CRAAM
Centro de Rádio Astronomia e Astrofísica Mackenzie

Stellar Activity and rotation from planetary transits

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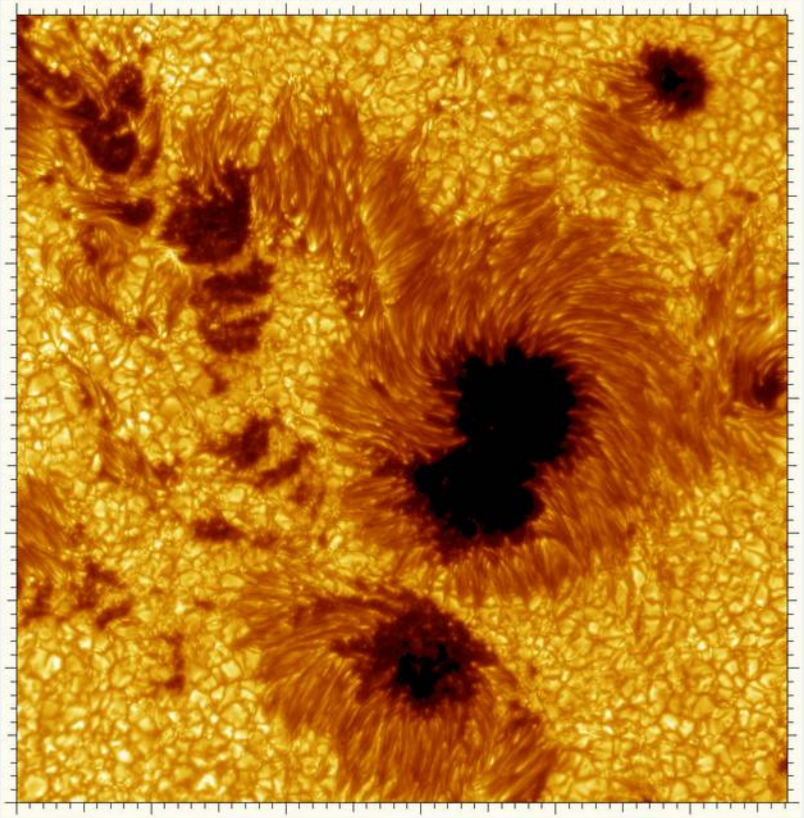
2019 Precision Spectroscopy, 6 September 2019

Contents

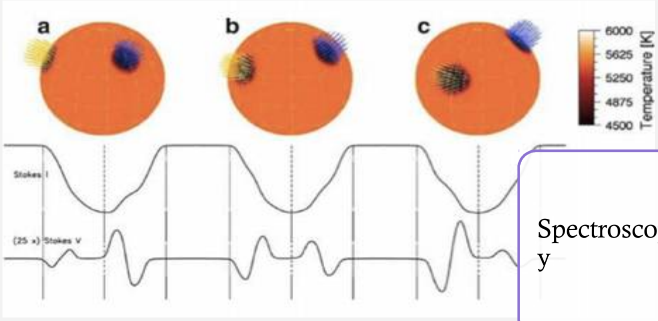
Spots

- Sunspots were the first indications of solar activity
- Very likely, all cool stars with a convective envelope like the Sun will have spots on their surfaces
- Current telescopes do not have the spatial resolution to detect spots similar to sunspots



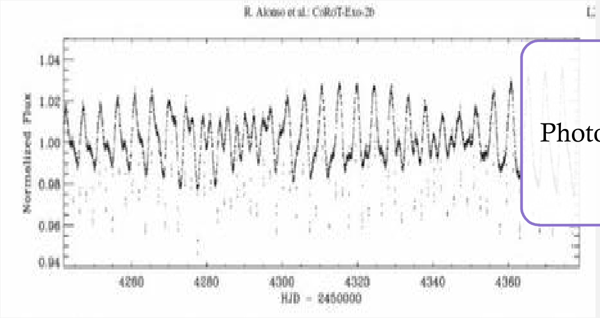
Star spots

Doppler Imaging



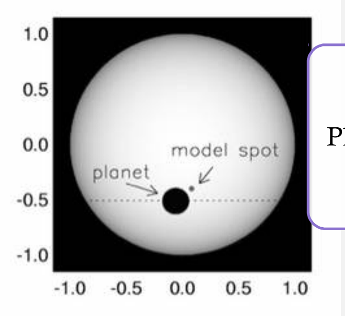
Spectroscopy

Light curve modulation



Photometry

Planetary transit

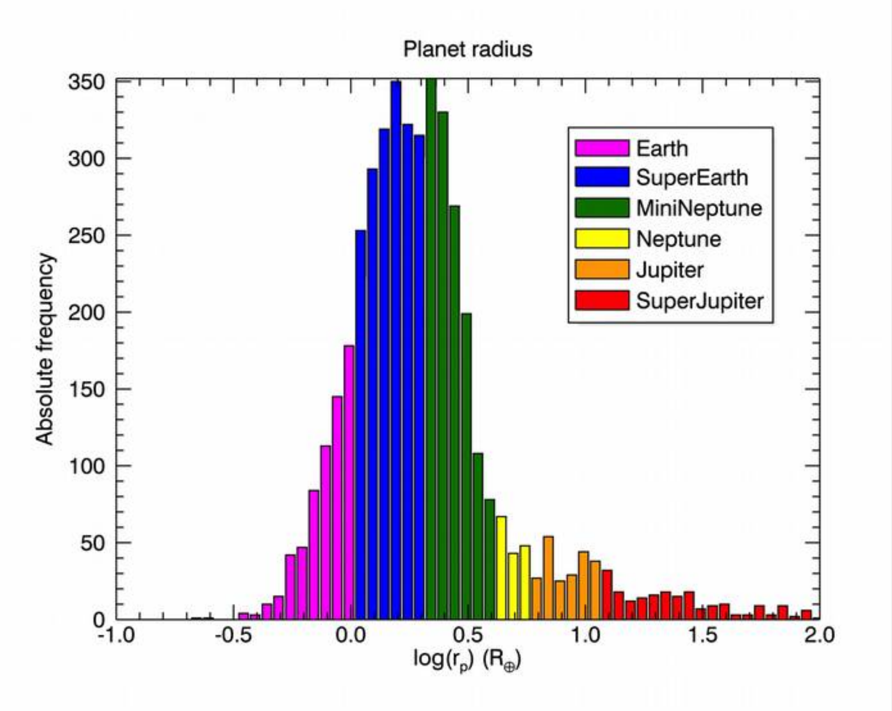


Photometry

1st paper: Silva (2003)

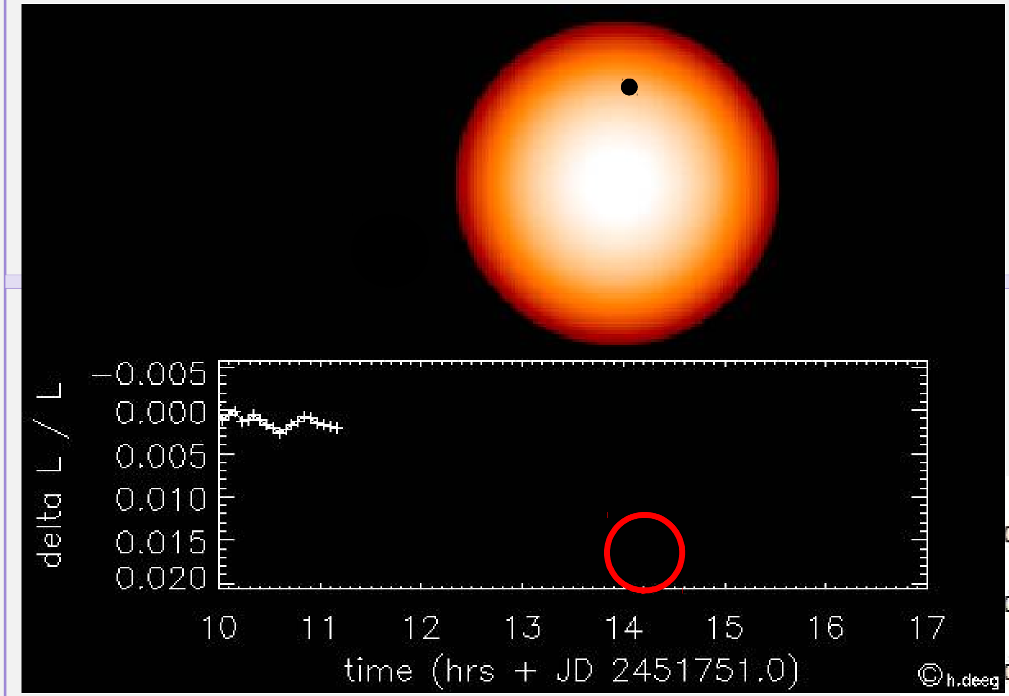
Extrasolar planets

- Total of 4109 confirmed exoplanets discovered (04/Sep/2019);
- 2955 (72%) planets transit in from of its host star;
- Satellites:
  - MOST
  - CoRoT
  - Kepler/K2
  - TESS

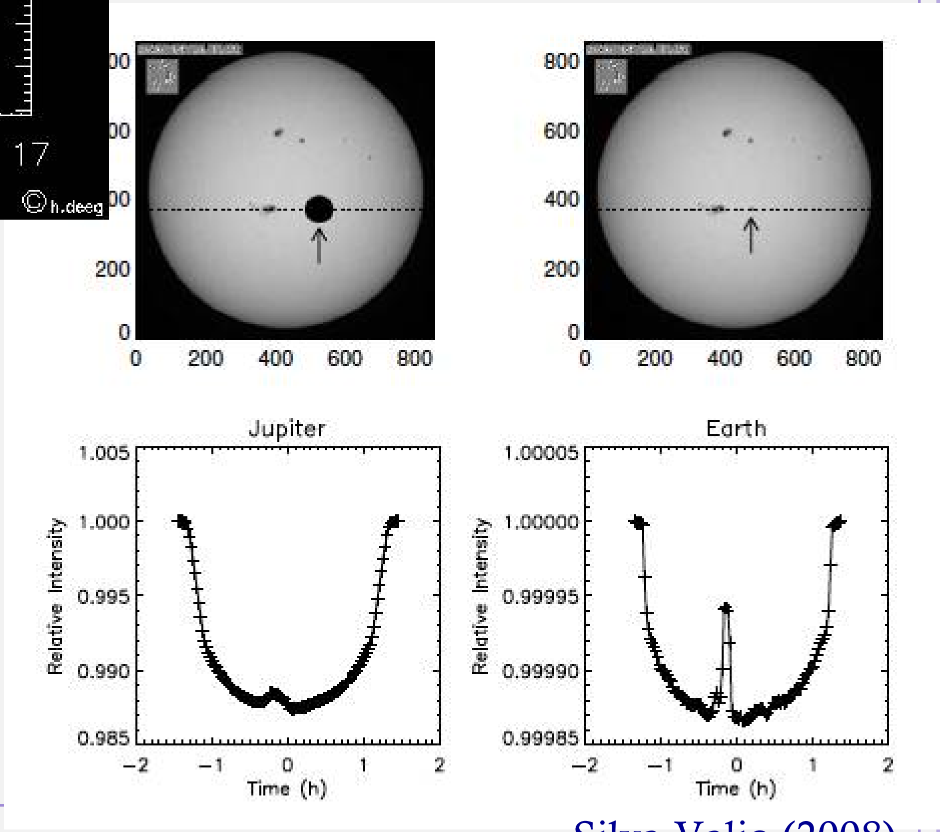


Guimarães & Valio (2018)

Transit

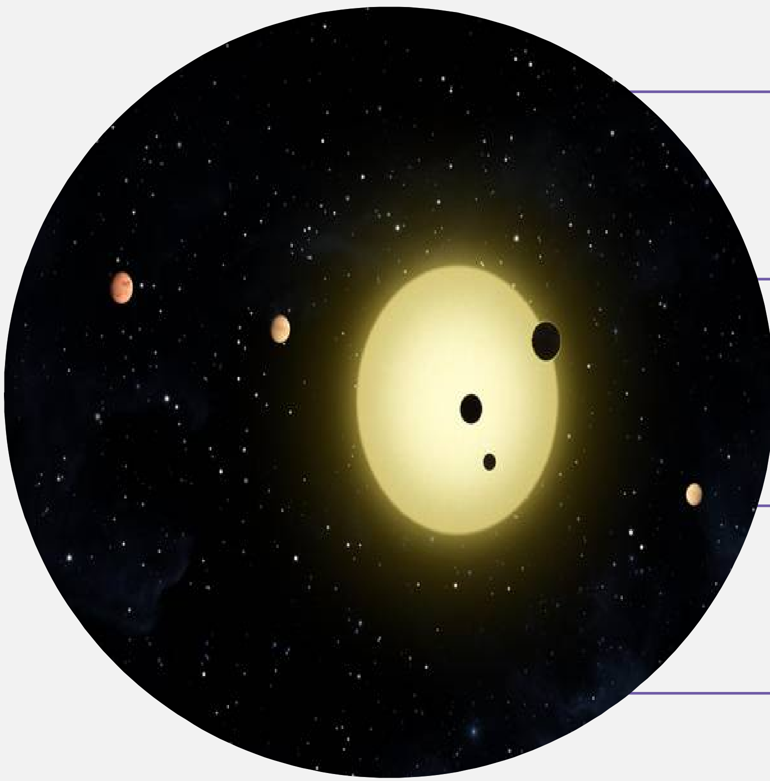


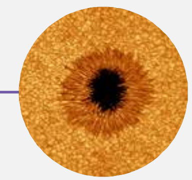
- Jupiter planet: 1 % decrease in flux
- Earth planet: 0.01% decrease in flux



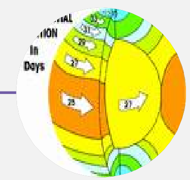
Silva-Valio (2008)

Stellar Activity



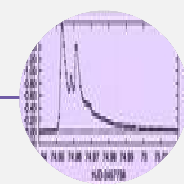


Spots



Rotation +
Differential rotation

Magnetic field +
cycle



Flares

Contents

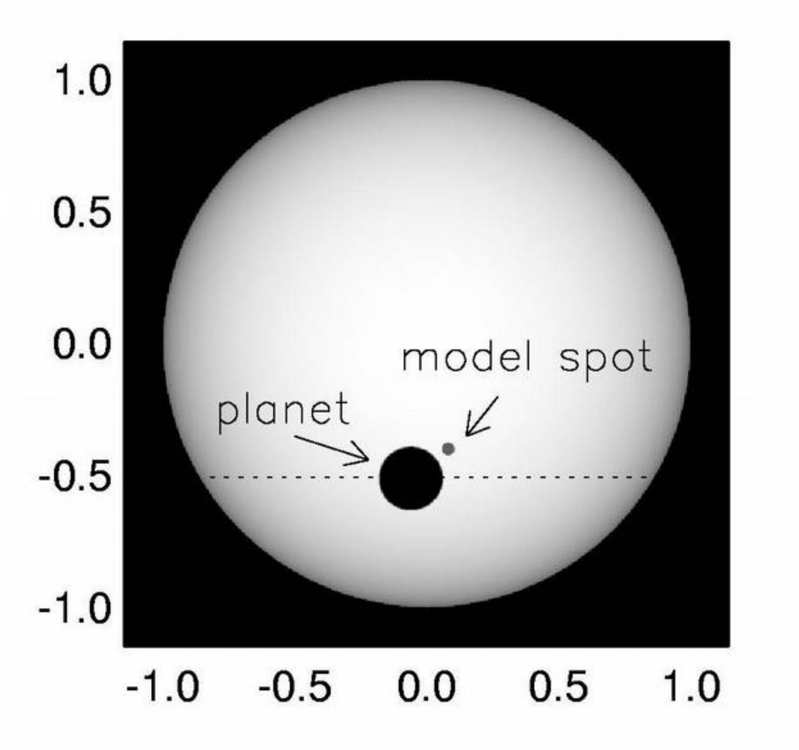
Model: ECLIPSE

- Star
  - Limb darkening
- Planet
  - Radius (fraction of R_{star})
- Orbit circular (e=0)
  - Semimajor axis (a)
  - Period (P_{orb})
  - Inclination (i)

