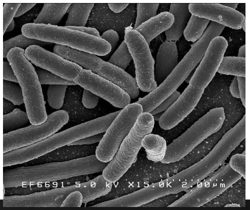

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Biological Impact: **ocean**

- For Kepler-96 system, the deep ocean might provide a safe refuge against the UV radiation.

- We assume here that Kepler-96b and a hypothetical Earth orbiting the star Kepler-96 have an Archean ocean where life could be protected.

Biological Impact: **ocean**

The propagation of the UV radiation in the ocean varies considerably with depth, and can be determined by the equation:

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

UV spectral irradiance at depth z

UV with the superflare contribution

Diffuse attenuation coeficient

Ocean depth

Estrela & Valio (2017), submitted to Astrobiology

Biological Impact: **ocean**

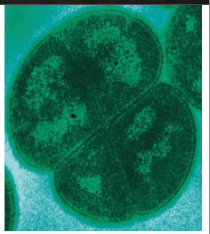
Ocean Depth (m)

	Kepler-96b	**Planet 1AU**
	48m → E. Coli	20m → E. Coli
	35m → D. Radiodurans	8m → D. Radiodurans

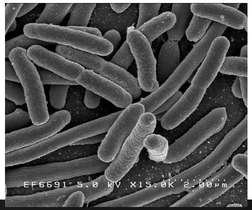
Flux (dosage) for 10% survival: $F_{10}^{UV} = 5.53\times\ 10^2 J/m^2$

