# Stellar activity and rotation of Kepler-63

Yuri Netto
Advisor: Dra. Adriana Valio
Co-Advisor: Dr. Nuccio Lanza

CRAAM - Presbyterian Mackenzie University, Brazil

Osservatorio Astrofisico di Catania, Italy

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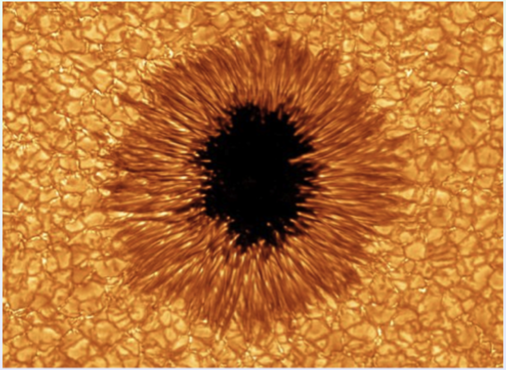
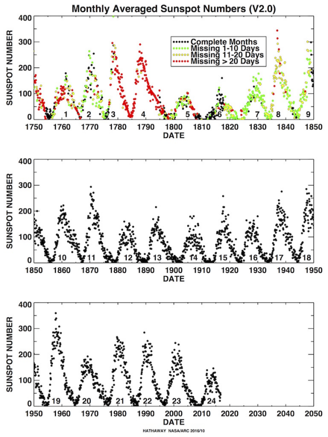


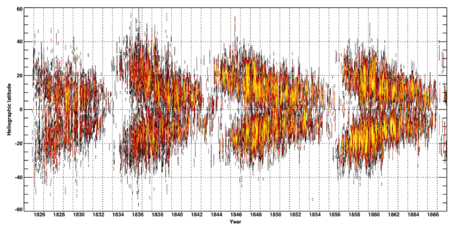
- Strong magnetic fields that inhibits the transference of energy from the convective zone.
- Are colder than the surrounding photosphere.
  - Umbra - 4200 K
  - Penumbra - 5000 K
  - Number of sunspots is not constant in time

# Sun and others stars

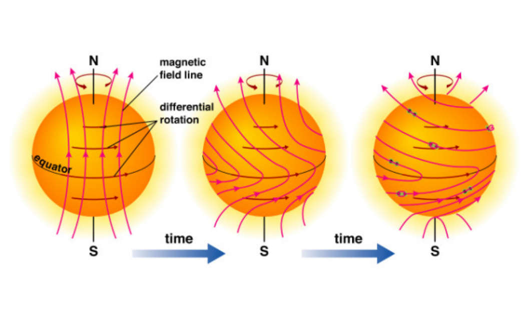
## Solar activity cycle



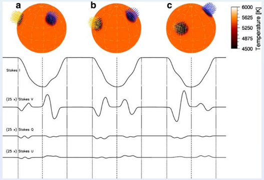

- In 1843 Schwabe noticed a periodic variation in the average number of sunspots

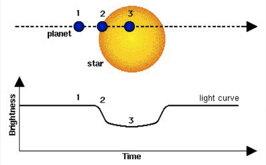


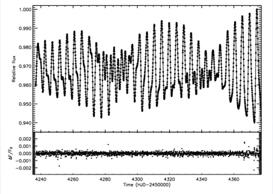
- Differential rotation: fundamental for the solar dynamo
  - Do not rotate as a solid sphere.
  - Differential rotation: 24 days (equator) e 31 days (poles)
  - Responsible for active regions



- Other stars also exhibit activity and have spots
- Basically 3 methods to study starspots:
  - Zeeman-Doppler imaging
  - Planetary transit (Silva, 2003)
  - Light curve rotational modulation (Lanza, Bonomo, Rodonò, 2007)