Silva (2003)

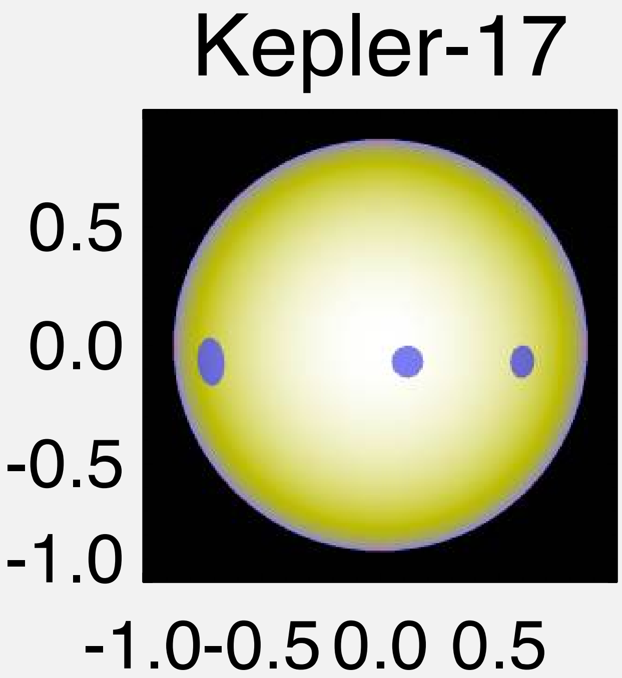
Spots

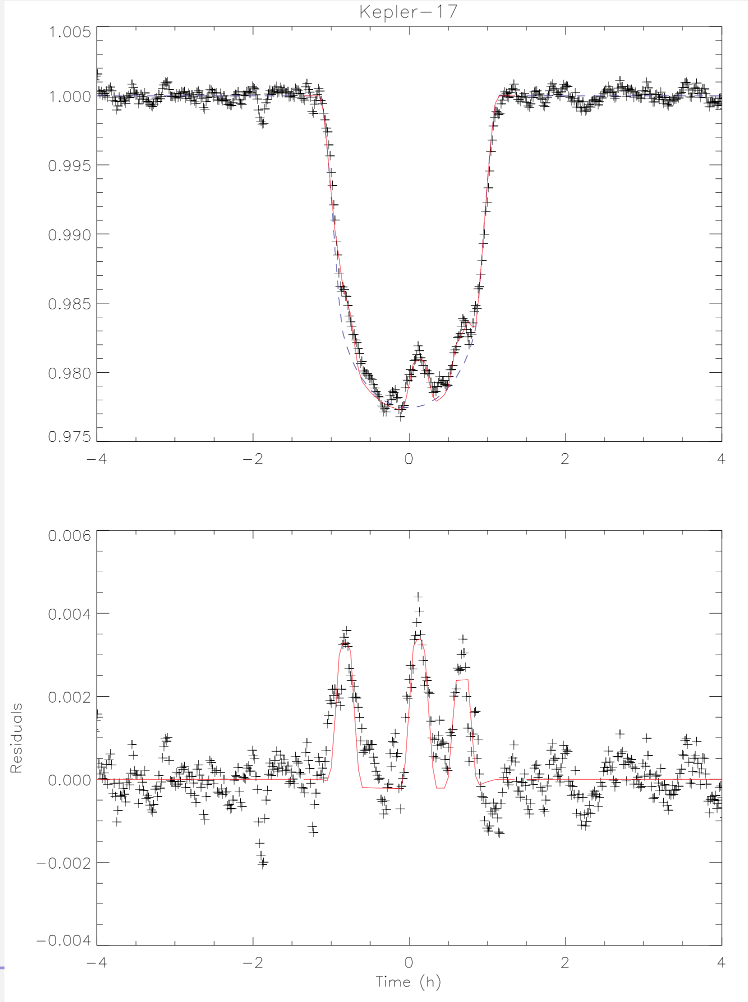
- Spot: 3 parameters:
  - Intensity (I_c)
  - Size (R_p)
  - Position:
    - Longitude & Latitude



- Foreshortenning effect of spots included

Light curve fitting





Valio et al. (2017)

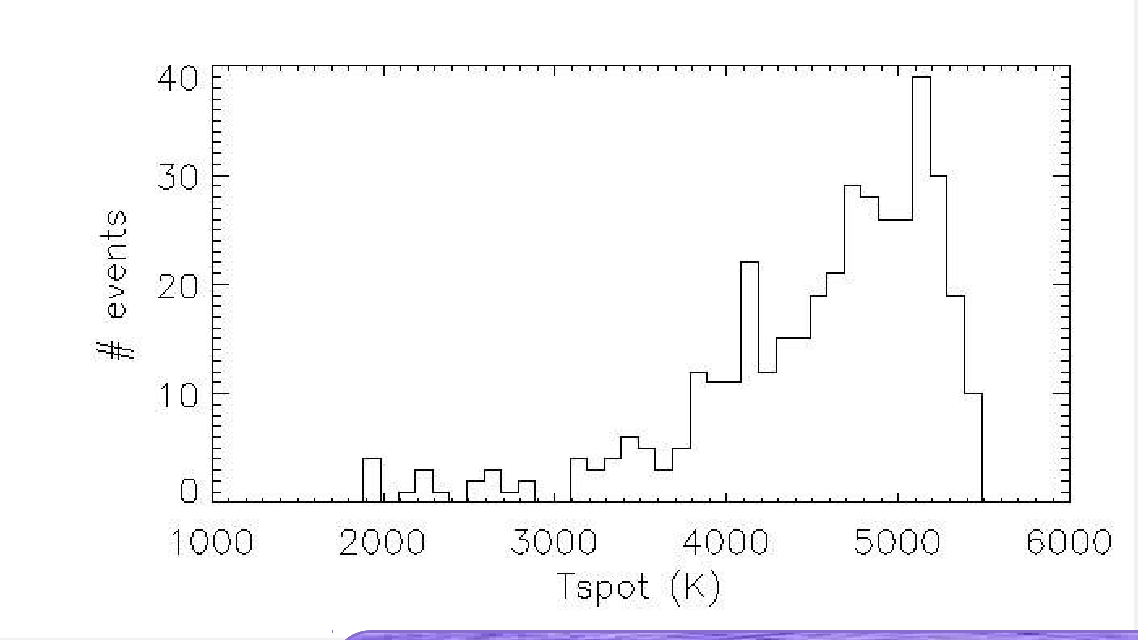
Stellar Systems

Star	CoRoT-2	CoRoT-4	CoRoT-6	CoRoT-8	CoRoT-18	Kepler-17	Kepler-63	Kepler-71
Spectral type	G7V	F8V	F9V	K1V	G9V	G2V	G8V	G7V
Mass (M_{sun})	0.97	1.10	1.055	0.88	0.95	1.16	0.984	0.997
Radius (R_{sun})	0.902	1.17	1.025	0.77	1.0	1.05	0.901	0.887
Prot (d)	4.54	8.87	6.35	21.7	5.4	12.28	5.4	19.77
Teff (K)	5625	6190	6090	5080	5440	5781	5576	5540
Age (Gyr)	0.13-0.5	0.7-2.0	1.0-3.3	2.0-3.0	?	>1.78	0.2	2.5-4
Planet								
Mass (M_{jup})	3.31	0.72	2.96	0.22	3.47	2.45	--	--
Radius (R_{star})	0.172	0.107	0.117	0.090	0.142	0.138	0.0662	0.1358
Porb (d)	1.743	9.203	8.886	6.212	1.90	1.49	9.434	3.905
a (R_{star})	6.7	17.47	17.95	17.61	6.35	5.73	19.55	12.186
Latitude (^{o})	-14.6	0	-16.4	-29.4	-22.8	-4.6	--	-5.4

Contents

Temperature

- Black body emission for spot & stellar photosphere



$$\frac{I_o}{I_e} = \frac{\exp\left(\frac{h\upsilon}{KT_e}\right) - 1}{\exp\left(\frac{h\upsilon}{KT_o}\right) - 1}$$

Silva-Valio et al. (2010)

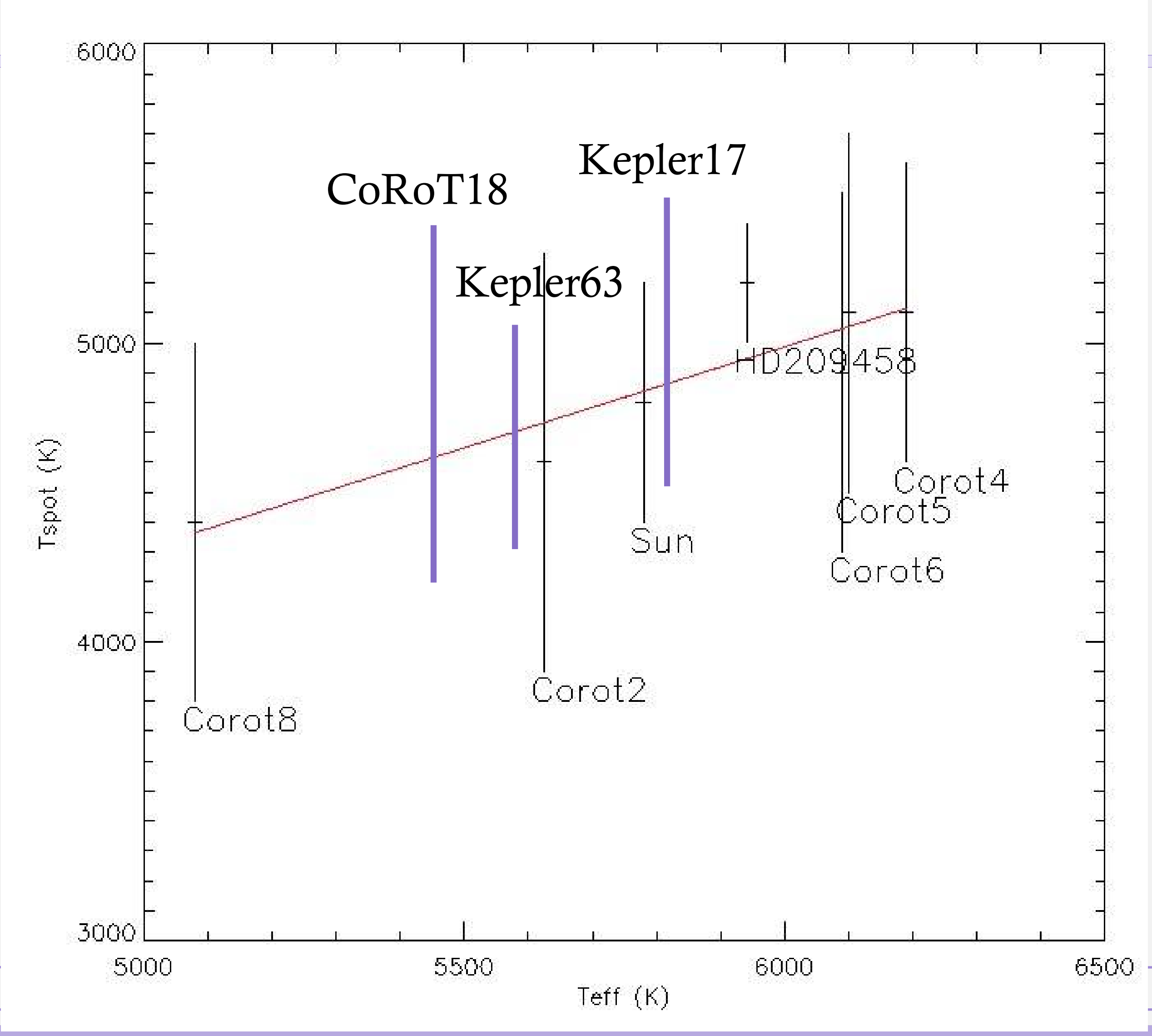
- CoRoT 2:
  - $T_{eff} = 5625$ K
  - $T_{spot} = 4700 \pm 300$ K (Sun: 3500 – 4500 K)

Spot characteristics

Star	CoRoT-2	CoRoT-4	CoRoT-6	CoRoT-18	Kepler-17	Kepler-63	Kepler-71	Sun
Radius (Mm)	55±19	51±14	48±14	65±19	80±50	32±14	51±26	12±10
Area (%)	13	6	9	13	11		4	< 1
Tspot (K)	4600±700	5100±500	4900±600	4800±600	5100±500	4700±400	4800±500	4800±400
T_{eff} (K)	5625	6190	6090	5440	5780	5576	5540	5780
T_{spot}/T_{eff}	0.818	0.824	0.804	0.882	0.875	0.846	0.866	0.830

