Photospheric activity and surface differential rotation in the planet-hosting stars CoRoT-Exo-2a and CoRoT-Exo-4a

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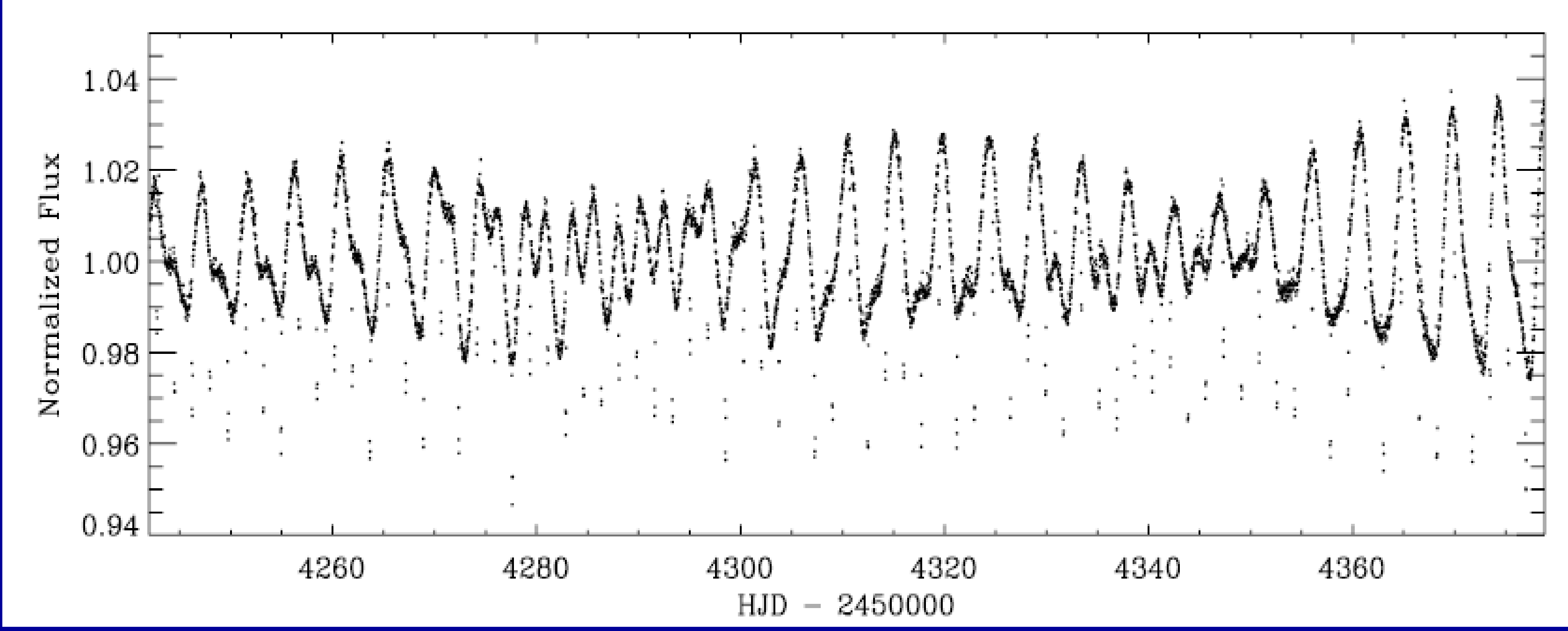
CoRoT-Exo-2a