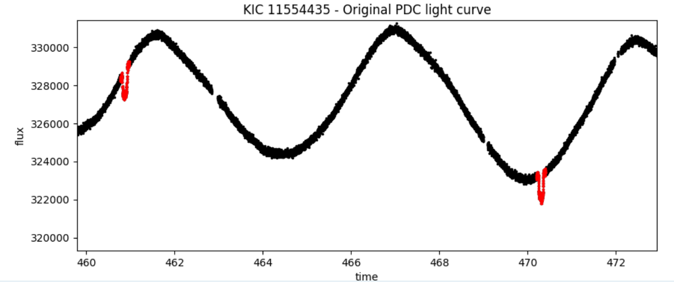


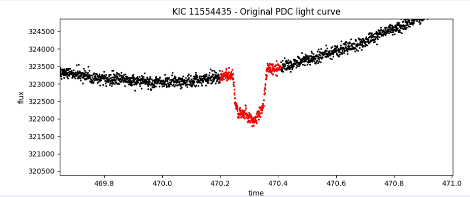



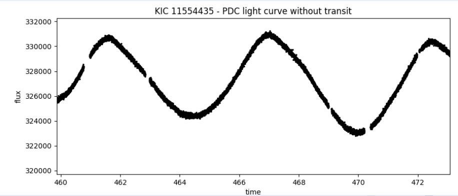
# Methodology

Planetary transit: Transit method



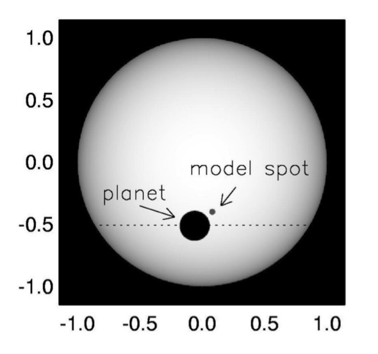

Light curve rotational modulation: Maximum entropy model



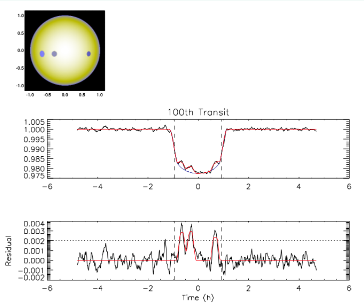
# Methodology

## Planetary transit method




- Model created by Silva (2003)
- Planetary transit:
  - Star: Sun image or synthesized image of a star with limb-darkening
  - Planet: dark disk $R_p/R_s$
  - Circular orbit, with semi-major axis $a/R_s$ and period $P_{orb}$

Physical characteristics of the spots: size, intensity e location.

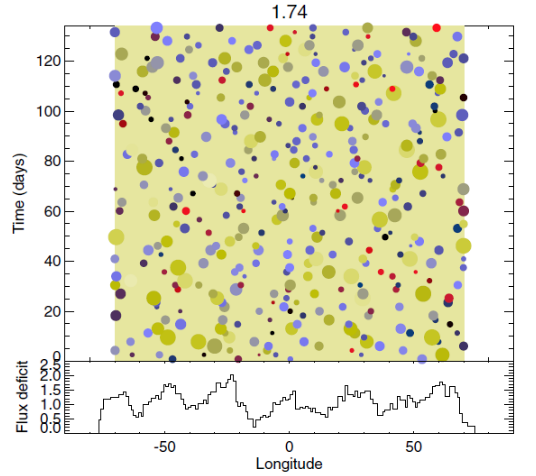



- Properties of the fitted spot:
    - Size: radius, in units of the radius of the planet, $R_p$
    - Intensity: fraction of the maximum brightness intensity of the star that can be converted to temperature
    - Position: longitude and latitude

$$T_m = \frac{h\nu}{K_B}\left[\ln\left(1 + \frac{e^{\frac{h\nu}{K_B T_e}} - 1}{f_i}\right)\right]^{-1}$$