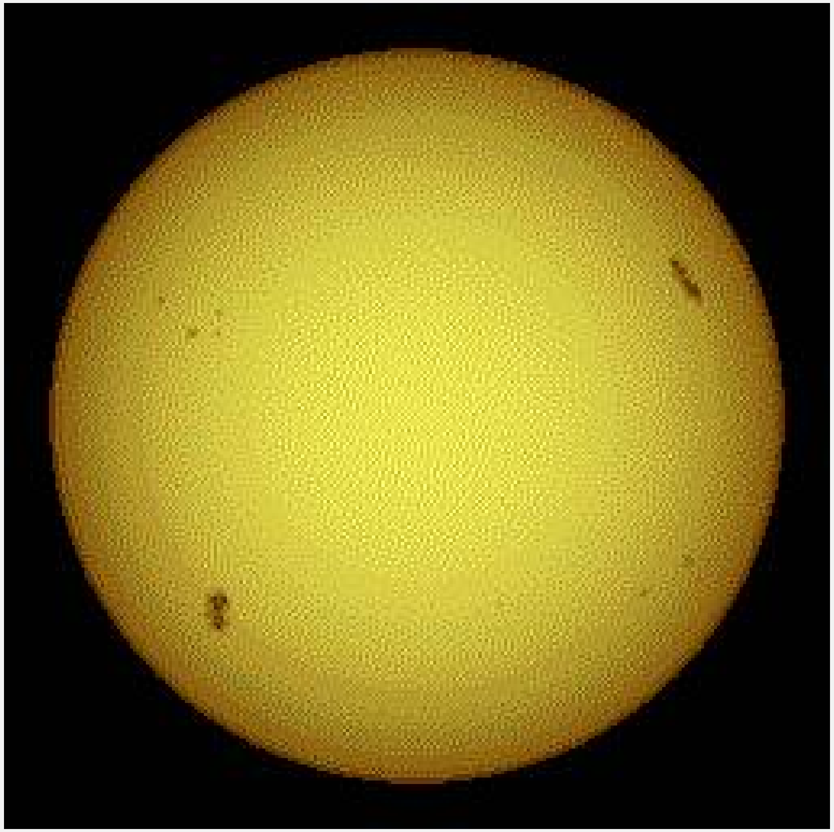
Temperature

$T_{spot}/T_{eff} = 0{,}84 \pm 0{,}10$



Contents

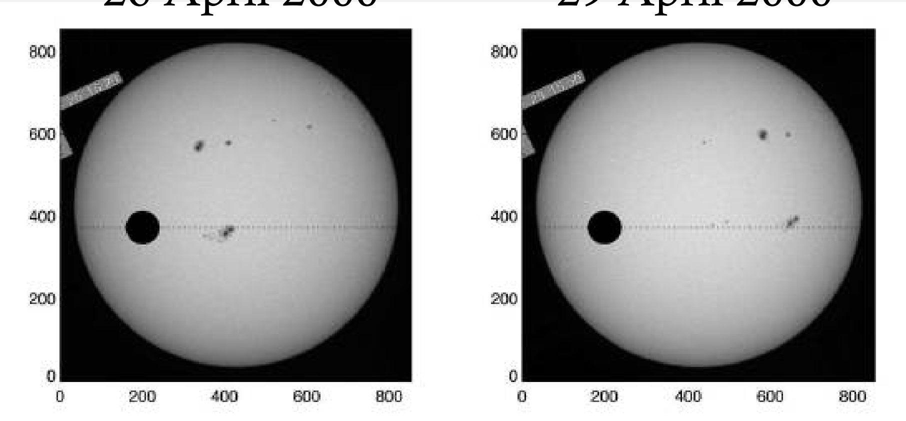
Solar Rotation

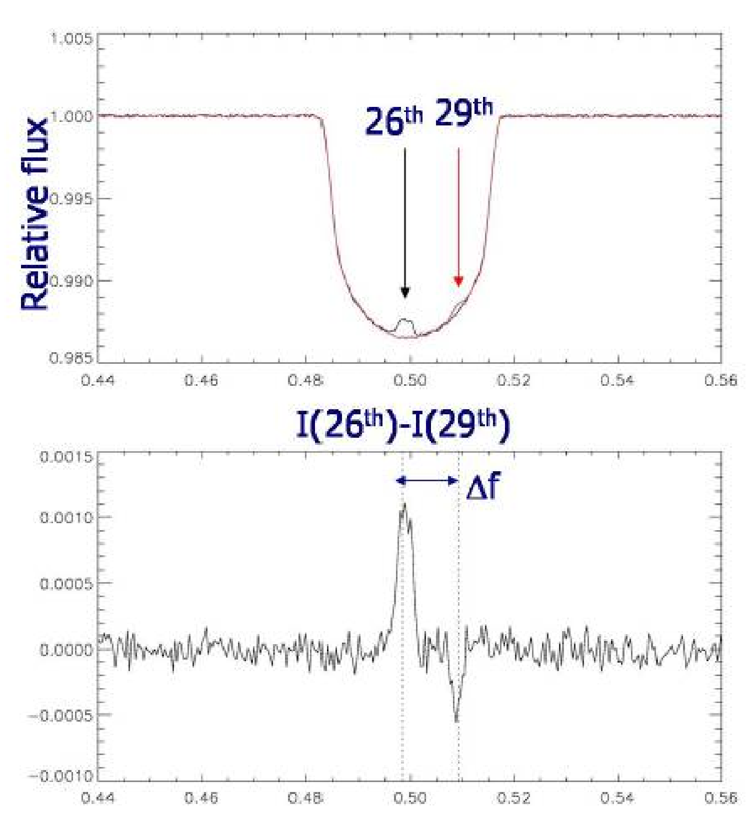


Rotation from transits

26 April 2000

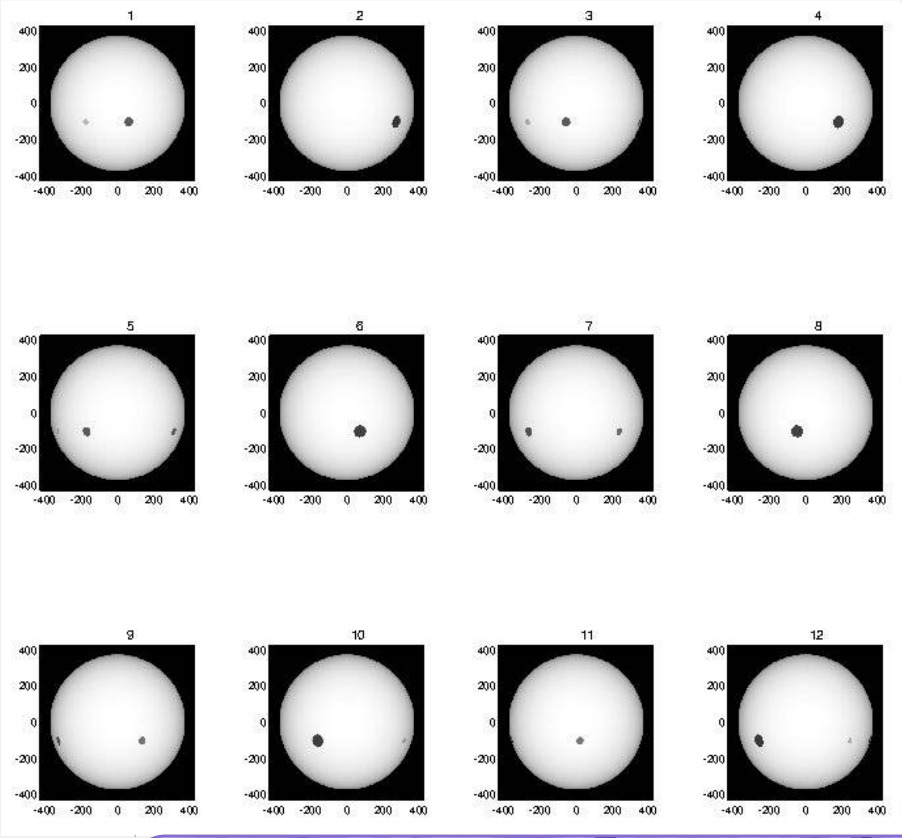
29 April 2000

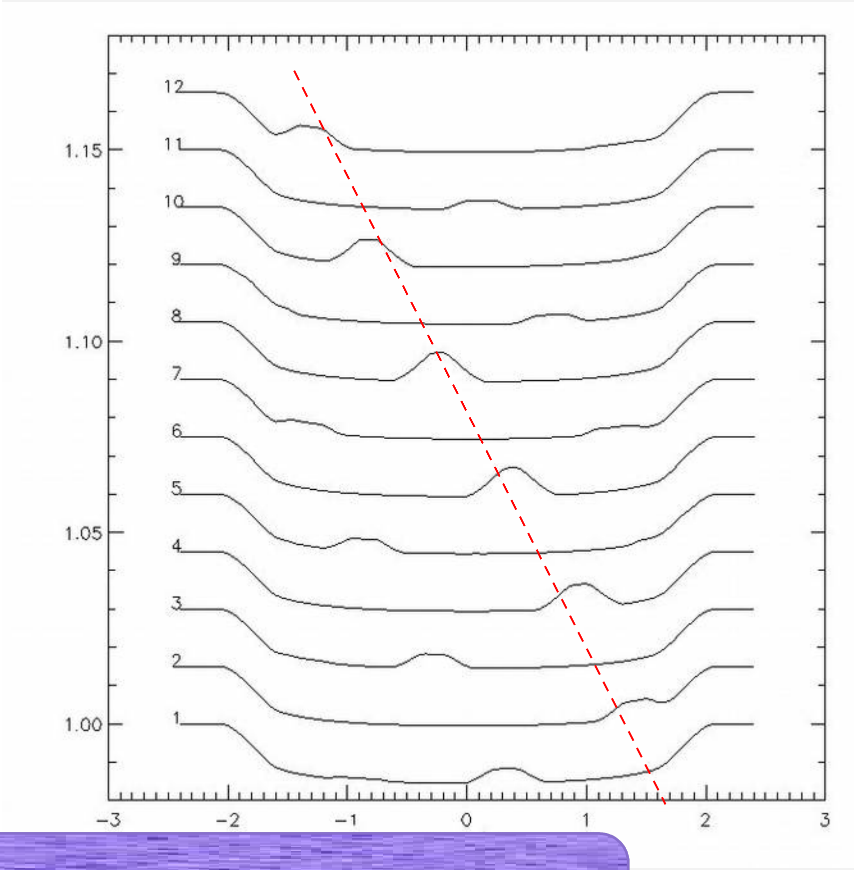




Silva-Valio (2008)

Simulation: 4 spots





- Porb = 8.88 d Average Prot= 6.35 d
- Prot at transit latitude = 6.03 d

Valio (2013)

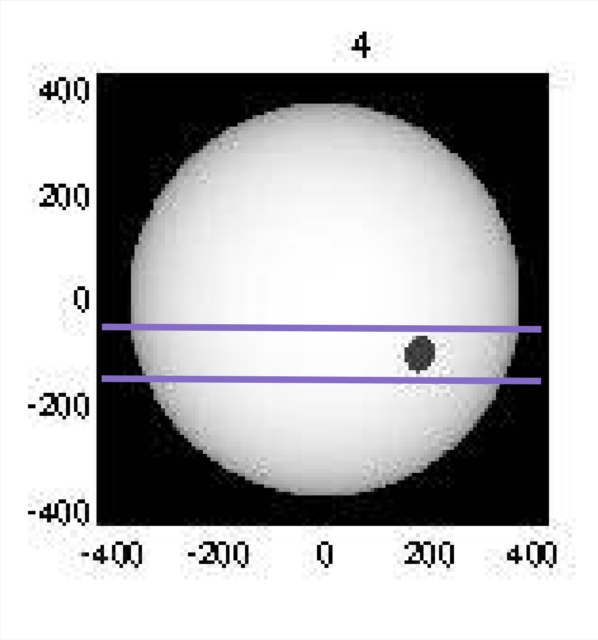
Rotational longitude

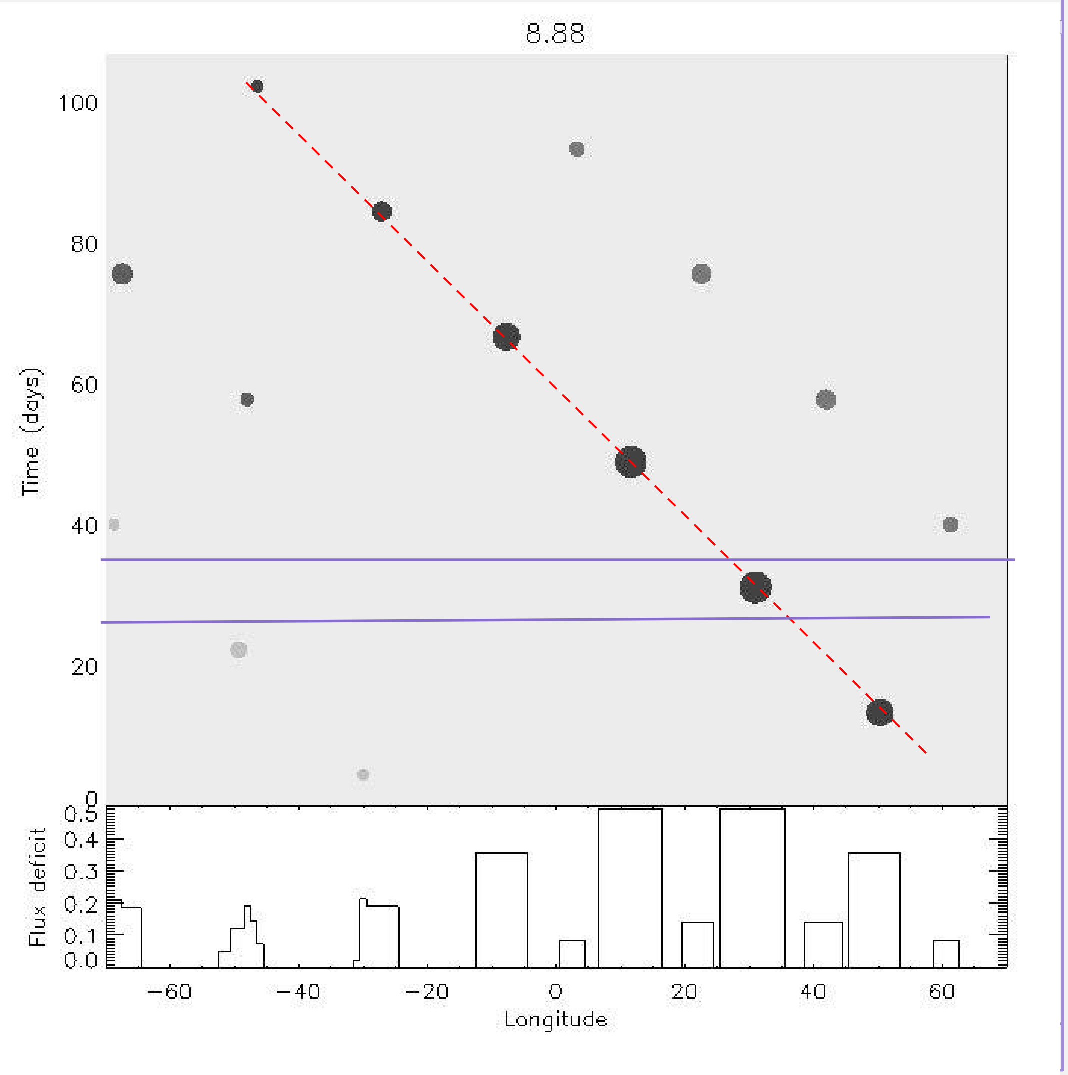
- Coordinate system transformation from Earth centered, β_{topo}, to a coord. system that rotates with the star with P_{rot}, β_{rot}

$$\beta_{rot} = \beta_{topo} - 360^o \frac{n\, P_{orb}}{P_{rot}}$$

- P_{orb} = orbital period (d)
- n = transit number
- Vary P_{rot} until spots align vertically in stellar surface map.