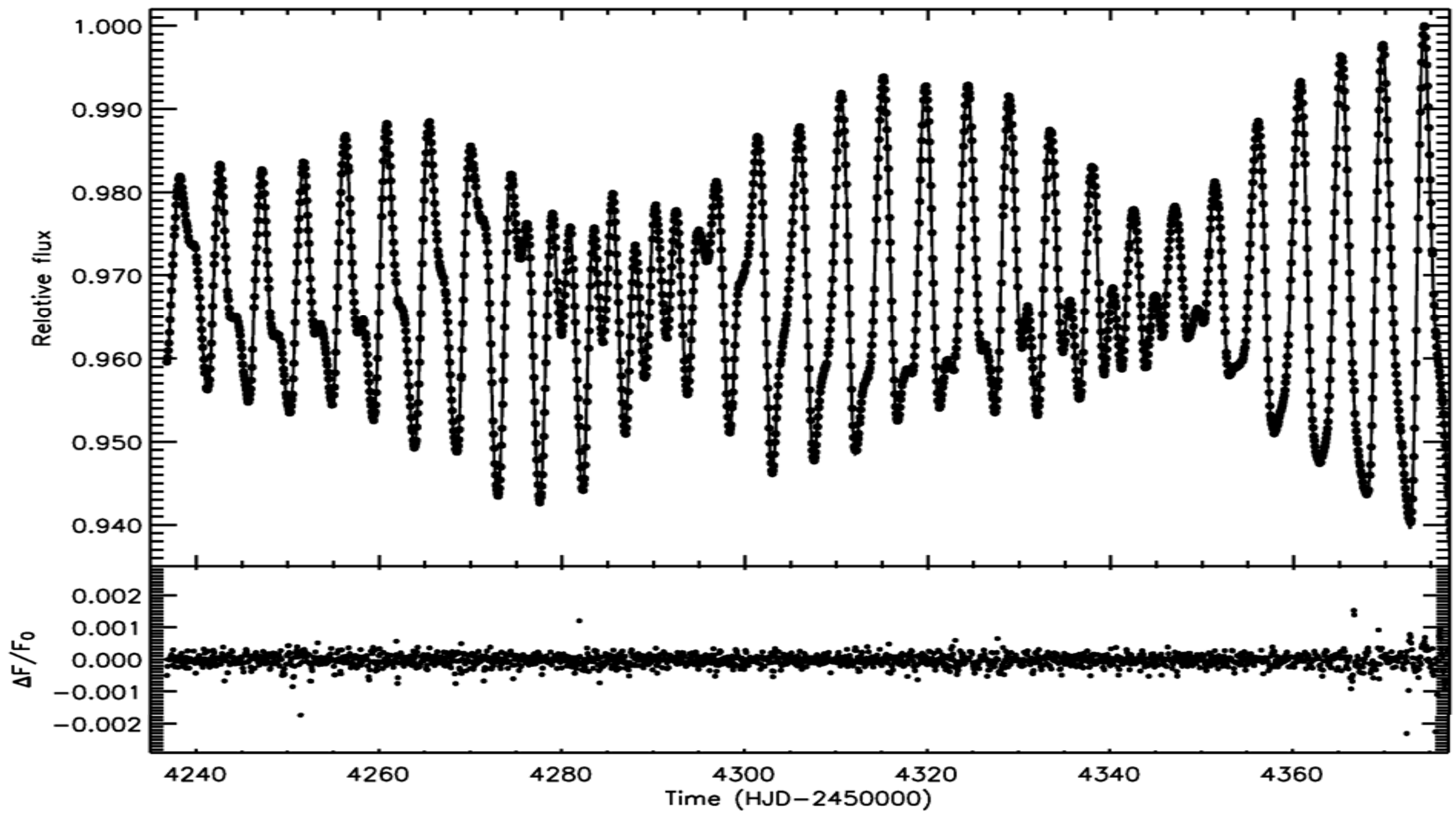
- A main-sequence G7 star (V=12.57), accompanied by a hot Jupiter with an orbital period of 1.743 d (Alonso et al. 2008; Bouchy et al. 2008);