# Methodology

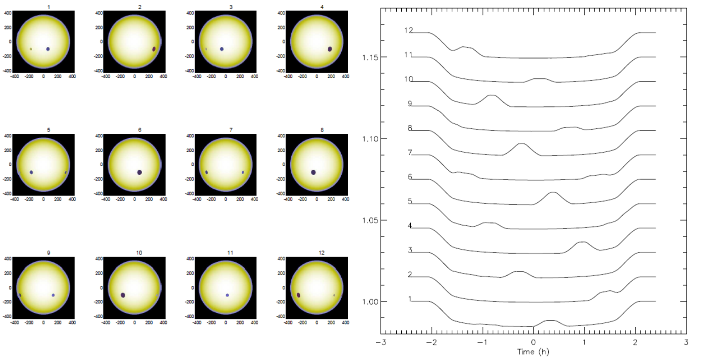
## Spotmap - Earth referential frame



# Methodology

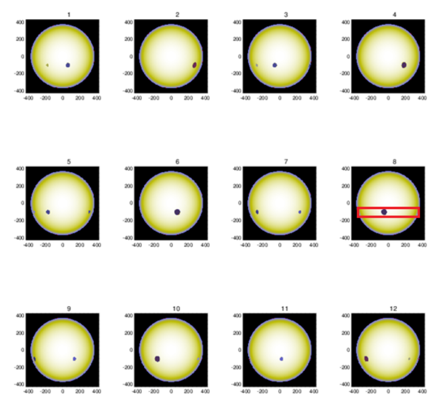
## Rotational period of the star at transit latitude

- To determine the rotational period at a given latitude, it is necessary to detect the same spot in several transits. (Valio, 2013)



# Methodology

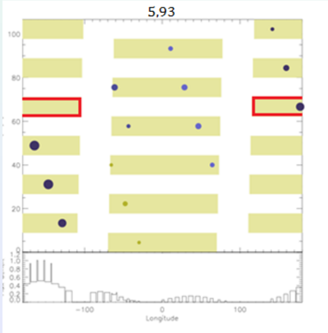
## Rotational period of the star at transit latitude




$$\beta_{rot} = \beta_{topo} - (360^\circ)\frac{nP_{orb}}{P_{star}}$$

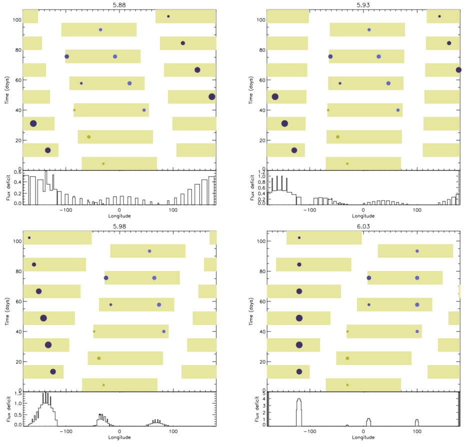
$\beta_{rot}$ = rotational longitude (star)

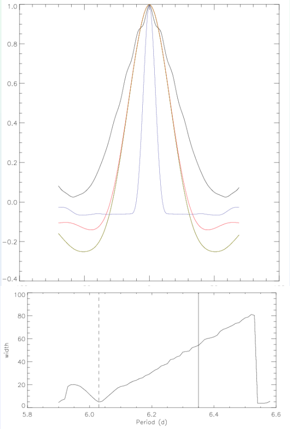
$\beta_{topo}$ = topocentric longitude (Earth)