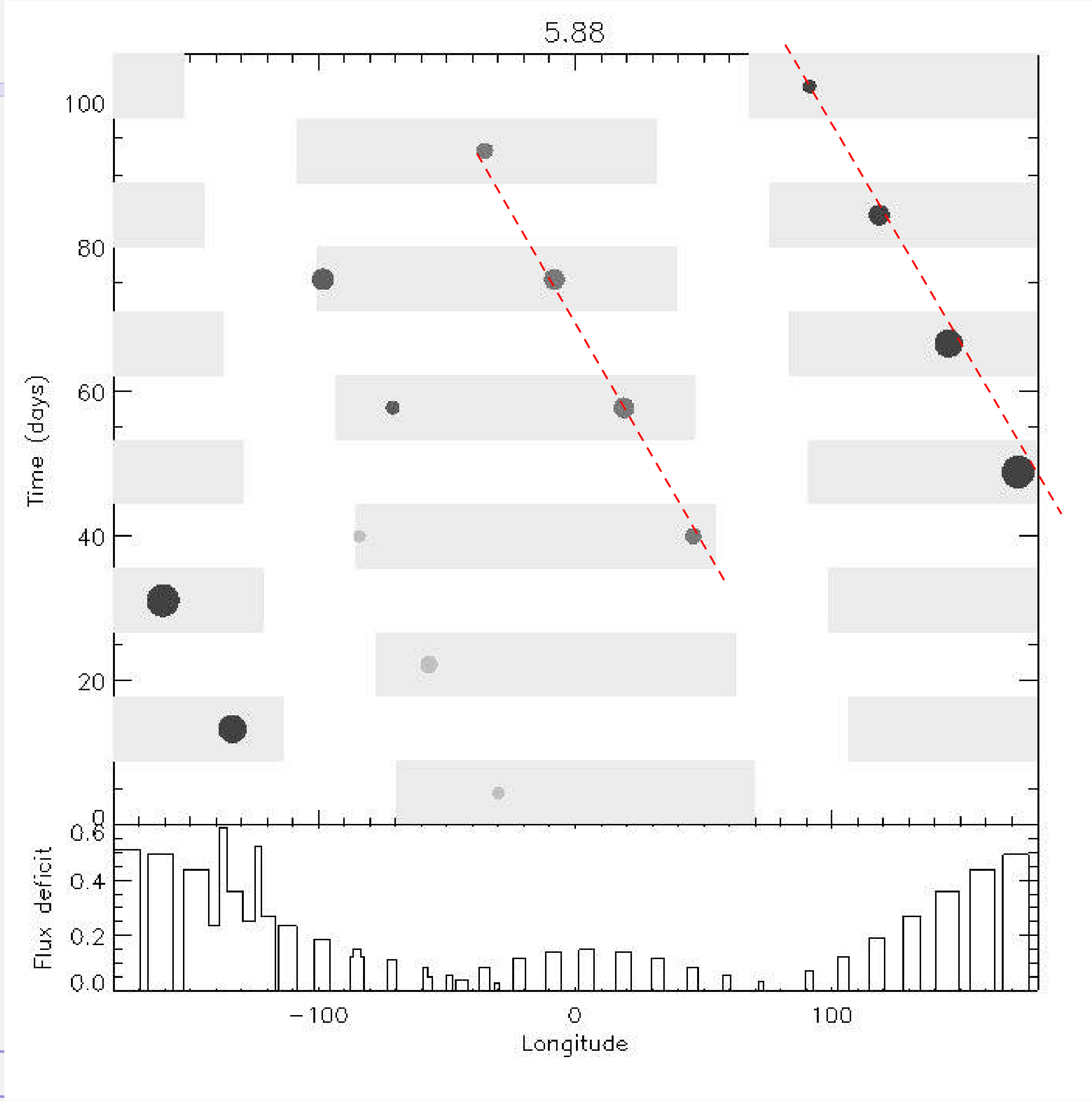
Stellar surface map





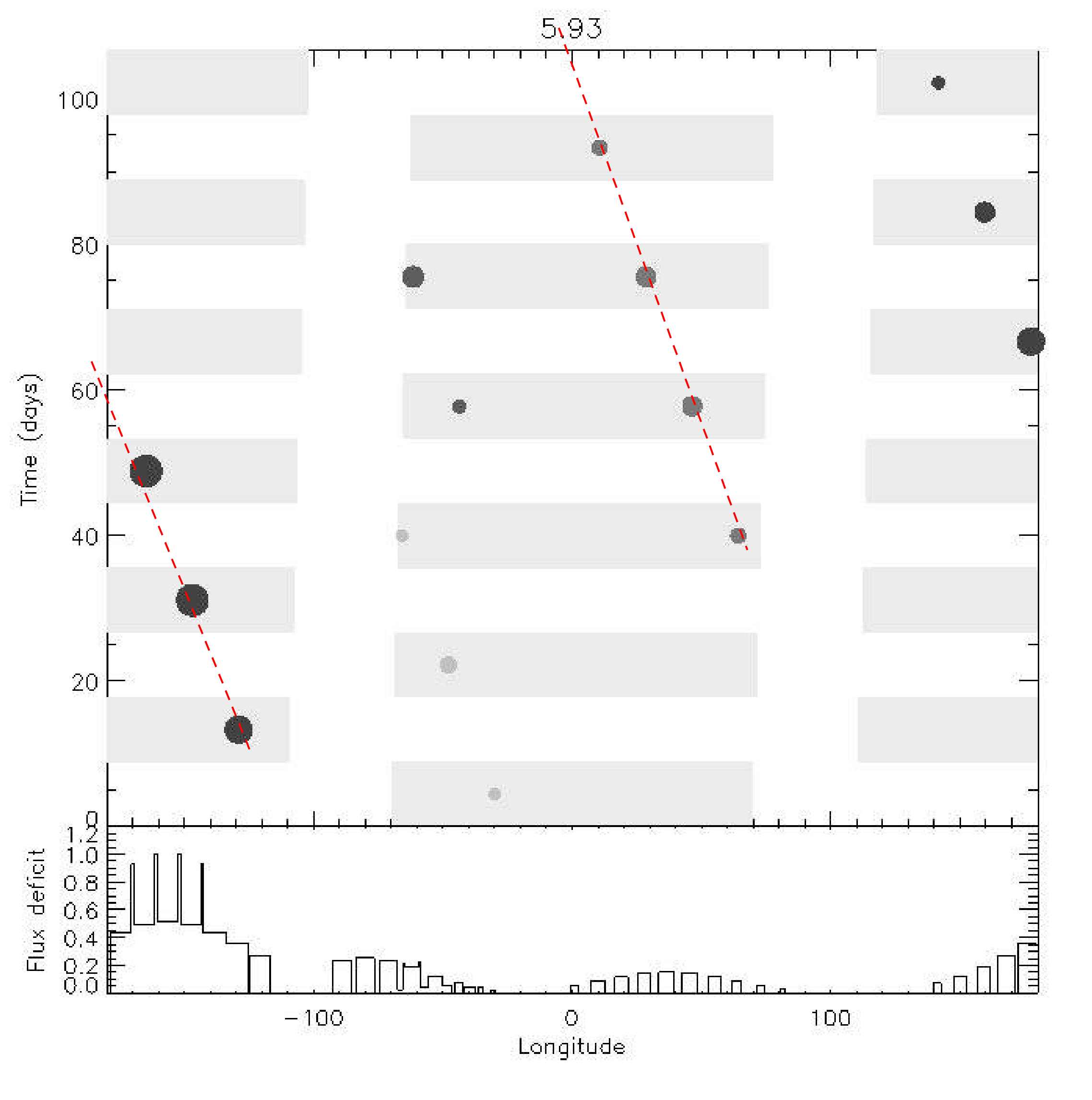
$$\beta_{rot} = \beta_{topo} - 360^o \frac{n P_{orb}}{P_{rot}}$$

P_{rot}=5.88 d



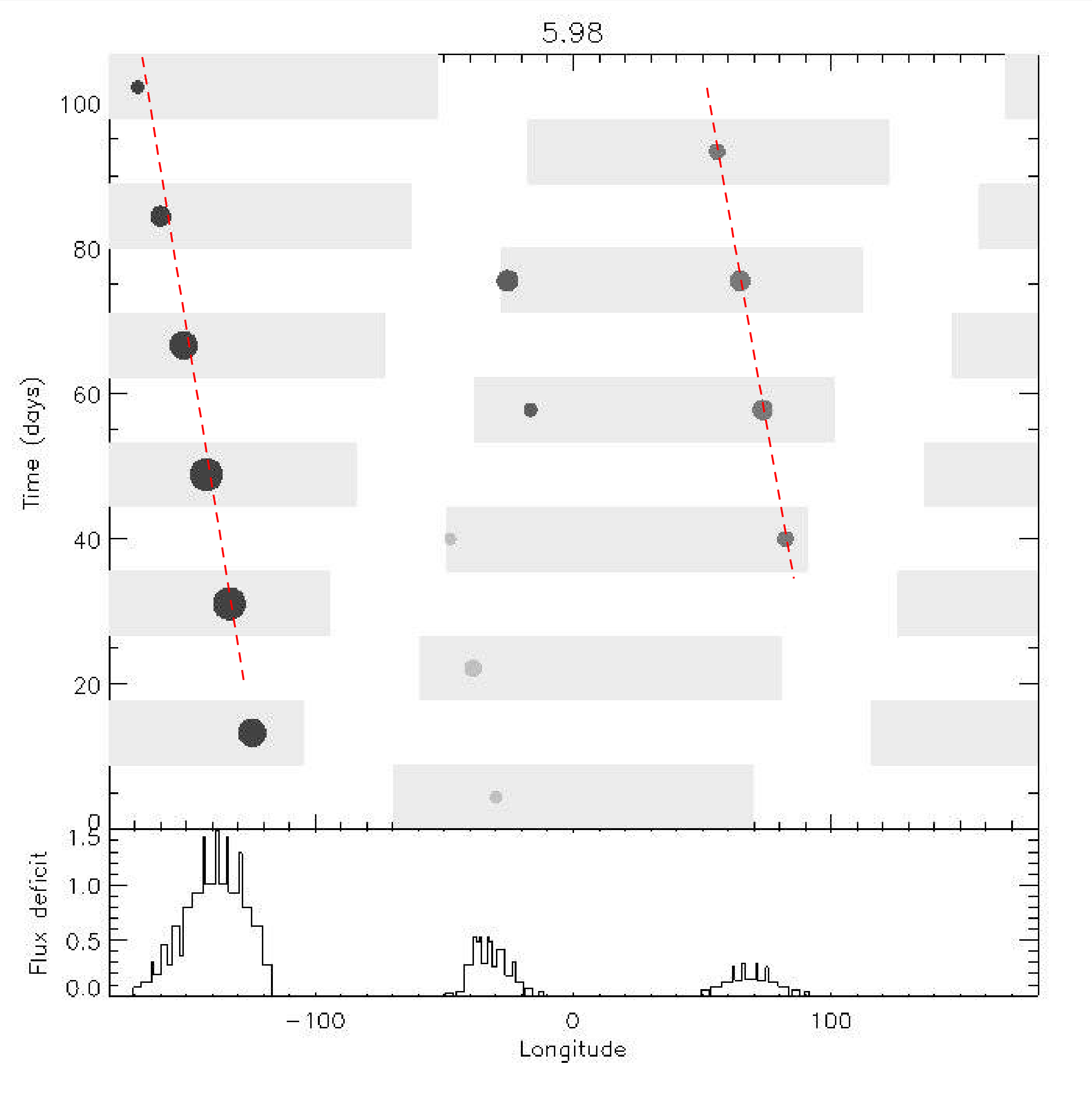
$$\beta_{rot} = \beta_{topo} - 360^{o}\frac{n\,P_{orb}}{P_{rot}}$$