Spot modelling

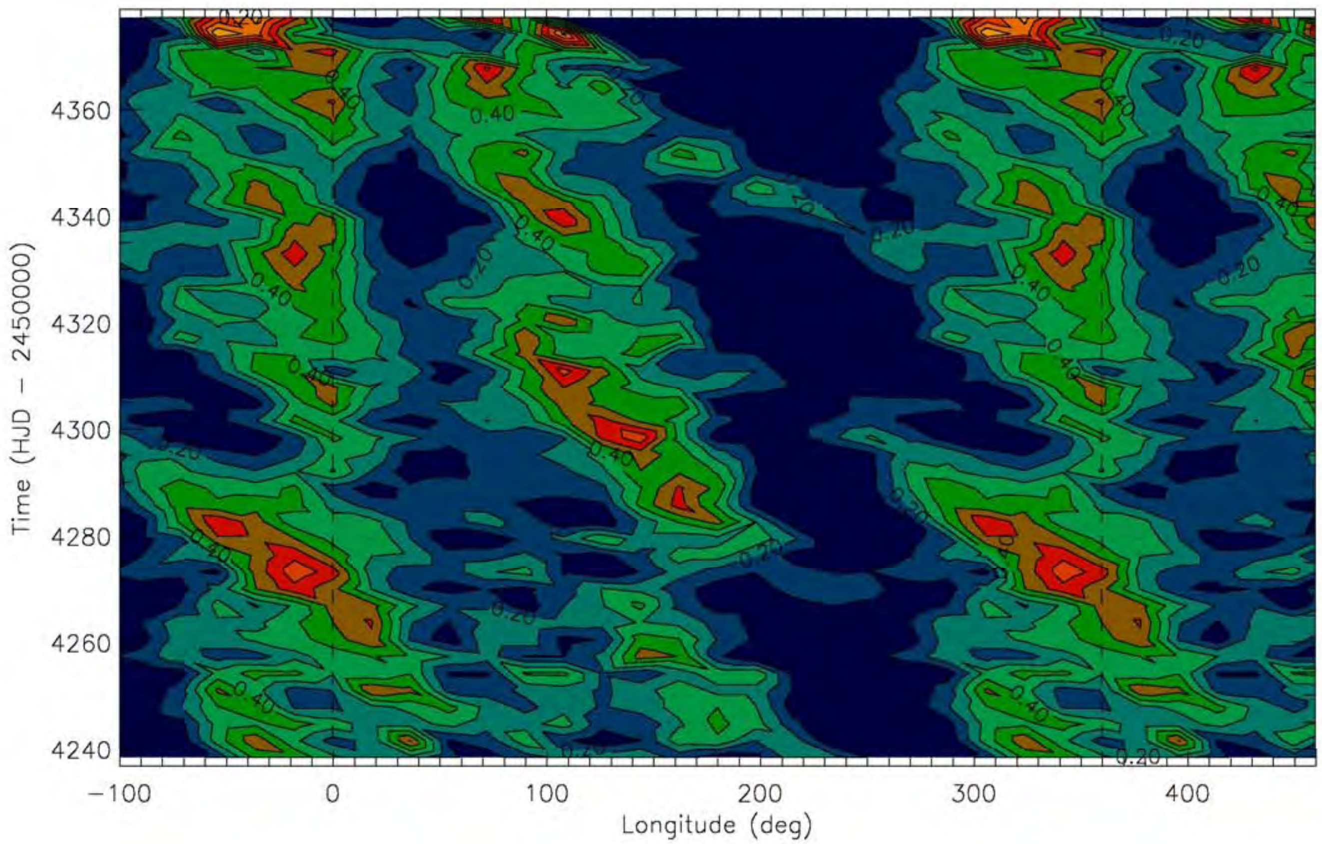
- The out-of-transit light modulation is attributed to *photospheric active regions (ARs),* carried into and out of view by stellar rotation;
- ARs are treated on the basis of a solar analogy, assuming they consist of *cool spots* and *solar-like faculae*;
- Maximum Entropy regularization is applied to warrant uniqueness and stability of the model (see Lanza et al. 2007; Lanza et al. 2009a).
- For different approaches to the spot modelling problem see, e.g., the posters by Froehlich et al. and Mosser (P-XII-112 and -116).

Best fit of the out-of-transit light curve



(normal points obtained by binning the data along each satellite orbital period of 6184 s)