# Methodology

## Rotational period of the star at transit latitude

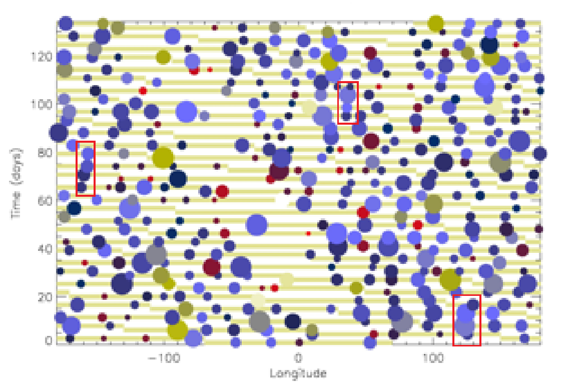


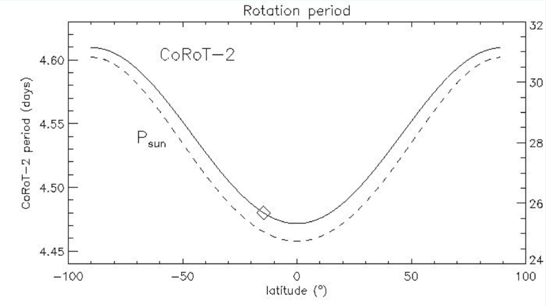



# Methodology

## Spotmap - Referential frame rotation with the star

Spotmap: CoRoT-2





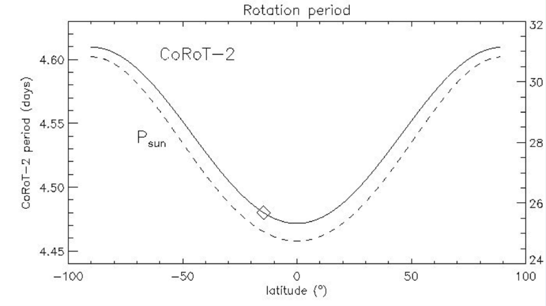

- Solar rotation profile: $\Omega = A - B\sin^2(\alpha)$ where $P = 2\pi/\Omega$

Mean rotation period $\rightarrow \Omega_0 = \frac{1}{(\alpha_2 - \alpha_1)} \int_{\alpha_1}^{\alpha_2} (A - B\sin^2\alpha) d\alpha$

Rotation period at the latitude $\alpha_1 \rightarrow \Omega_1 = A - B\sin^2(\alpha_1)$

# Methodology

## Rotation and differential rotation of stars




- Solar rotation profile: $\Omega = A - B\sin^2(\alpha)$ where $P = 2\pi/\Omega$

- Differential rotation measured in radian per day ($rd/d$), is given by $\Delta\Omega = \Omega_{eq} - \Omega_{pole}$
- Relative differential rotation, in %, is given by $\Delta\Omega/\Omega_0$

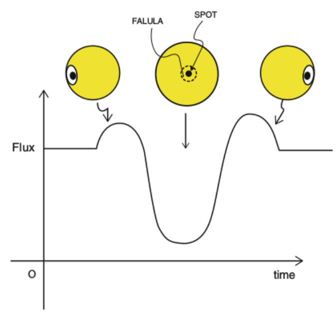
$$\Delta\Omega = \Omega_{eq} - \Omega_{pole}$$
$$\Omega_{eq} = \Omega(lat = 0) = A$$
$$\Omega_{pole} = \Omega(lat = 90^\circ) = A - B$$

- $Q$: Ratio between areas of faculae and spot
- $Q$ is obtained by a model developed by Lanza (2003):
  - Rotational modulation fit: 3 active region (spots and faculae)
  - Few free parameters
  - Determination of $\Delta t_f$, longer time interval that the active regions remain stable
  - $Q$ is determined by minimizing $\chi^2$

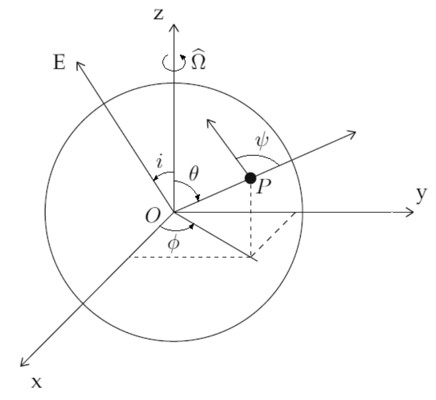
# Methodology

## Maximum Entropy Model (MEM)

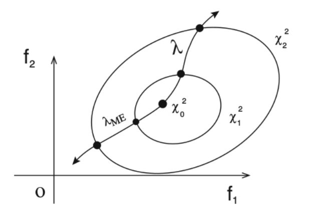
- Model by Lanza, Bonomo, Rodonò (2007)
- Maximum entropy model:
  - Based on continuous active region distributions
  - Subdivided into 200 surface elements that contain unperturbed photosphere, dark spots, and faculae
  - Filling factor: spot area ($f_k$), faculae area ($Qf_k$) e quiet photosphere ($1 - (Q+1)f_k$)

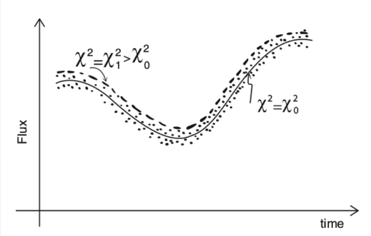


$$\Omega = \textit{angular velocity}$$
$$\theta = \textit{colatitude}$$
$$\phi = \textit{longitude}$$