P_{rot}=5.93 d



$$\beta_{rot} = \beta_{topo} - 360^o \frac{n P_{orb}}{P_{rot}}$$

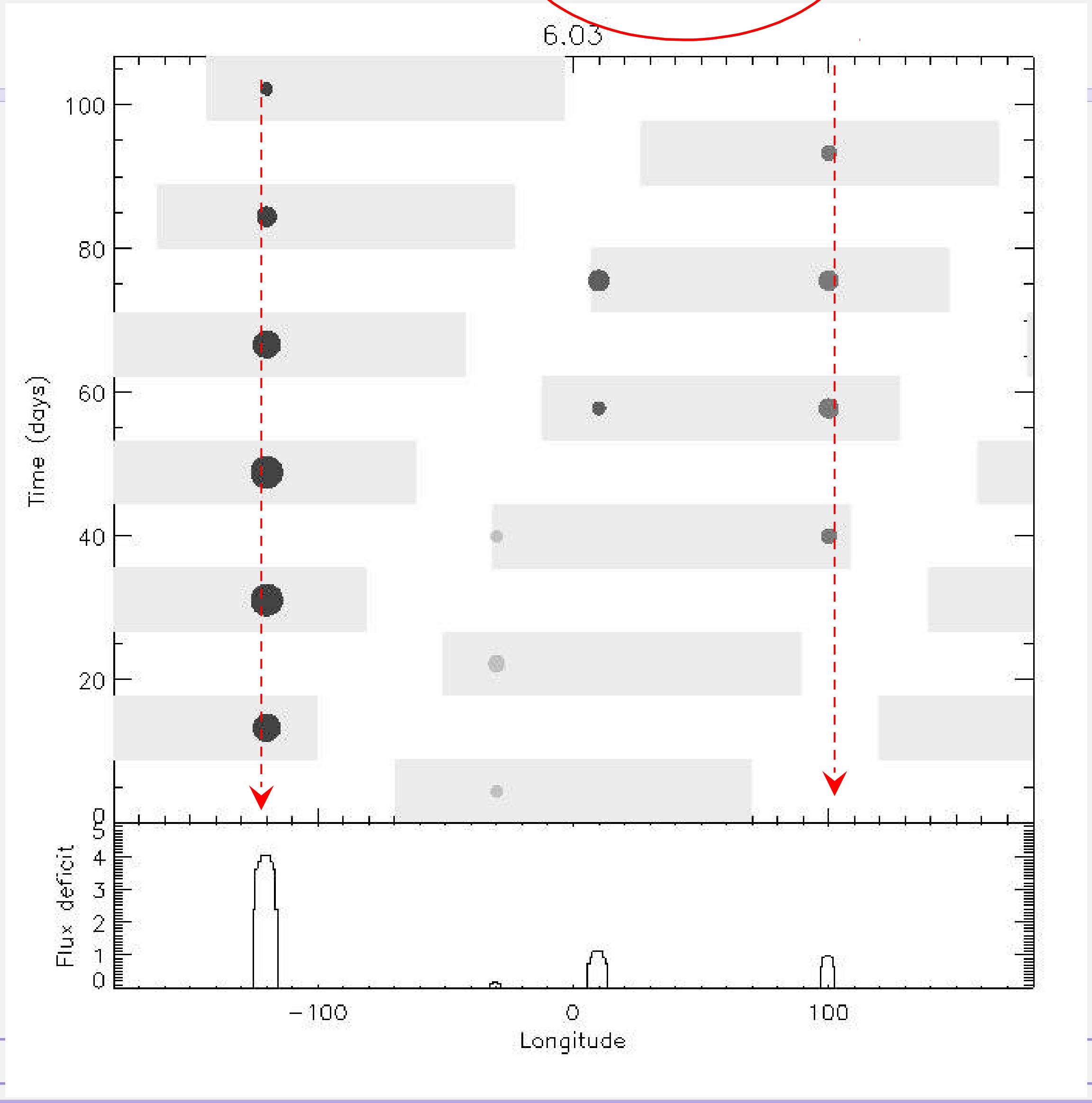
P_{rot}=5.98 d



$$\beta_{rot} = \beta_{topo} - 360^o \frac{n P_{orb}}{P_{rot}}$$

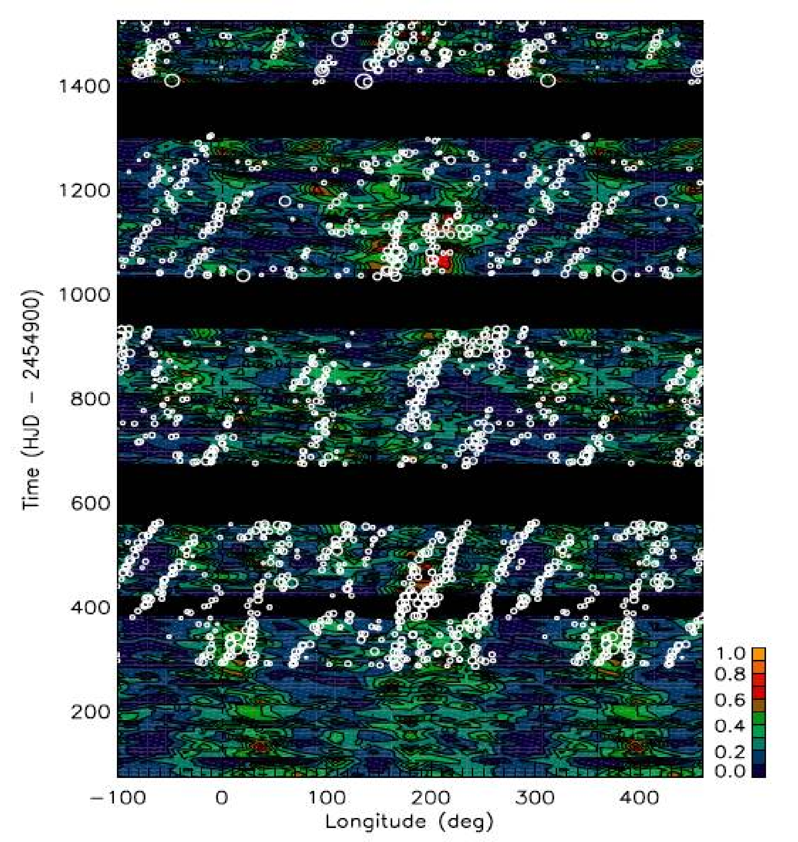
P_{rot}=6.03 d

P_{rot} at transit latitude

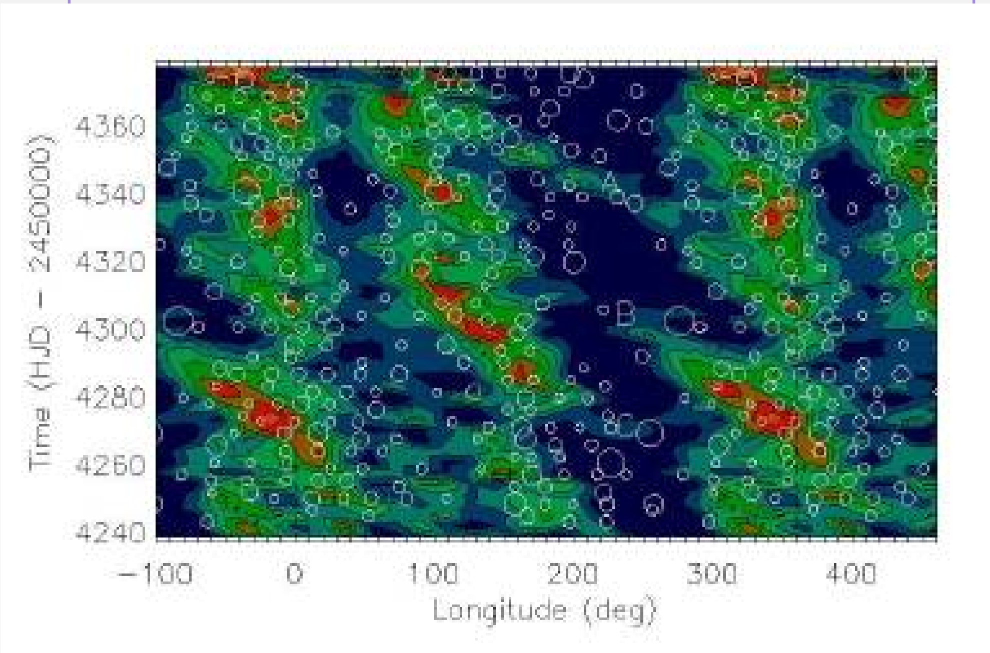


Out-of-transit X transit modeling

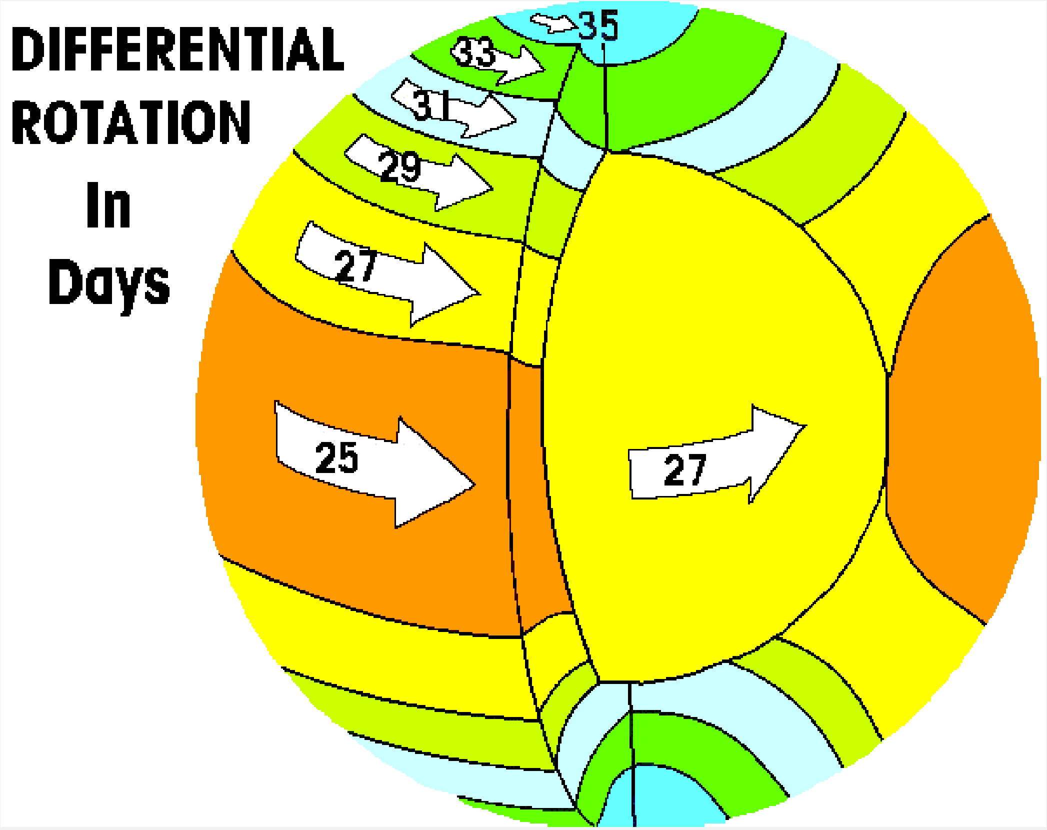
Kepler-17



CoRoT-2



Solar differential rotation



Yuri Netto

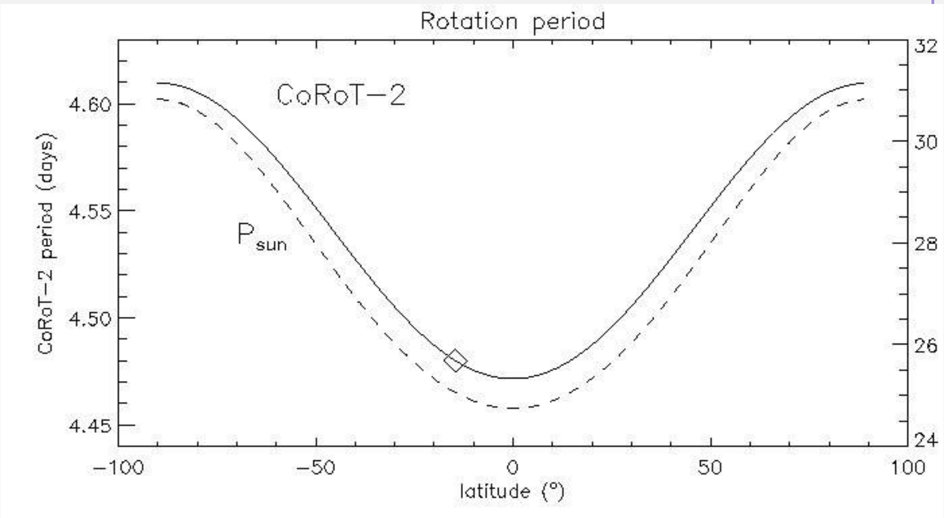
Differencial rotation

Coplanar orbit

- Assume solar profile

$$\Omega = A - B\sin^2(\alpha)$$

- where $P = \dfrac{2\pi}{\Omega}$



- Two measurements:
  - Average P_{rot} : $\Omega_0 = \dfrac{1}{\alpha_2 - \alpha_1}\displaystyle\int_{\alpha_1}^{\alpha_2}(A - B\sin^2\alpha)\,d\alpha$
  - P_{rot} at latitude α_1 (transit): $\Omega_1 = A - B\sin^2\alpha_1$
- Differential rotation : $\Delta\Omega$ (rd/d) = Ω_{eq} - Ω_{pole}
- Relative differential rotation: $\Delta\Omega/\Omega$ (%)

Stellar rotation

Star	CoRoT-2	CoRoT-4	CoRoT-6	CoRoT-18	Kepler-17	Kepler-71	Sun
Mass (M_{sun})	0.97	1.10	1.055	0.95	1.16	0.997	1.0
Latitude (°)	-14.6	0	-16.4	-22.8	-4.6	-5.4	0
P_{rot} (d)	4.54	8.87	6.35	5.4	12.28	19.77	27.6
P_{rot}(lat) (d)	4.48	8.71	6.08	4.68	11.4	19.71	
Diff Rot (rd/d)	0.042	0.026	0.101	0.45	0.077	0.005	0.050
Relat Diff Rot. (%)	3.04	3.64	10.2	38.0	15.0	< 2	22.1
P_{equat} (d)	4.47	8.53	5.98	4.5	11.4	19.67	24.7
$P_{orb} : P_{equat}$	2 : 5	1 : 1	3 : 2	2 : 5	1 : 8	1 : 5	

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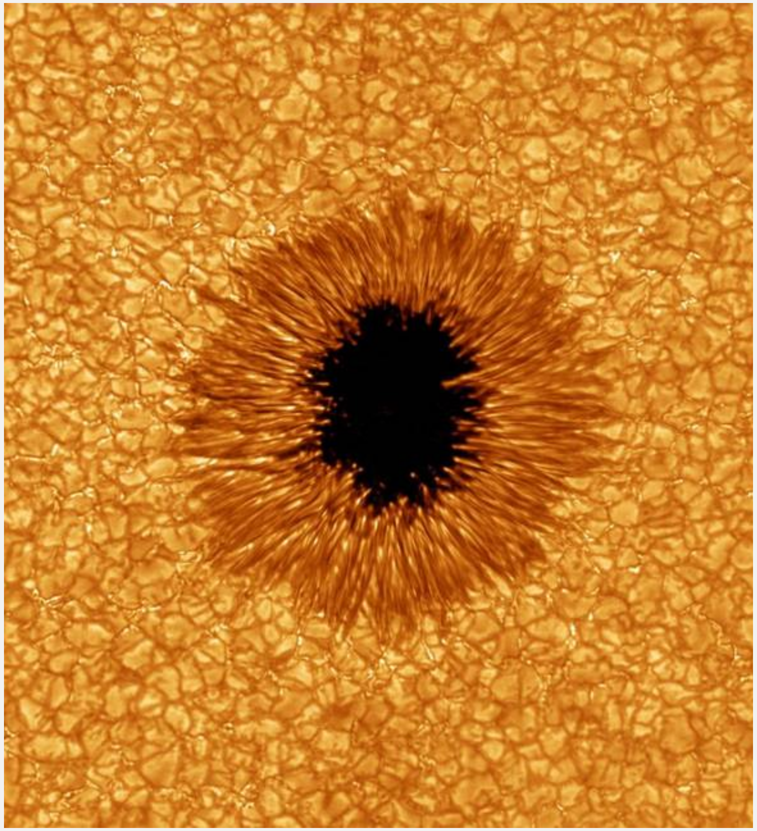
- Model
- Spots characteristics
- Stellar rotation & differential rotation
- Magnetic field & magnetic cycles
- Flares and biological impact
- Summary & conclusions

Sun

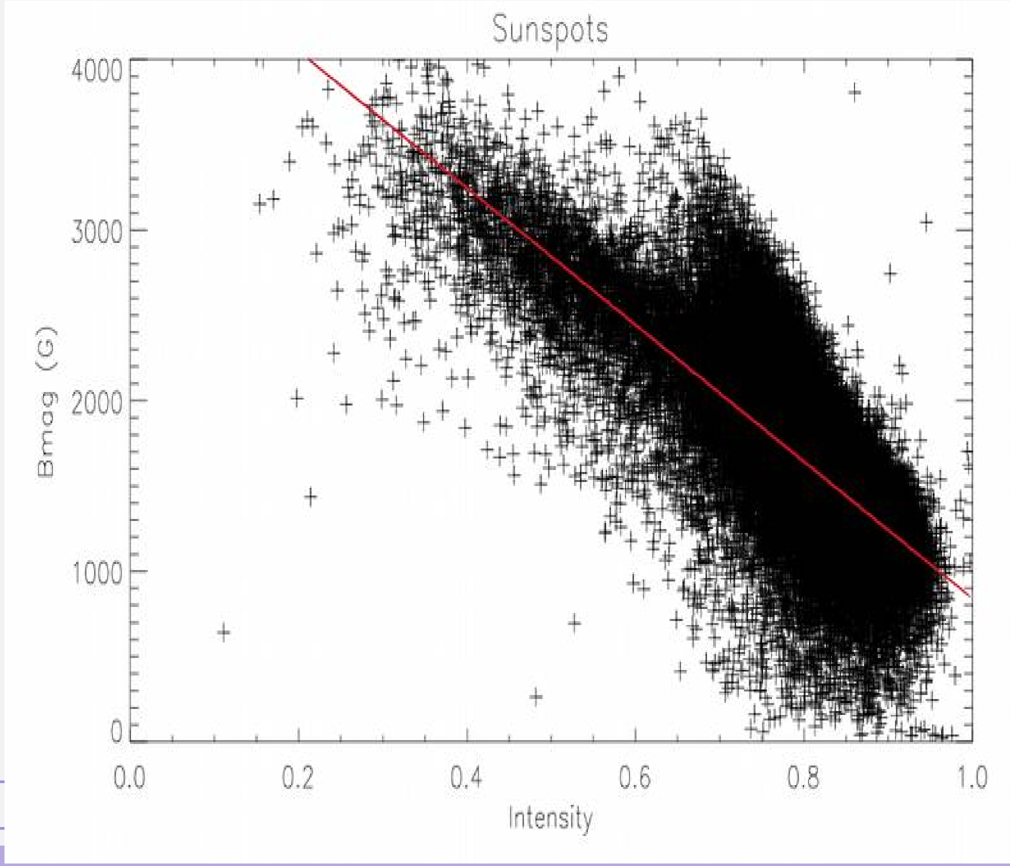
Eduardo Spagiari

- 32,317 sunspots from 6970 SOHO/MDI images and magnetograms (cycle 23: 1996-2008)



Sunspots characteristics

$$B_{mag} = (4848 \pm 15) - (4008 \pm 20) \cdot \frac{I_{spot}}{I_{star}}$$



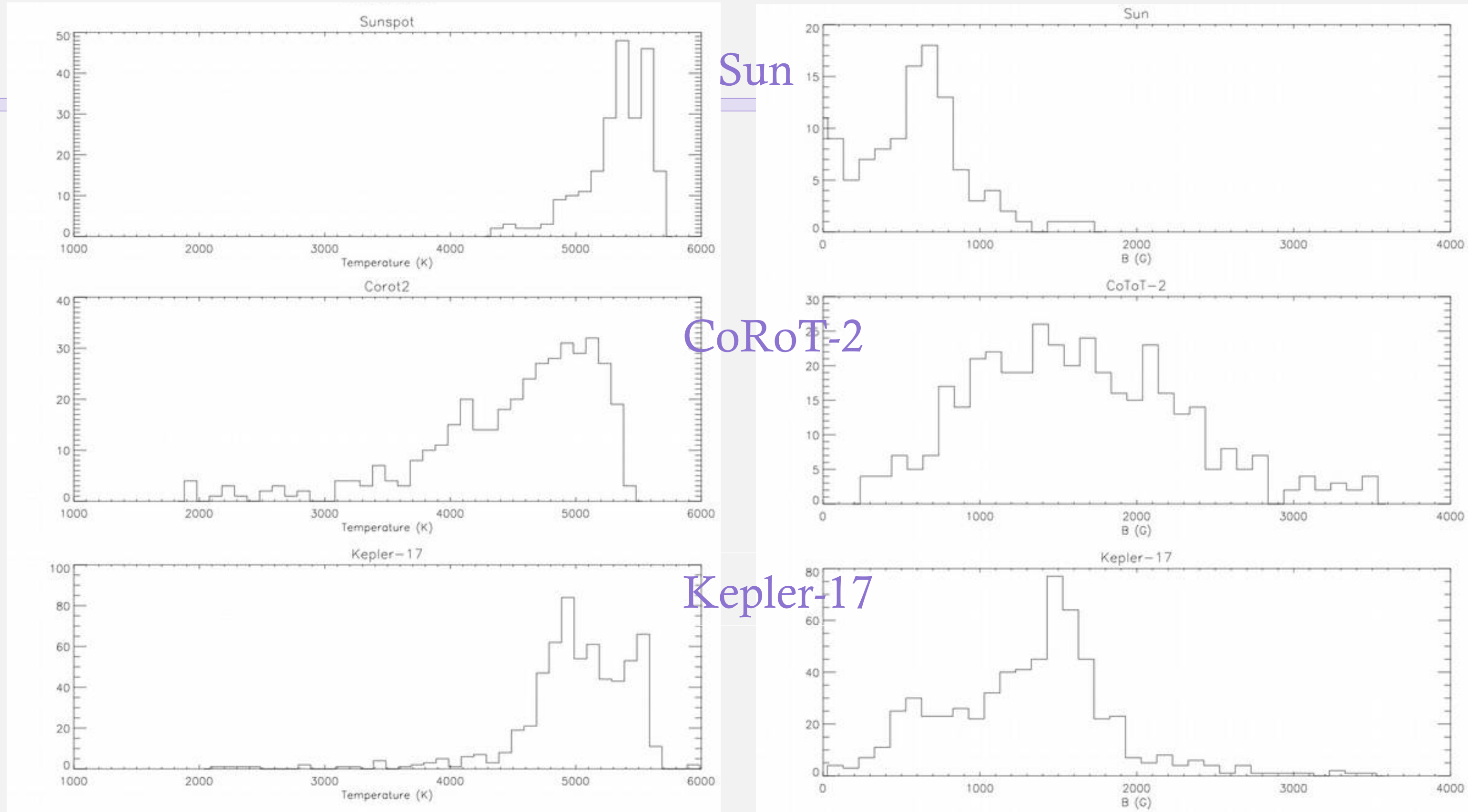
Spagiari et al. (2019)