$F_{10}^{UV} = 22.5 J/m^2$

Deinococcus radiodurans



Escherichia coli



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5. **Summary+comments**

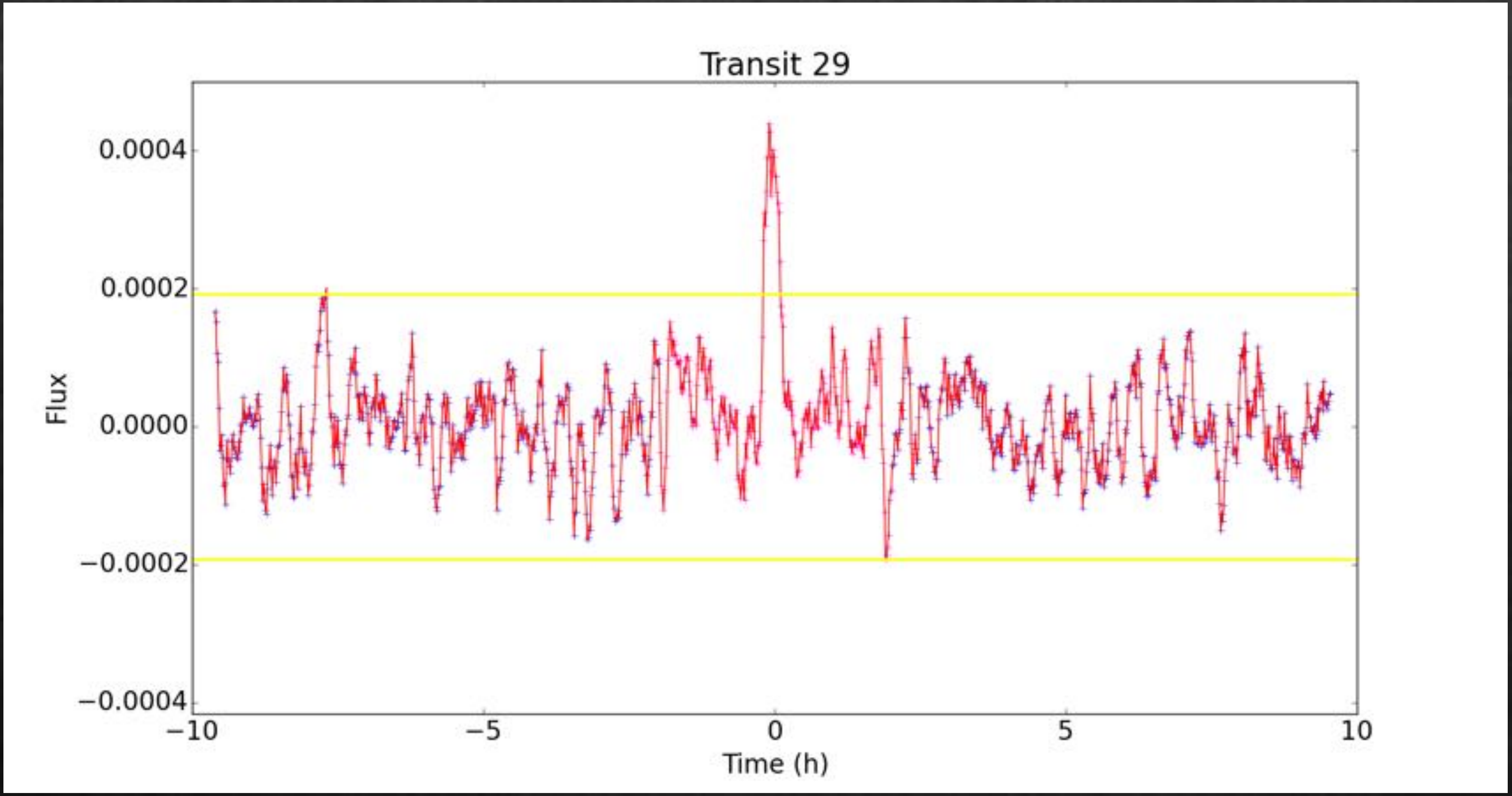
Summary+comments

- We analysed flares presented in 3 planetary 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 only alow the presence of life in a planet with ozone.

- An ocean in these planets would still support life in depths within the Earth photic zone (down to 200m).

Removing data noise from transits

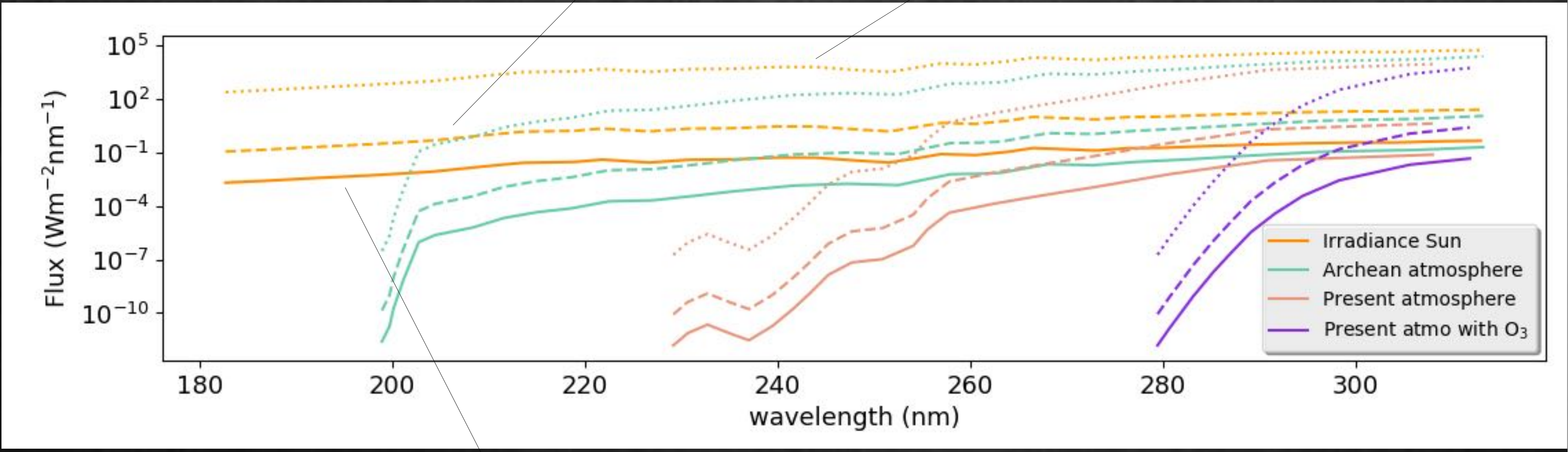


- Sigma clipping technique
- Values beyond and lower 10 CDPP were considered outiler and rejected