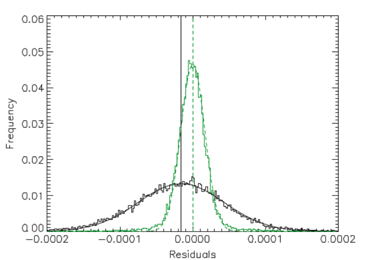


- Light curve is fitted by changing the filling factor ($f$)
- $Q$ is kept constant
- $Z = \chi^2(f) - \lambda S(f)$
- $\lambda = 0$ = unstable

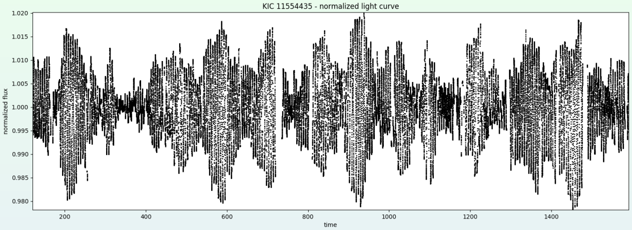


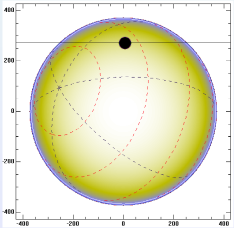




- Optimal value of $\lambda$:
  - mean of the residuals $|\mu_{reg}| = \sigma_0/\sqrt{N}$, where $\sigma_0$ is the standard deviation of the residuals of the unregularized model ($\lambda = 0$).

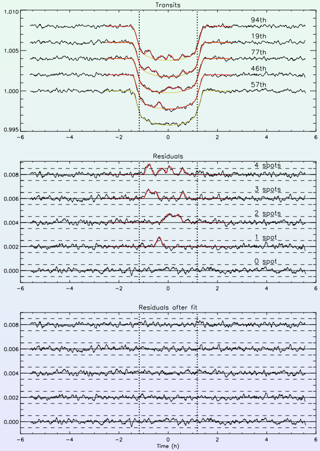


# Star: Kepler-63



| Parameter | Unit | Value |
|---|---|---|
| | Star | |
| Effective Temperature, $T_{eff}$ | [K] | 5576 (±50) |
| Mass, $M_\star$ | [$M_\odot$] | 0.984 (-0.04, +0.035) |
| Radius, $R_\star$ | [$R_\odot$] | 0.901 (-0.022, +0.027) |
| Rotation Period, $P_{star}$ | [*days*] | 5.400 (±0.009) |
| Age | [*Myrs*] | 210 (±45) |
| Sky-projected Stellar Obliquity | [*deg*] | -110 (-14, +22) |
| Inclination of rotation axis | [*deg*] | 138 (±7) |
| | Planet | |
| Mass, $M_p$ | [$M_{Jup}$] | 0.4 |
| Radius, $R_p$ | $R_p/R_\star$ | 0.0662 |
| Orbital Period | [*days*] | 9.4341505 (± $1\times10^{-6}$) |
| Semi major axis | $a/R_\star$ | 19.35 |
| Orbital inclination angle, $i$ | [*deg*] | 87.806 (-0.019, +0.018) |

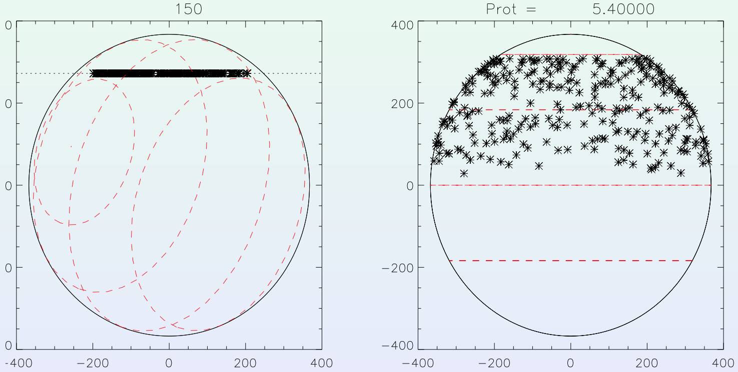



- 150 transits
- Curve without spot: 10 deepest transits without any visible spot signature
- Final fit: AMOEBA
- 297 spots