Other stars

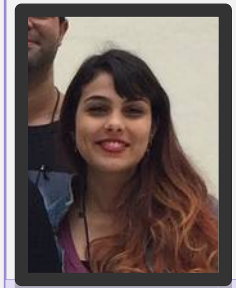
- Four stars with transiting planets were analyzed;
- Small variations in the transit light curves of these stars have been fit yielding the characteristics of:
  - 392 spots - CoRoT-2
  - 1069 spots - Kepler-17
  - 297 spots – Kepler-63
  - 76 spots – Kepler-71
- Spot intensity => Magnetic Field

$$B_{mag} = (4848 \pm 15) - (4008 \pm 20) \cdot \frac{I_{spot}}{I_{star}}$$

B_{max}

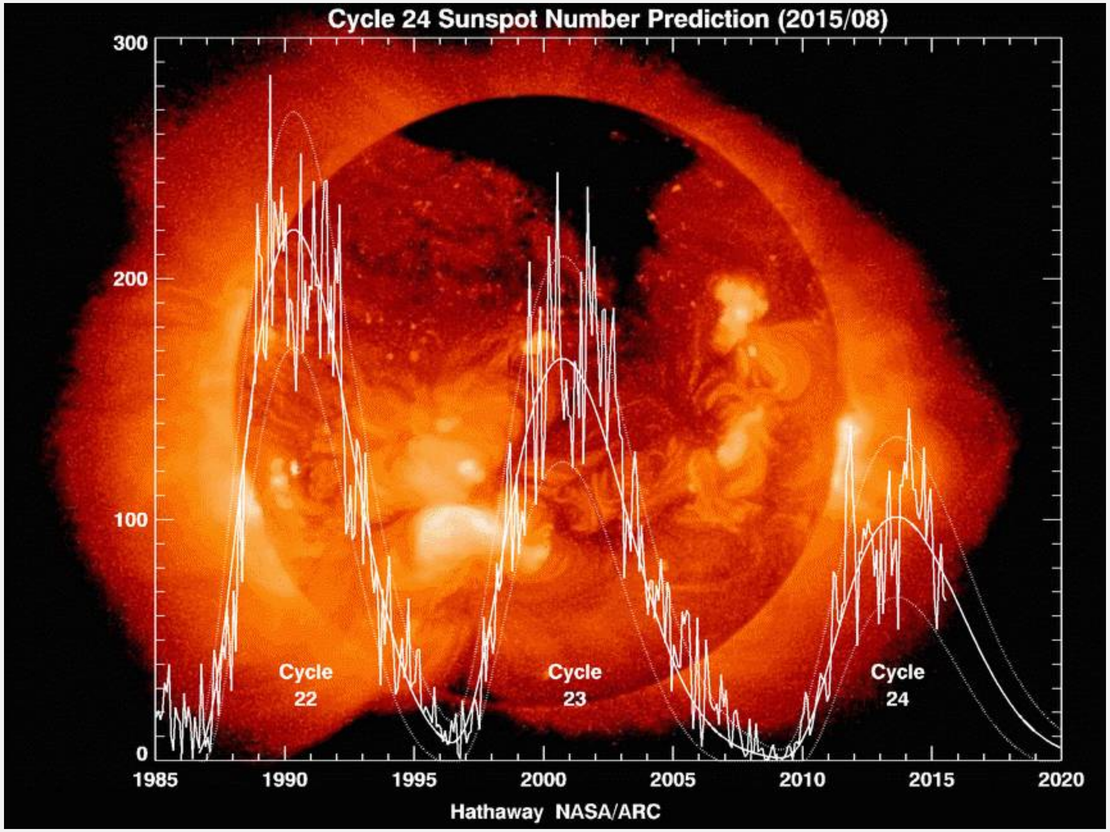


Star	CoRoT-2	Kepler-17	Kepler-63	Kepler-71	Sun
Radius(Mm)	55±19	80±50	32±14	51±26	12±10
Area (%)	13	11	14	4	< 1
Tspot (K)	4600±700	5100±500	4700±400	4800±500	4800±400
B_{max} (G)	3000±1000	2650±800	2950±600	2600±900	1700±600



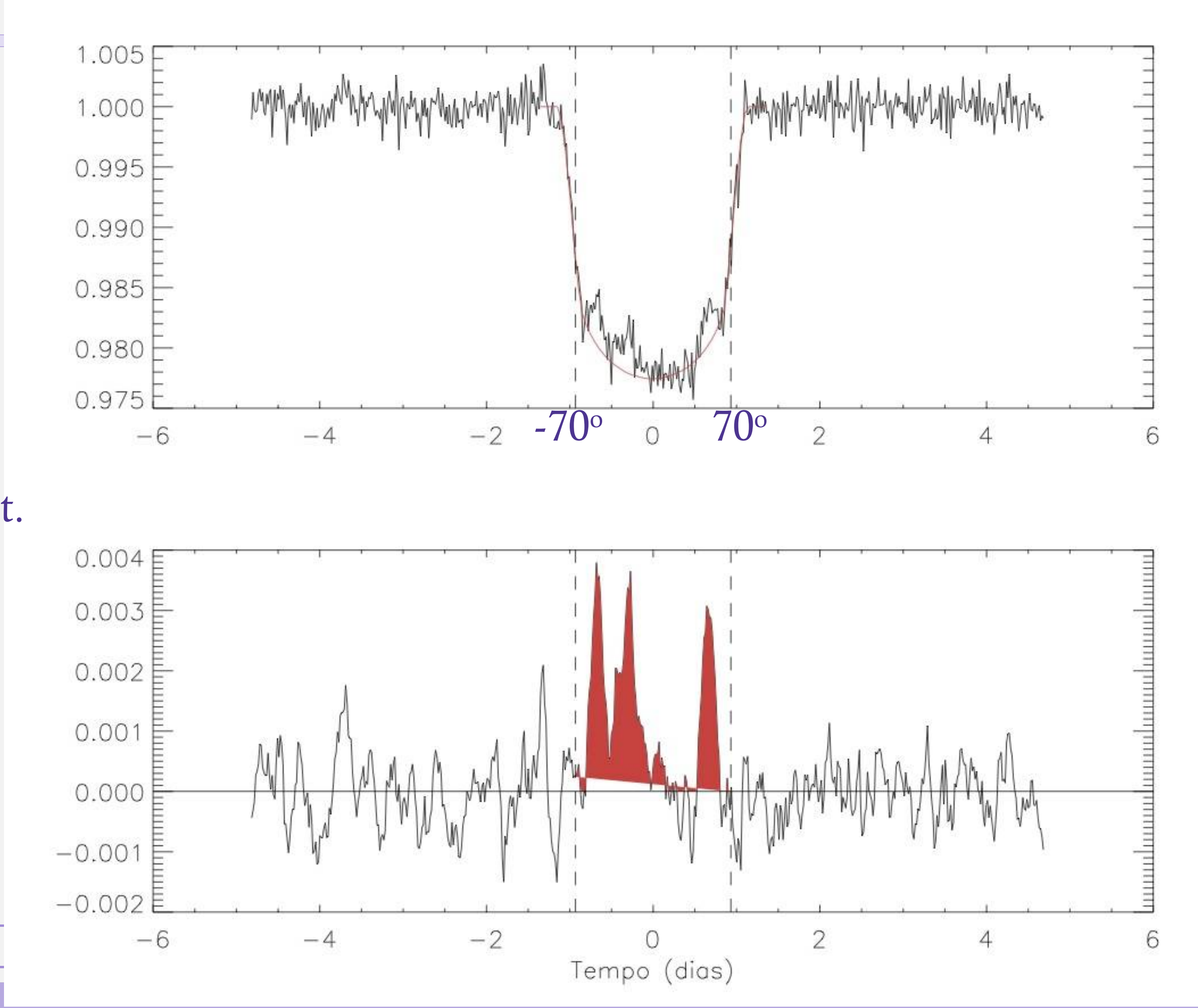
Raissa Estrela

Magnetic Cycles

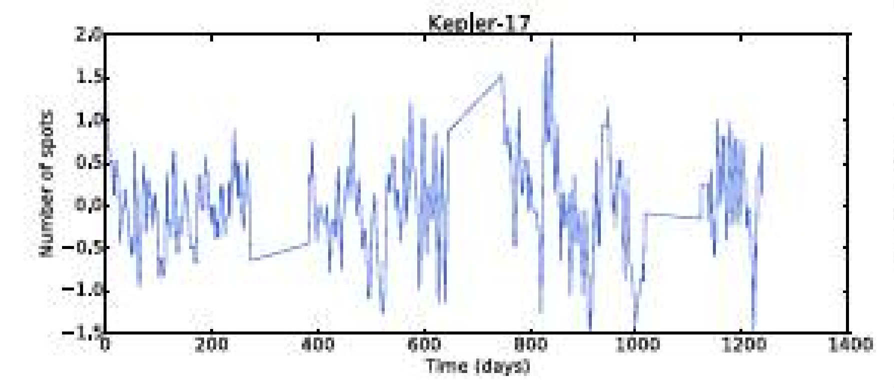


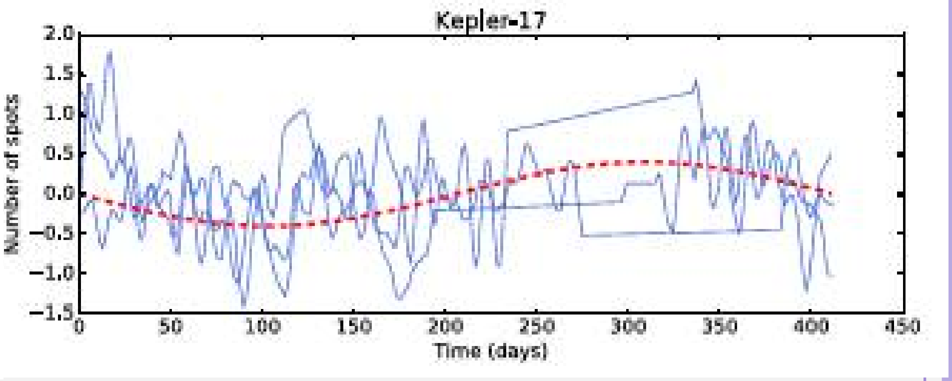
Magnetic activity

Kepler-17
100th transit.

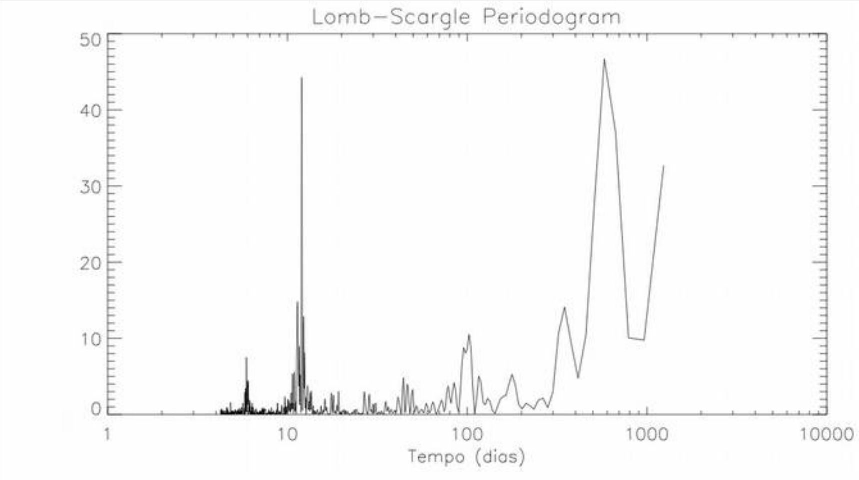


Magnetic cycle: Kepler-17



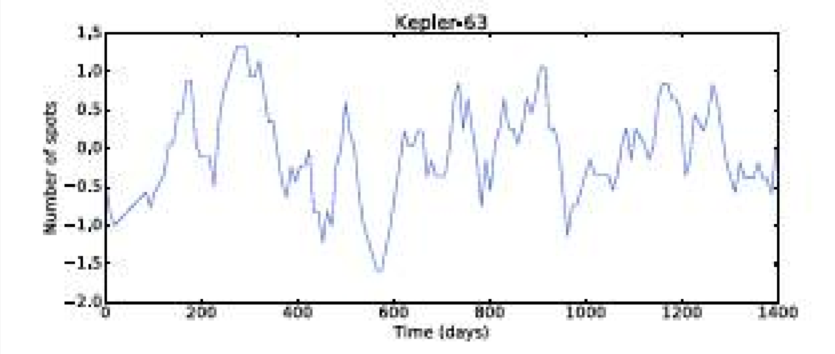


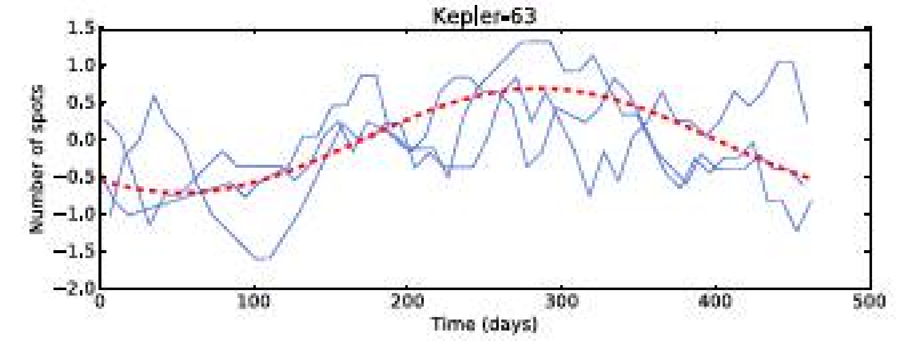
- Magnetic cycle of 410 days or 1.13 yr



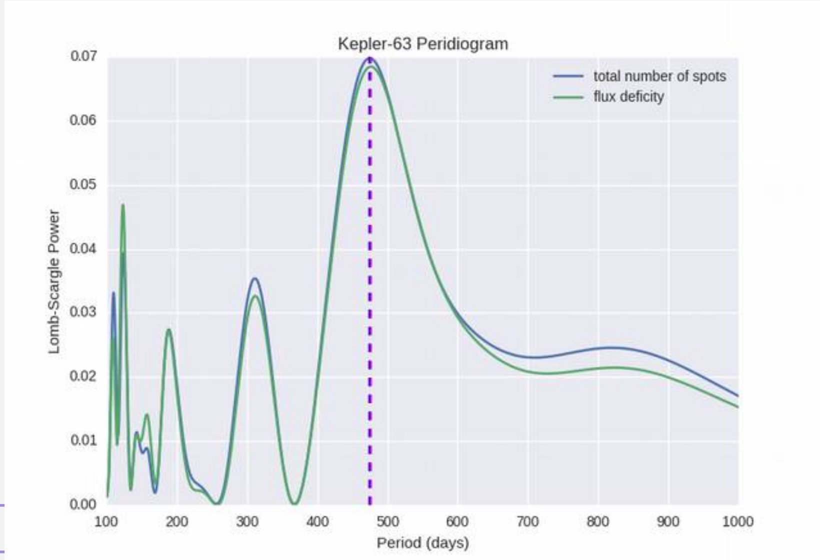
Estrela & Valio (2016)