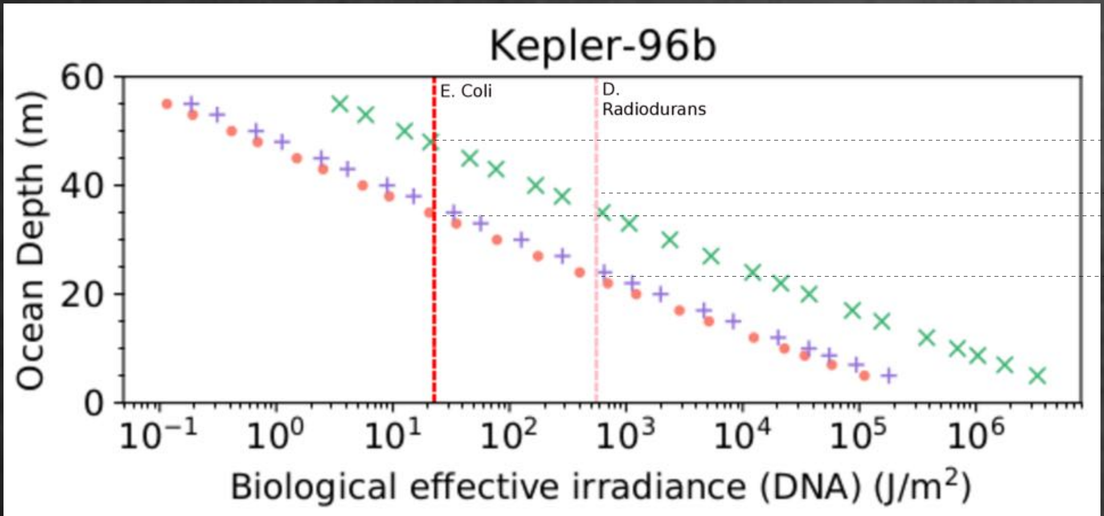
Biological Impact

Contribution of the superflare

Contribution of the superflare + Rescaled flux for Kepler-96b



UV flux received
By a planet at 1AU



Strongest superflare

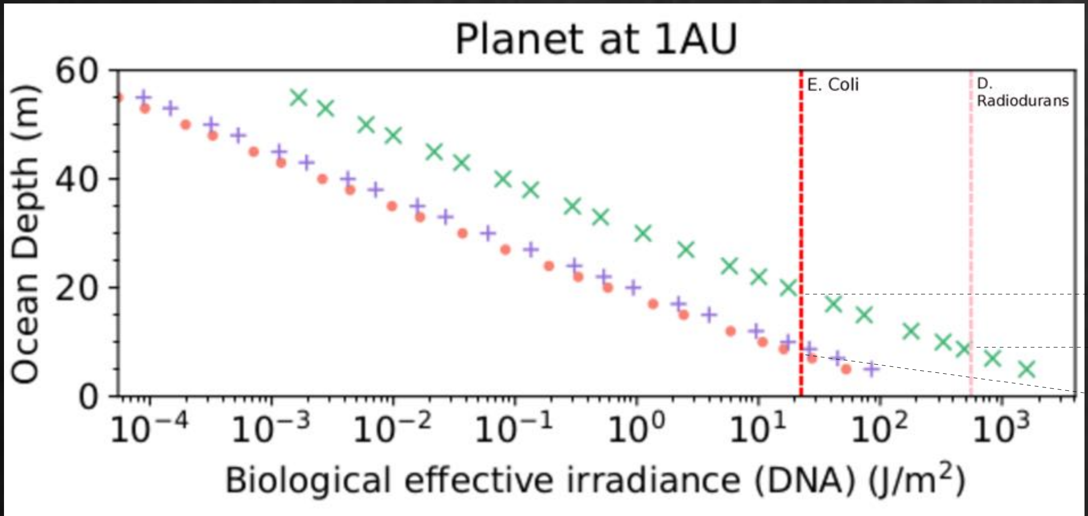
48m → E. Coli

35m → D. Radiodurans

35m →E.Coli

22m → D. Radiodurans

Lower superflares



Strongest superflare