Spot area vs. longitude and time



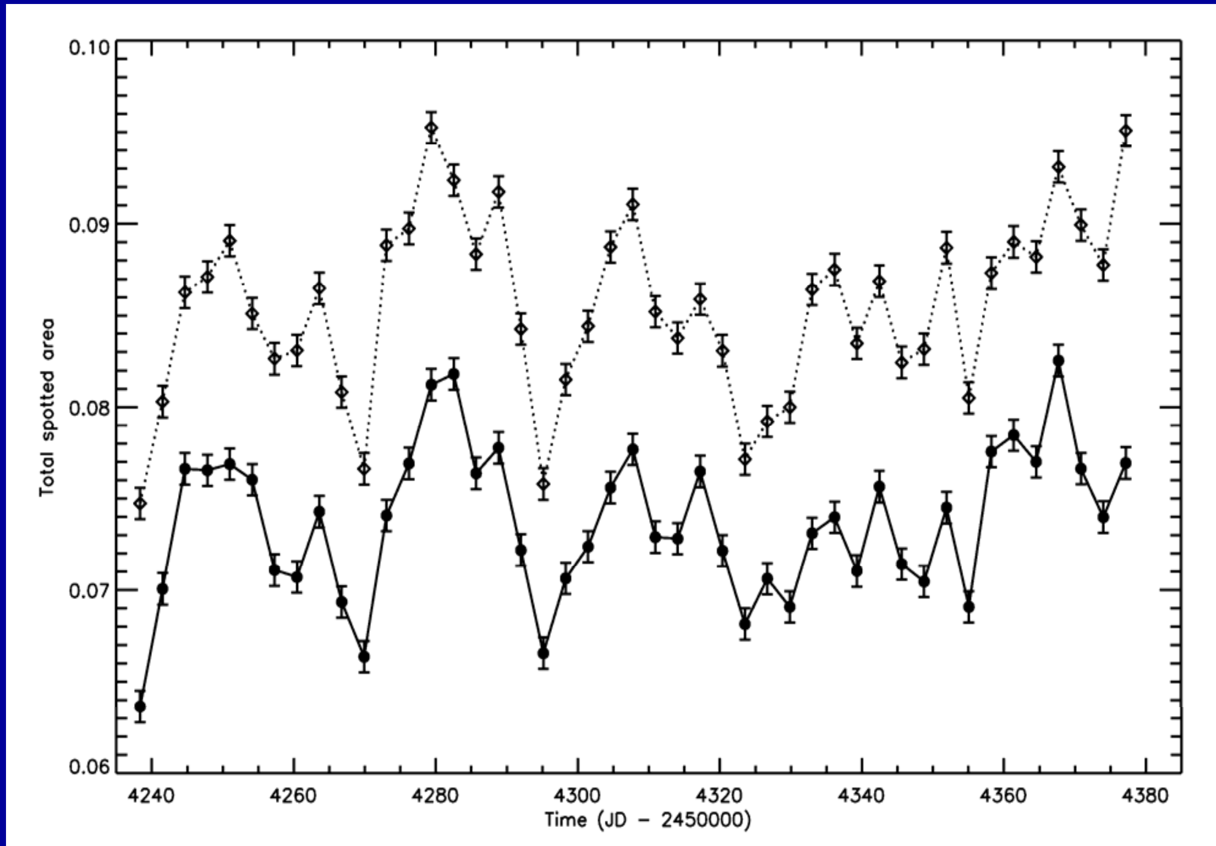
(The rotation period of the longitude reference frame is 4.5221 days)

Differential rotation

- Individual spot groups migrate backward in longitude during their lifetime, i.e., their angular velocity is lower than that of the active longitudes (cf. *sunspot group braking*; Zappalà & Zuccarello 1991; Schuessler & Rempel 2005);

- One of the active longitudes is almost fixed while the other migrates backward, suggesting a surface differential rotation with a relative amplitude of $\approx$ 0.9 percent.

Variation of the spot area vs. time (a possible Rieger cycle)



Spots only (solid line): P_{cyc} = 28.9 ± 4.8 d;
Spots and faculae with $Q \equiv A_{fac}/A_{spot}$ = 1.5 (dot-dashed line): P_{cyc} = 29.5 ± 4.8 d;

Possible origin of the Rieger cycle in CoRoT-Exo-2a

a) Rossby-type waves trapped in the outer layers of the stellar convection zone, as suggested for the Sun (Lou 2000):