Kepler-63

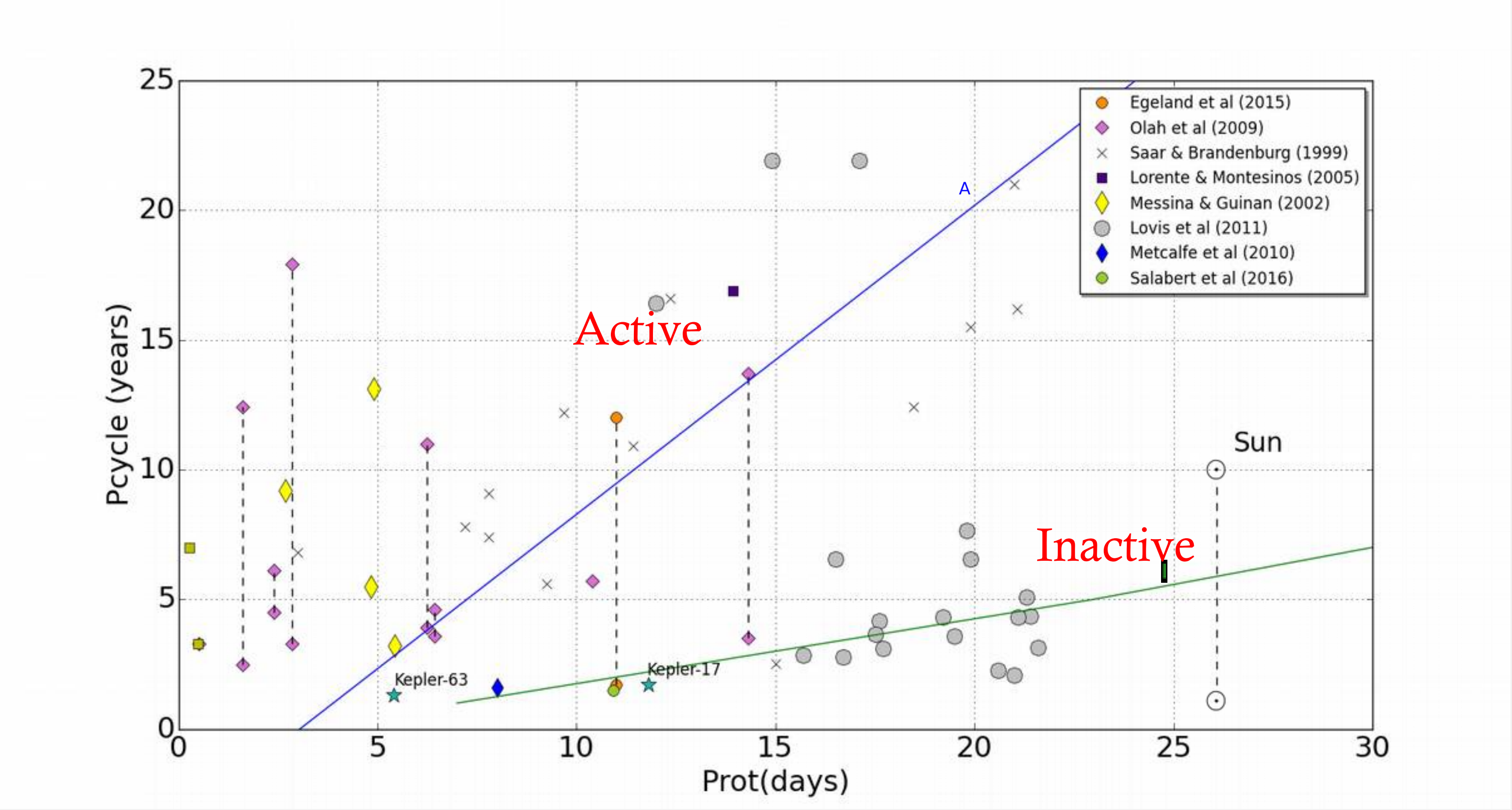




P = 1.3 yr
= 460 days



P_{cycle} x P_{rot}



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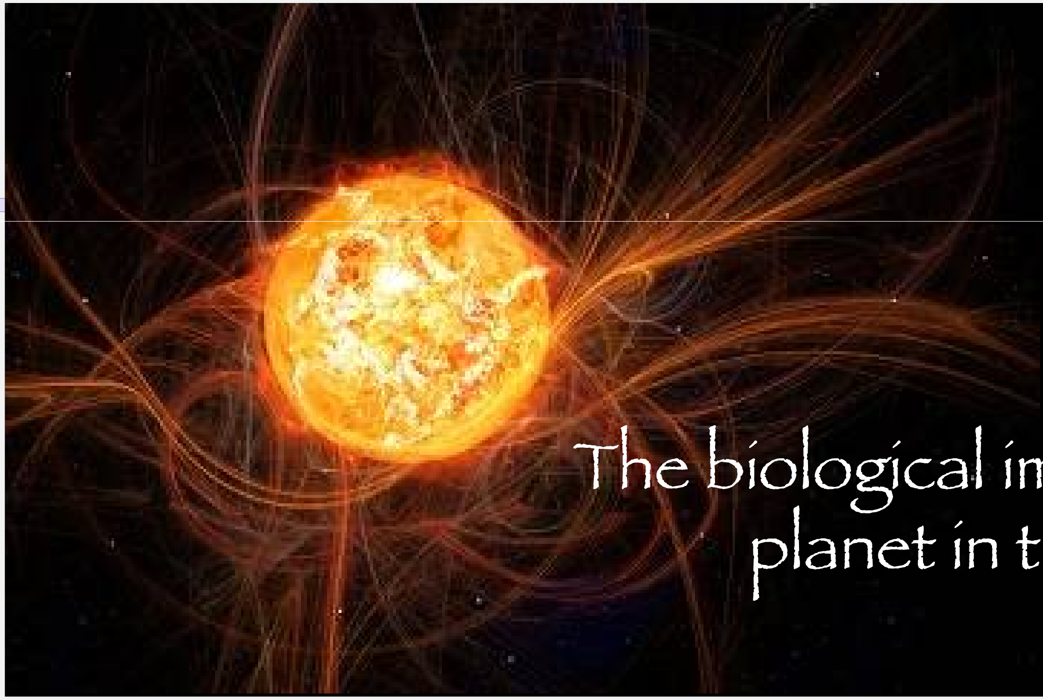


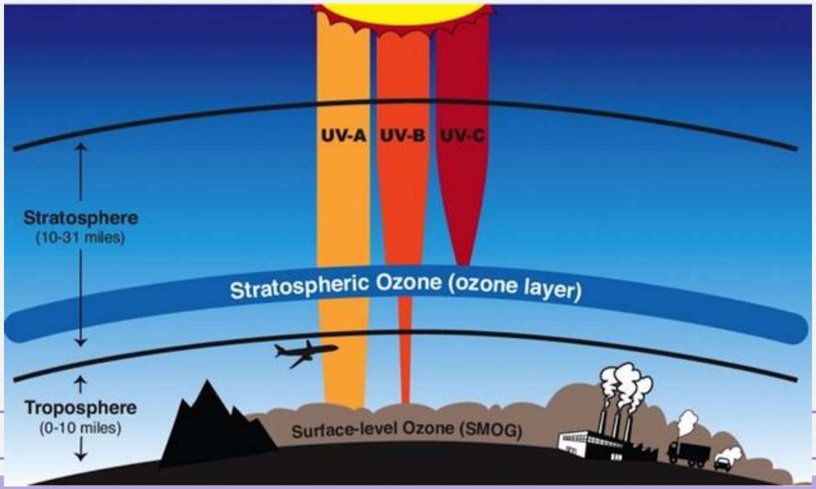
The biological impact of superflares on a planet in the Habitable Zone

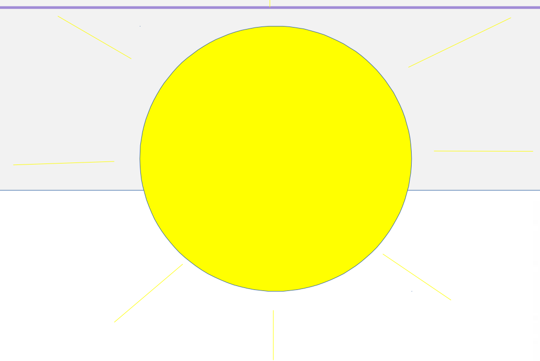
Raissa Estrela and Luisa Cabral

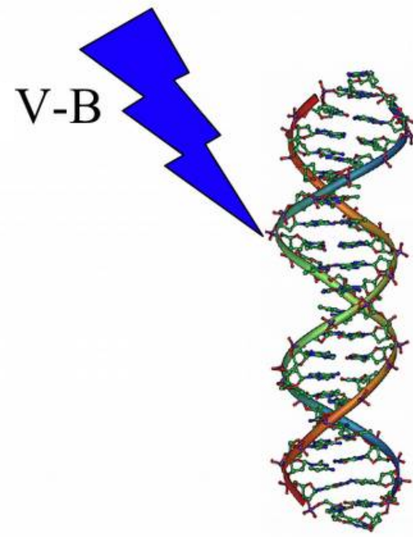
Superflares effects on habitability

- Superflares release significant amounts of X-rays, EUV, and UV radiation
- Depending on the energy of the flare, they can cause changes in the planetary atmosphere:
  - Atmospheric loss
  - Alter 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







• Goal:

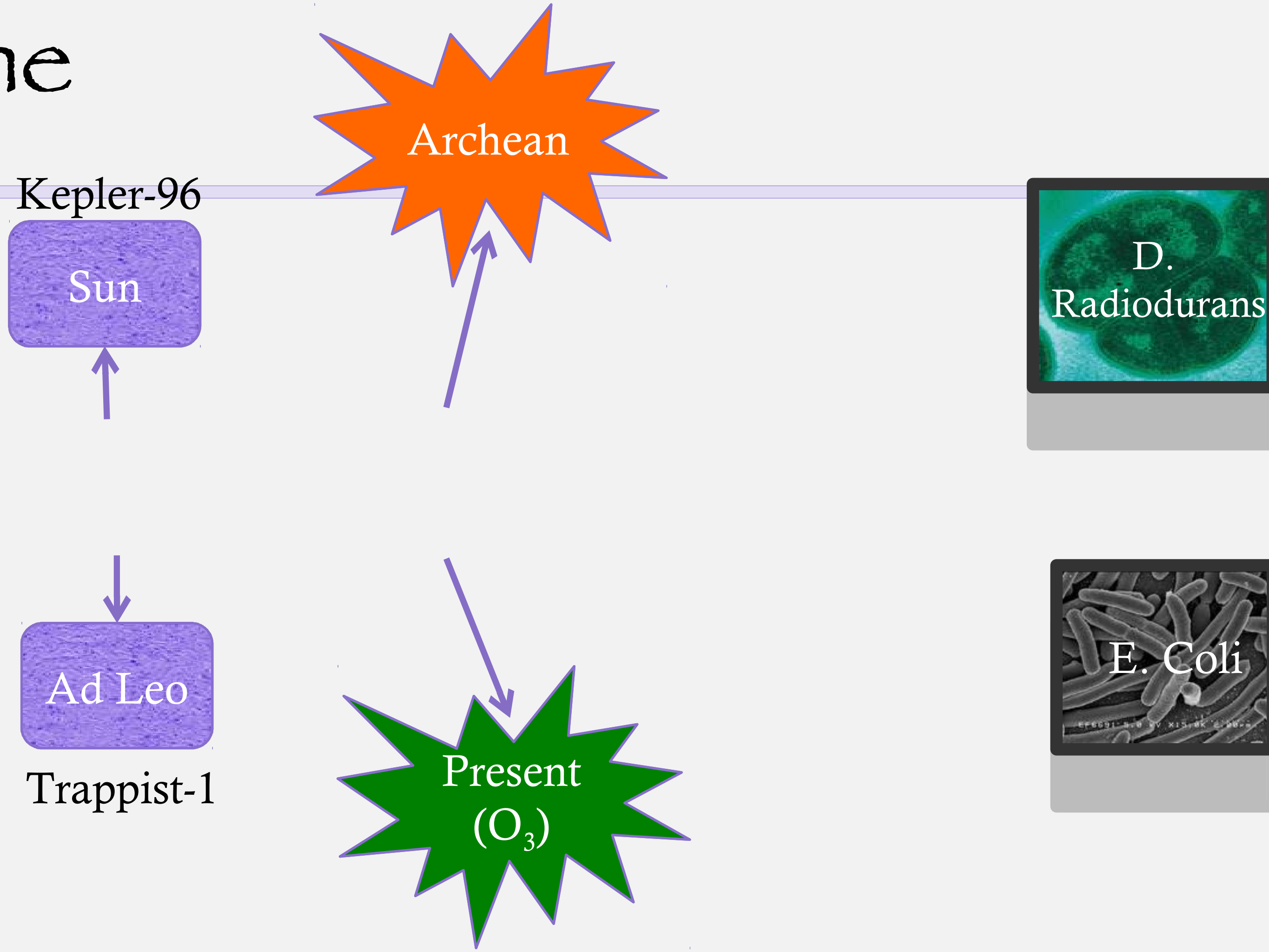
Determine if the superflares can be dangerous to life present in the surface/ocean of:

★ Hypothetical planet in the habitable zone of Kepler-96

★ Kepler-96b ← Not habitable at all!
High temperature ~ 2000 / 3000K

★ Trappist-1: 3 planets in the HZ

Outline



Kepler-96
Sun
Archean
D. Radiodurans
Ad Leo
Trappist-1
Present (O_3)
E. Coli

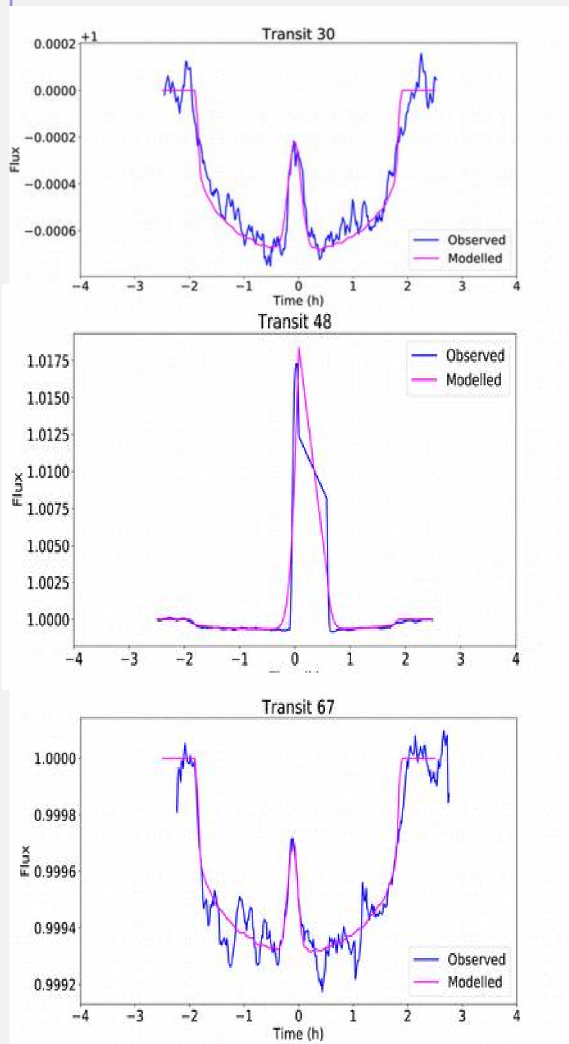
Kepler-96 has an age that corresponds to the end of the Archean Era on Earth

Great Oxygenation Event

This can be used as a proxy to understand:

1) the primitive Earth environment
2) a planet in HZ with Archean conditions
(assuming it had enough time to evolve)

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

First approach: analogy with the Sun

To analyse E_{eff}, we used the UV flux (180-300nm) passing through atmospheres at different epochs in Earth:

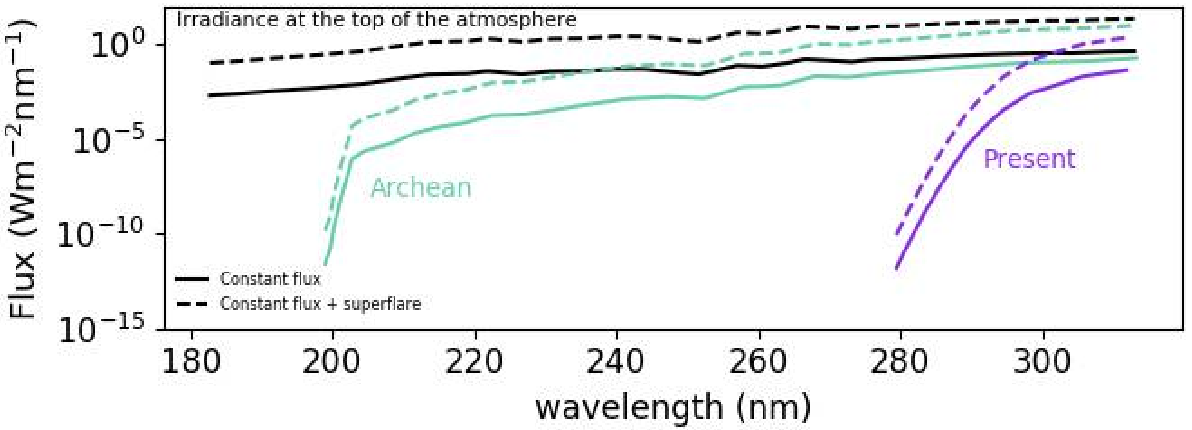
- Archean (3.9 Gyr – 2.5 Gyr): 80% N_2, 20% CO_2
- Present day: 80% N_2, 20% O_2