Almost polar orbit → rotation matrix

# Application of models

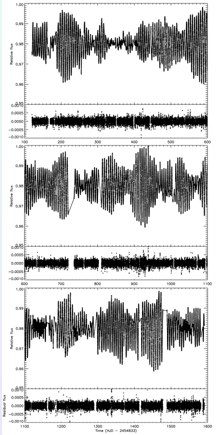
## Kepler-63 - Planetary transit method

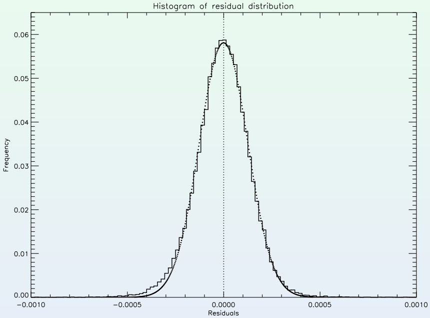


# Application of models

## Kepler-63 - MEM

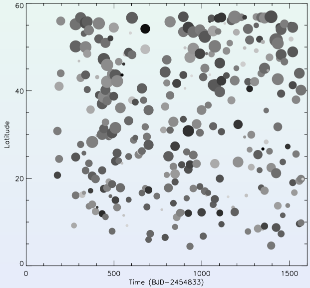
Kepler-63 light curve with the fit

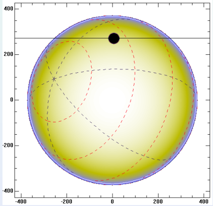


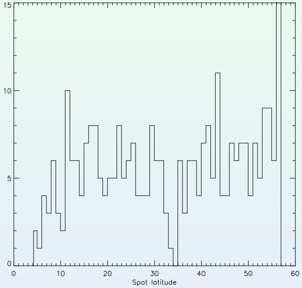




- mean of the residuals $\mu_{reg}$ = - $4.972 \times 10^{-6} \simeq -\sigma_{BL}/\sqrt{N}$
- standard deviation of the residuals $\sigma_{reg} = 1.401 \times 10^{-4}$

Butterfly diagram



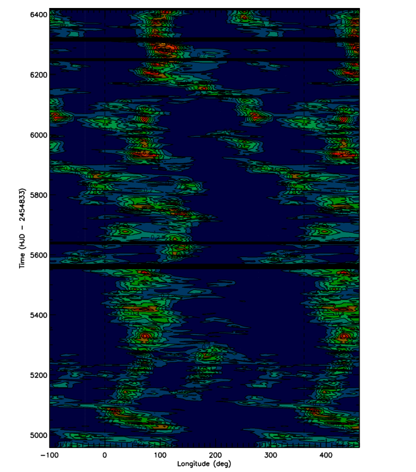



| Parameter | Unit | Average |
|---|---|---|
| Radius | ($R_p$) | $0.65 \pm 0.13$ |
| Radius | (Mm) | $26 \pm 5$ |
| Intensity | ($I_c$) | $0.43 \pm 0.15$ |
| Temperature | (K ) | $4700 \pm 300$ |

297 spots

# Results

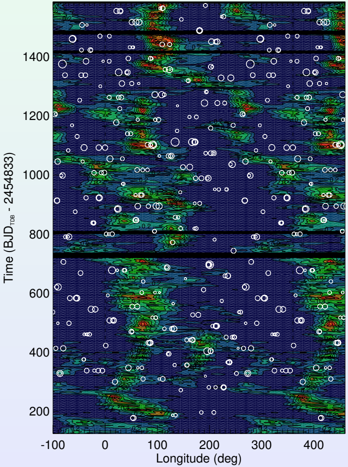
## Kepler-63 - MEM




- active regions migration:
  5000-5100
  5700-5900
  6100-6200
- migration rate $\sim 1^\circ/\text{day}$
- $\Delta\Omega/\overline{\Omega} = 1.5\%$

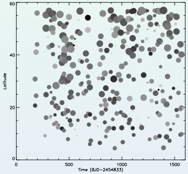
# Results

## Kepler-63 - MEM



# Conclusion

- Transit method:
  297 spots
  It is not possible to calculate a differential rotation
  Butterfly diagram