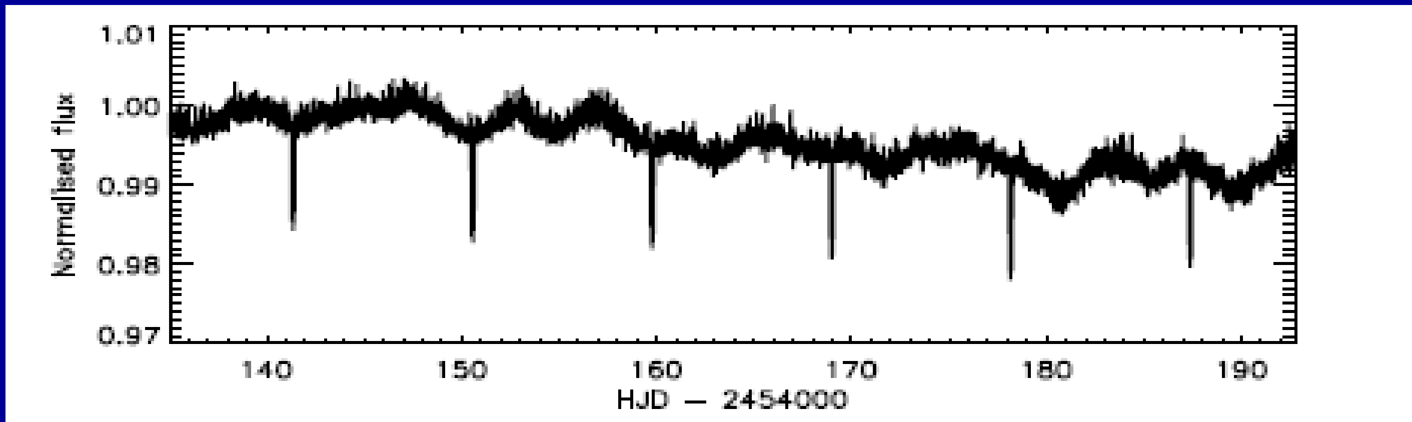
$$\omega_{\mathrm{Rossby}} \propto \Omega;$$

b) a possible star-planet magnetic interaction: the synodic period of the planet with respect to the stellar rotation period is 2.89 days (i.e.,$1/P_{syn} = 1/P_{orb} - 1/P_{rot}$);

(see Lanza et al. 2009a for details).