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

Solar Flare X17 28 October 2003 (12%): **5400%** the MUV flux due to superflare



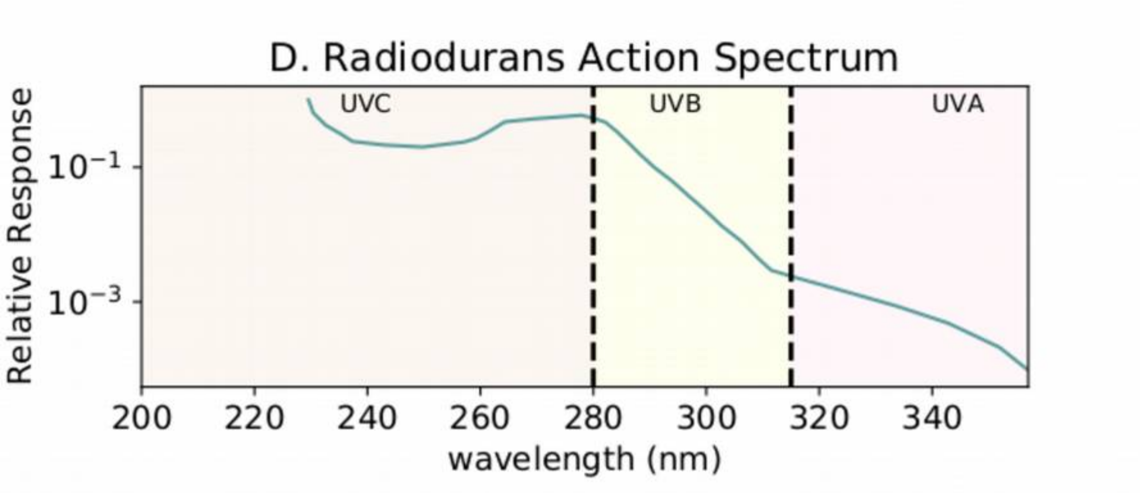
Biological Impact

- Superflares can increase the UV flux of the star
- If a planet has an atmosphere with absorbers N_2, CO_2, O_2 :

short wavelengths (0.1-200nm) are attenuated at the top of the atmosphere

EUV VUV

- UVB and UVC can be attenuated by an ozone layer. For a depleted ozone layer:



The DNA is mainly damaged in the UVC and UVB range ~ MUV (200-300nm)

Based on Setlow et al. (1965), Calkins (2013) and O'malley & Kaltenegger (2017)

Biological Impact: surface

Biological effective irradiance from Kepler-96, E_{eff} [J/m^2] Contribution of the **strongest** superflare (10^{35} erg)			
	No atmosphere	Archean atmosphere	Present-day atmosphere
E. Coli	1.4×10^5	2×10^4	22
D. Radiodurans	8×10^4	1.3×10^4	7.5
Contribution of a smaller superflares (10^{33} erg)			
E. Coli	3×10^3	455	0.5
D. Radiodurans	2×10^3	282	0.16

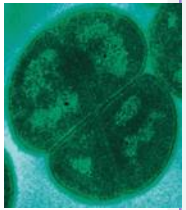
$$E_{eff} = \int_{180}^{300} F(\lambda) S(\lambda) d\lambda$$

→ Only with ozone

→ D. Radiodurans could survive in an Archean atmosphere

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 (2005)
Gascón et al (1995)

Biological Impact: ocean

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

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

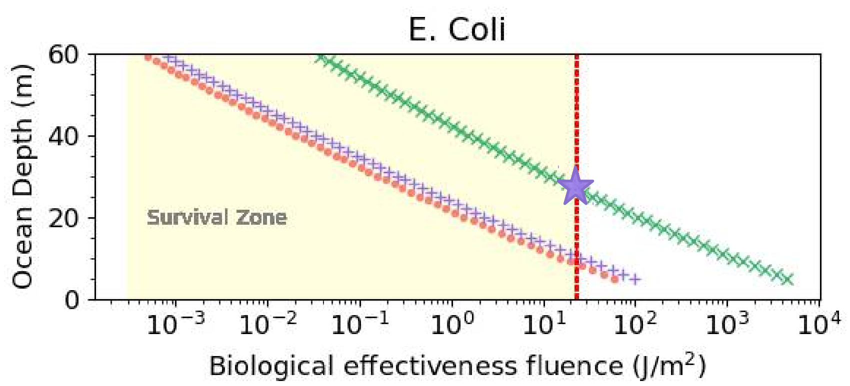
- UV spectral irradiance at depth z
- UV with the superflare contribution
- Diffuse attenuation coeficient
- Ocean depth

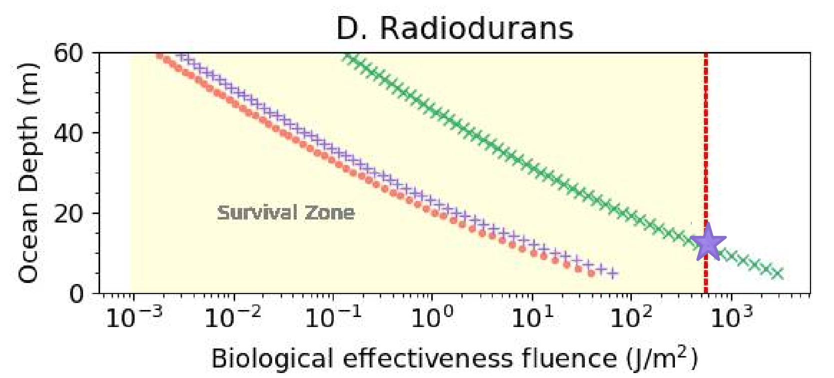
- For Kepler-96 system, the ocean might provide a safe refuge against the UV radiation.
- We assume here that the hypothetical Earth orbiting the star Kepler-96 has an Archean ocean where life could be protected.

Estrela & Valio (2018), Astrobiology
arXiv:1708.05400

Biological Impact: ocean

Considering the UV flux increased by the strongest superflare: Planet at 1AU



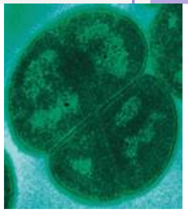


Ocean Depth (m) 28 m → E. Coli 12 m → D. Radiodurans

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

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

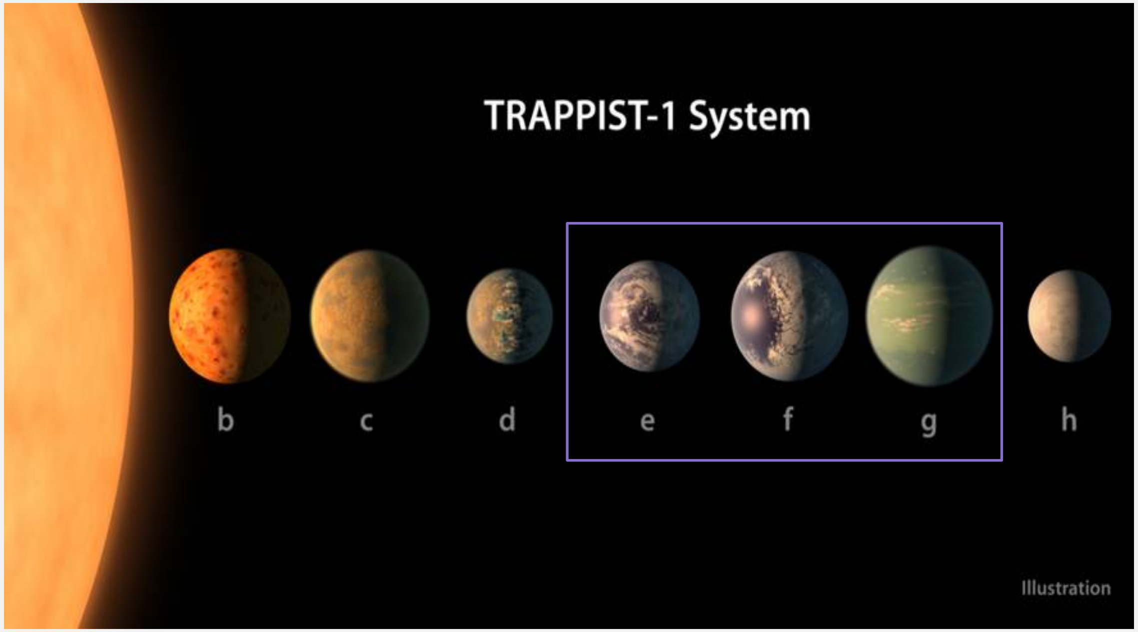
Deinococcus radiodurans



Escherichia coli

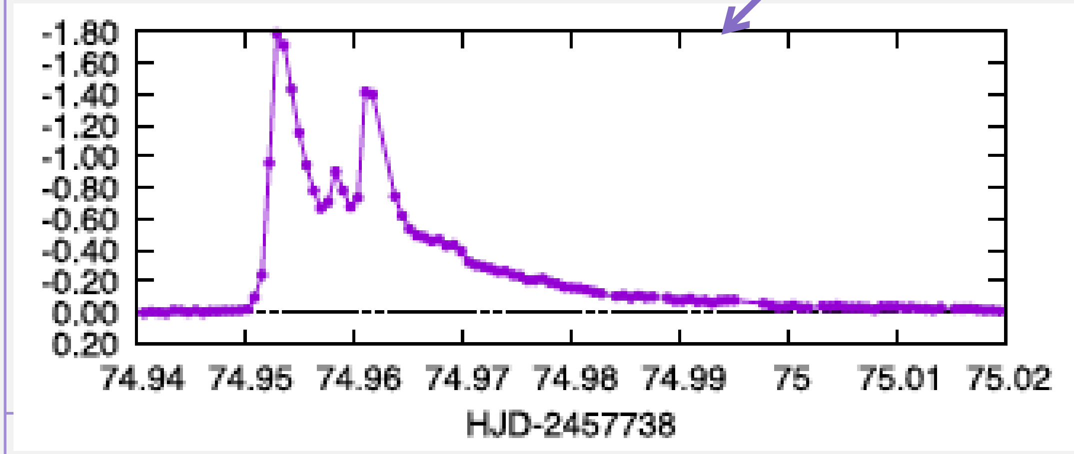
Trappist-1 system

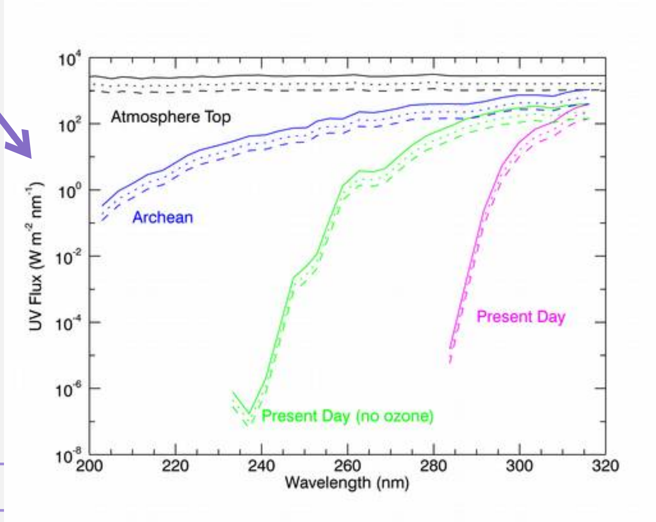
- M8 red dwarf
- Planetary system of 7 terrestrial planets, three of them in the HZ.



Trappist-1 system

- This star is known to flare with 47 flares detected with energies between 10^{30} and 10^{33} ergs (Vida et al. 2017).
- Largest flare 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 measured from flares of Ad Leo, also a M red dwarf (Hawley & Pettersen 1991).
- Atmosphere model from O'Malley & Kaltenegger (2017)





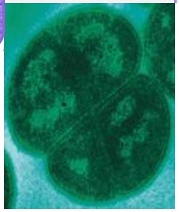
Impact for life on the surface

Biological effective irradiance from TRAPPIST-1, E_{eff} [J/m²] **Contribution of the strongest superflare (10^{33} erg)**			
Planet	Bacteria	Archean atmosphere	Atmosphere with ozone
TRAPPIST-1e	*E. Coli*	9000	8.2
	D. Radiodurans	5100	2.5
TRAPPIST-1f	*E. Coli*	5200	4.7
	D. Radiodurans	2900	1.5
TRAPPIST-1g	*E. Coli*	3300	3.0
	D. Radiodurans	1900	0.9

Without ozone

With ozone

Deinococcus radiodurans



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

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

Escherichia coli

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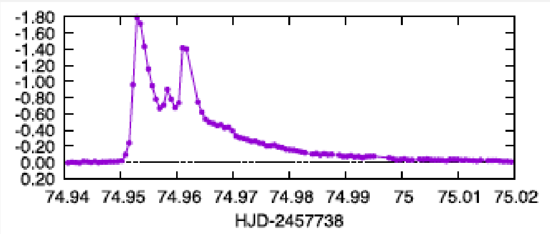
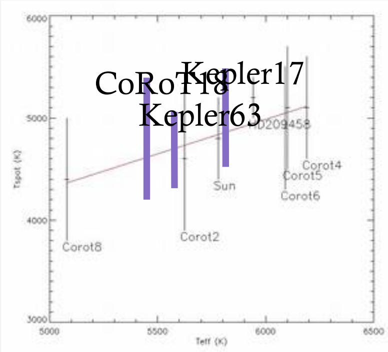
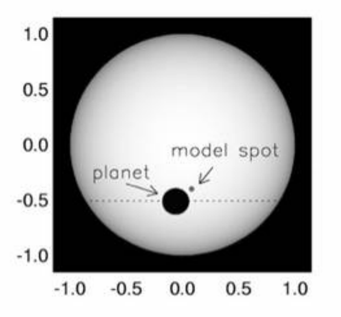
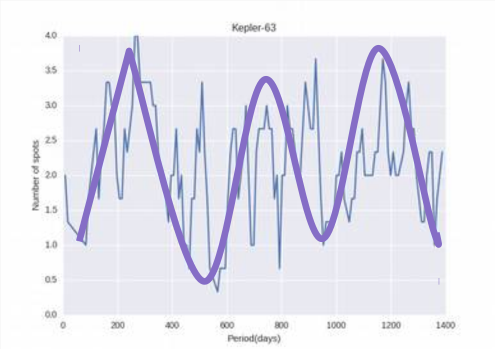
- Stellar rotation & differential rotation
- Magnetic field & magnetic cycles
- Flares and biological impact
- Summary & conclusions

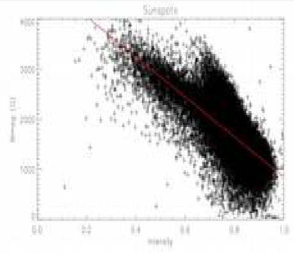
Summary

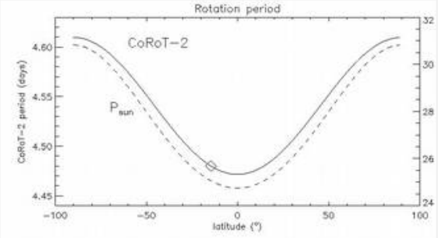

HJD-2457738


CoRoT18
Kepler17
Kepler63
HD209458
Corot4
Corot5
Corot6
Sun
Corot2
Corot8
Tspot (K)
Teff (K)


model spot
planet


Kepler-63
Number of spots
Period(days)




Rotation period
CoRoT−2
P_{sun}
CoRoT−2 period (days)
latitude (°)

Conclusions

- First modelling of small variations in transit light curves *(Silva 2003, ApJL, 585, L147)*

- Multiple transits:
  - Stellar rotation *(Silva-Valio 2008, ApJL, 683, L179)*
  - Differential rotation *(Silva-Valio et al. 2010, A&A, 510, 25; Silva-Valio & Lanza 2011, A&A, 529, 36; IAUS328; Valio et al. 2017, ApJ, 835, 294)*
  - Magnetic cycles *(Estrela & Valio 2017, ApJ, 831, 57)*
- Flares:
  - UV flux: Impact on living organism *(Estrela & Valio 2018, Astrobiology)*
  - Impact on planetary atmospheres

OBRIGADA!

Code ECLIPSE available in IDL or Python

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Mack Pesquisa

FAPESP