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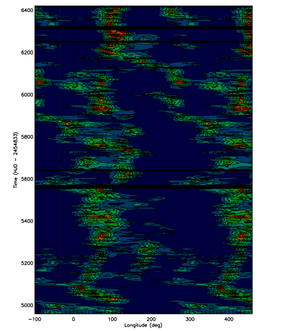
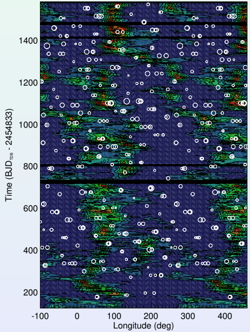
| Temperature | (K ) | $4700 \pm 300$ |

- MEM:
  Active longitude at $\sim 100°$
  Lower limit for $\Delta\Omega/\overline{\Omega} =$ 1.5%




- Comparison between the maps was not possible



# Conclusion

| Star | Kepler-17 | Kepler-63 | Kepler-71 | CoRoT-2 | Sun |
|---|---|---|---|---|---|
| Mass ($M_{Sun}$) | 1.16 | 0.984 | 0.997 | 0.97 | 1.0 |
| Radius ($R_{Sun}$) | 1,05 | 0.901 | 0.887 | 0.902 | 1.0 |
| $T_{eff}$ (K) | 5780 | 5576 | 5540 | 5575 | 5778 |
| Age (Gyr) | 1.78 | 0.2 | 2.5-4.0 | 0.13-0.5 | 4.6 |
| Dif. Rot. ($rd/d$) | 0.041 | 0.081 | 0.005 | 0.042 | 0.05 |
| Relat. dif. rot. (%) | 8.0 | 1.5 | $< 2$ | 3.04 | 22.1 |
| Planet | Kepler-17b | Kepler-63b | Kepler-71b | CoRoT-2b | |
| Radius ($R_{star}$) | 0.138 | 0.0662 | 0.1358 | 0.172 | |
| a ($R_{star}$) | 5.738 | 19.35 | 12.186 | 6.7 | |
| Spots | | | | | |
| Radius (Mm) | $49 \pm 10$ | $26 \pm 5$ | $51 \pm 26$ | $55 \pm 19$ | $12 \pm 10$ |
| $T_{spot}$ (K) | $5100 \pm 300$ | $4700 \pm 300$ | $4800 \pm 500$ | $4600 \pm 700$ | $4800 \pm 400$ |

- Kepler-63 and CoRoT-2 have slightly cooler spots than evolved stars
- Discarding Kepler-71, the younger the star is, the lower the relative differential rotation it presents.

Thanks!

# Application of the models

## Kepler-63 - Planetary transit model

$$
\begin{aligned}
x_1 &= R_\star \times \cos(lat)\cos(long) \\
y_1 &= R_\star \times \cos(lat)\sin(long) \\
z_1 &= R_\star \times \sin(lat)
\end{aligned}
$$

- Rotation matrix $A$ around the $x$ axis $\rightarrow (x, y', z')$

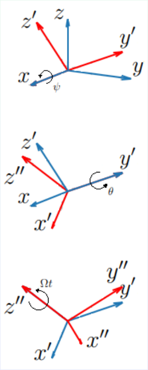
$$
A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\psi) & -\sin(\psi) \\ 0 & \sin(\psi) & \cos(\psi) \end{pmatrix}
$$

- Rotation matrix $B$ around $y'$ axis $\rightarrow (x', y', z'')$

$$
B = \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix}
$$

- Rotation matrix $C$ around $z''$ axis $\rightarrow (x'', y'', z'')$

$$
C = \begin{pmatrix} \cos(\Omega t) & \sin(\Omega t) & 0 \\ -\sin(\Omega t) & \cos(\Omega t) & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$



$\psi$ = stellar obliquity
$\theta$ = Inclination of rotation axis

$$\Omega t = \frac{2\pi}{P_{rot}} \cdot k \cdot P_{orb}$$

$$M_{rot} = C \cdot B \cdot A$$

$$M_{rot} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix}$$