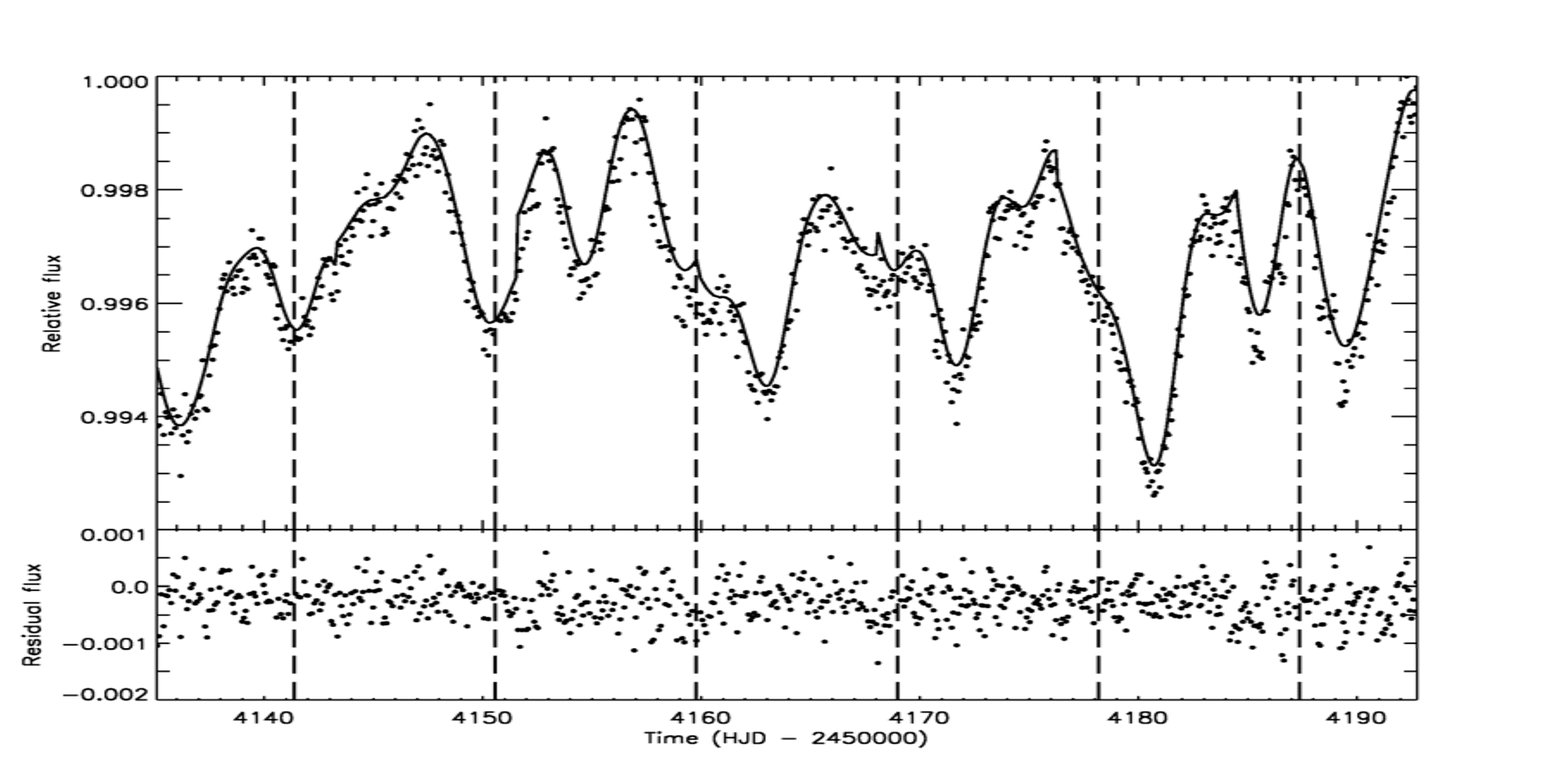
CoRoT-Exo-4a

- A F7 main-sequence star (V~13.7) accompanied by a transiting hot Jupiter with a period of 9.202 days.



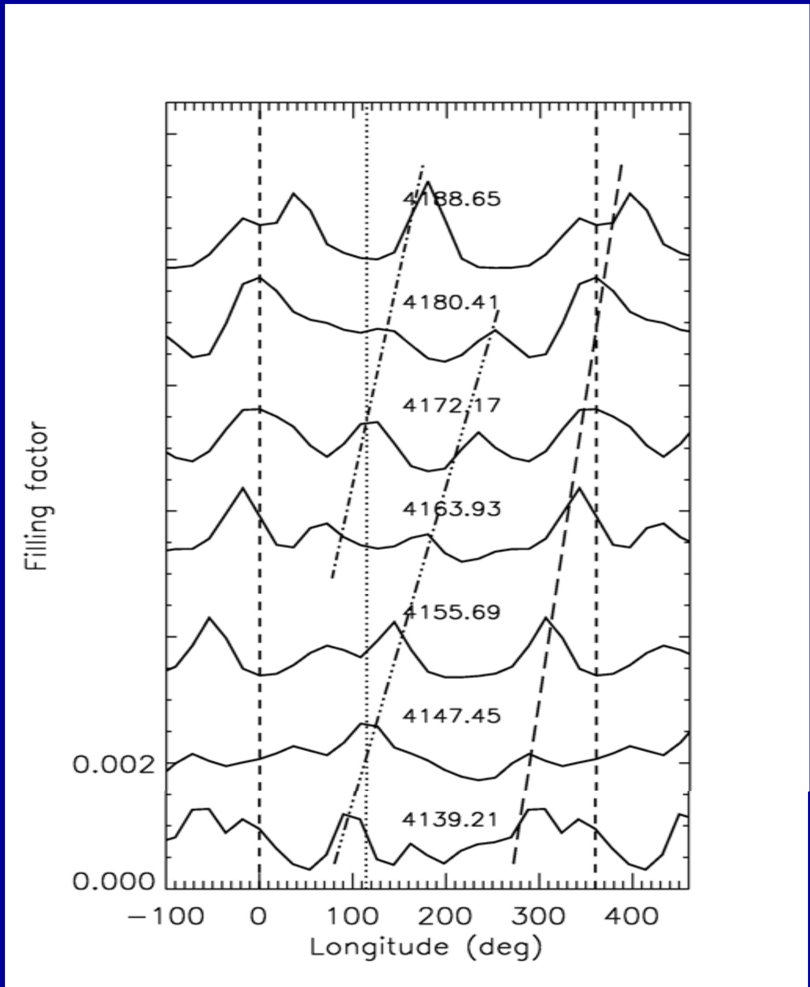
(Aigrain et al. 2008; Moutou et al. 2008)