20m → E. Coli

8m → D. Radiodurans

8m → E. Coli

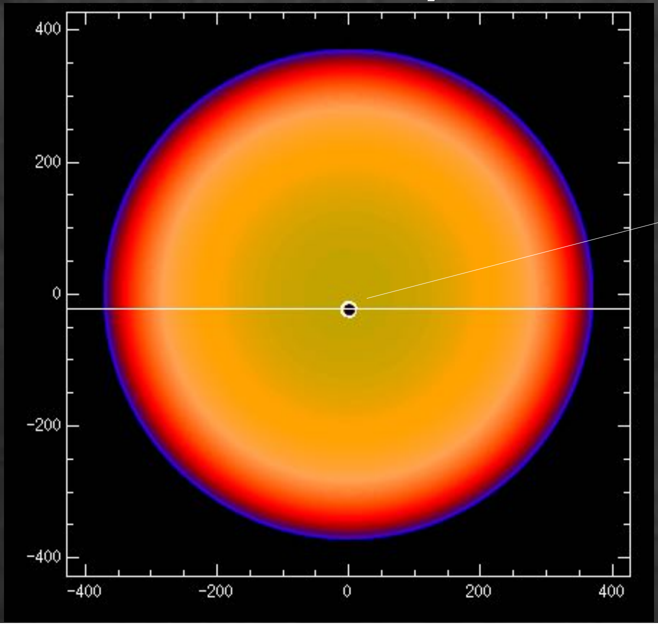
D. Radiodurans could live in the surface

Lower superflares

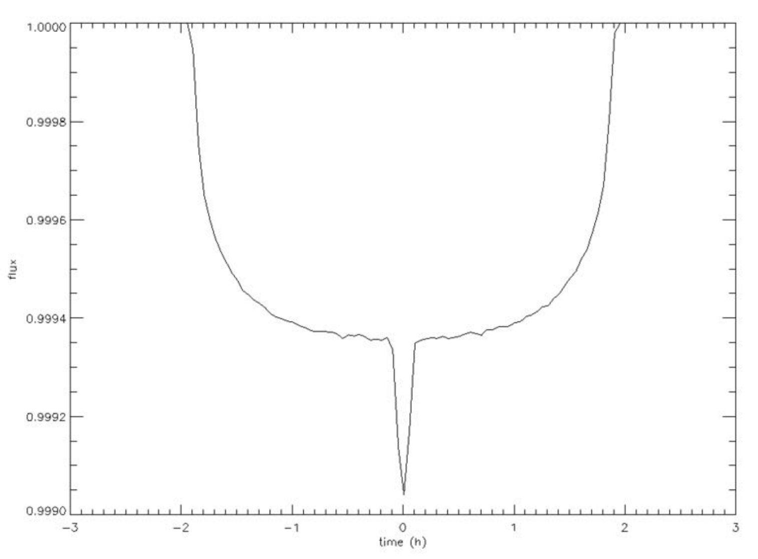
Modelling flares in planetary transits

Model that simulates planetary transit and allows the insertion of features in the stellar disc, such as spots and flares (Silva, 2003).

1)Flare occulted by the transit



- Flare
- Planet



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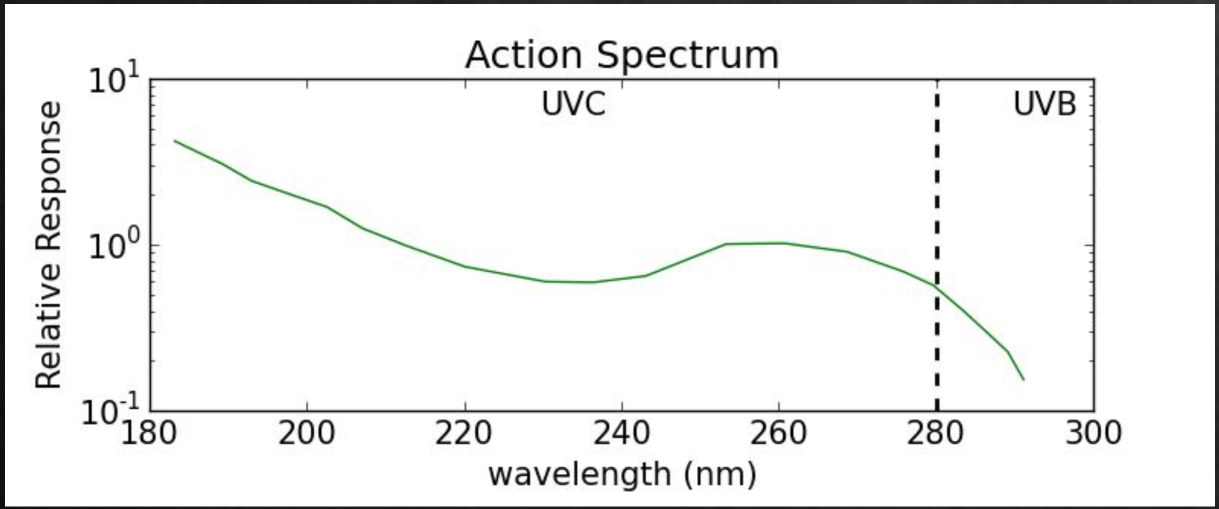
Biological Impact

Biological effective of UV radiation (E_{eff})

Information about the total flux in the UV band that falls onto unit area of the biological body.

- The response of a biological body varies as function of the wavelength. It is necessary to weigh the UV Flux with the Action Spectrum



From Cnossen et al (2007) and Setlow (1974)

$$E_{eff} = \int_{180}^{300} F(\lambda)S(\lambda)d\lambda$$

Action Spectrum

UV Flux arriving in the planet surface with the contribution of the superflare

Biological Impact: surface

Biological effective irradiance from Kepler-96, E_{eff} [J/m^2] †

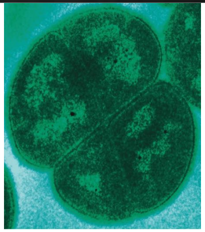
	No atmosphere	Archean atmosphere	Present atmosphere without O_3	Present atmosphere with O_3
Contribution of 5400% to the UV flux				
Kepler-96b	3.2×10^8	3.4×10^7	5×10^6	178
Planet at 1AU	1.5×10^5	1.6×10^4	2401.2	0.0084
Contribution of 60% to the UV flux				
Kepler-96b	7×10^6	7×10^5	1.10×10^5	3.85
Planet at 1AU	3.2×10^3	349.5	52	0.0018
Contribution of 35% to the UV flux				
Kepler-96b	4.4×10^6	4.7×10^5	6.7×10^4	2.5
Planet at 1AU	2.1×10^3	221	33	0.0011

† To obtain the values in Joules, we multiplied the values in Watts by the total duration of the flare.

Only with ozone

Microorganisms that define survive zone for life:

Flux (dosage) for 10% survival: $F_{10}^{UV} = 5.53\times\ 10^2 J/m^2$ → Deinococcus radiodurans



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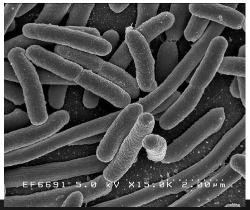

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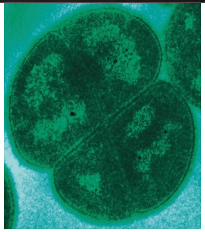

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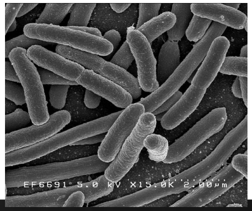

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Only with ozone

D. Radiodurans could survive in an Archean atmosphere

E. Coli could live only in a planet with ozone

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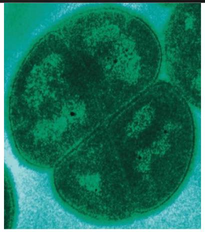

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