Best fit of the out-of-transit light curve



(normal points obtained by binning the observation along each CoRoT orbital period; the long-term linear trend has been removed; dashed vertical lines mark the epochs of mid-transits)

Plots of the spotted area vs. longitude: Surface Differential Rotation



(Time labels are HJD-2450000.0)

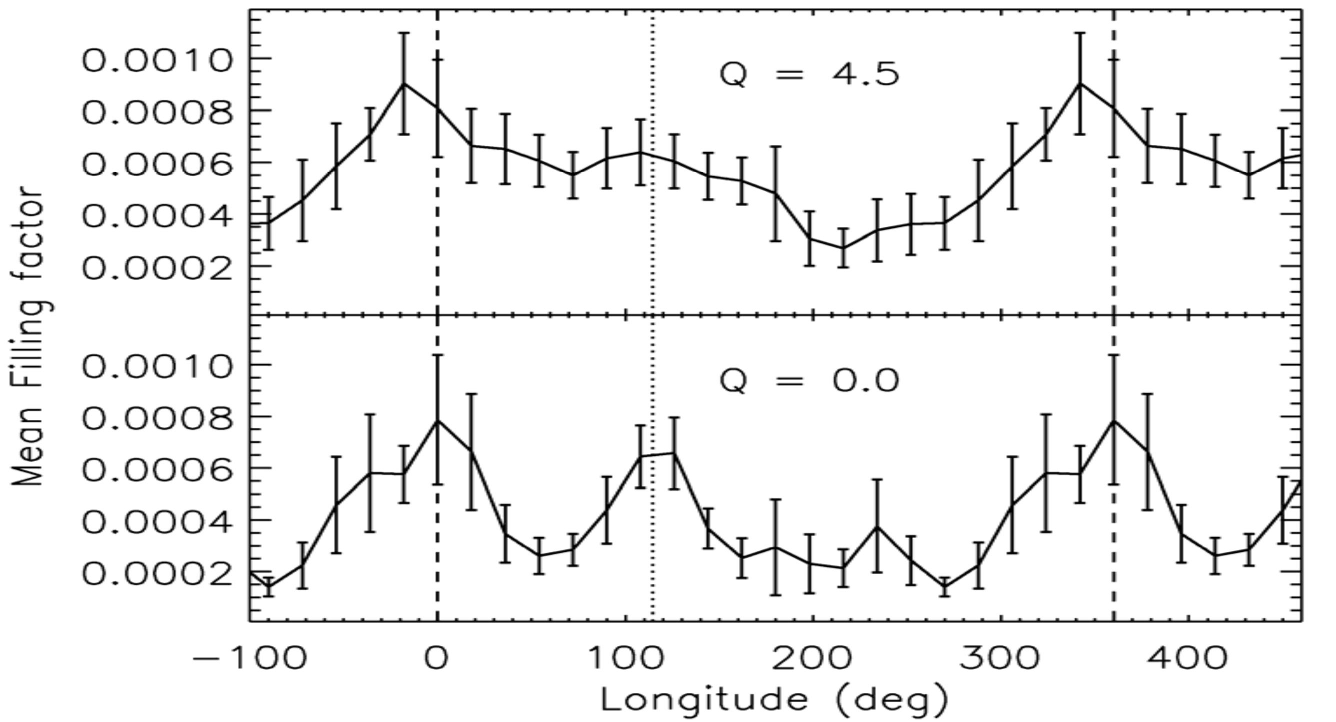
Active longitude relative migration rates in a reference frame with a rotation period of 9.202 days:

a) long-dashed: $\Delta\Omega/\Omega = 0.052 \pm 0.010$;
b) 3-dot-dashed: $\Delta\Omega/\Omega = 0.108 \pm 0.010$;
c) dot-dashed: $\Delta\Omega/\Omega = 0.100 \pm 0.024$.

From the difference between the greatest and the lowest migration rates, we estimate:

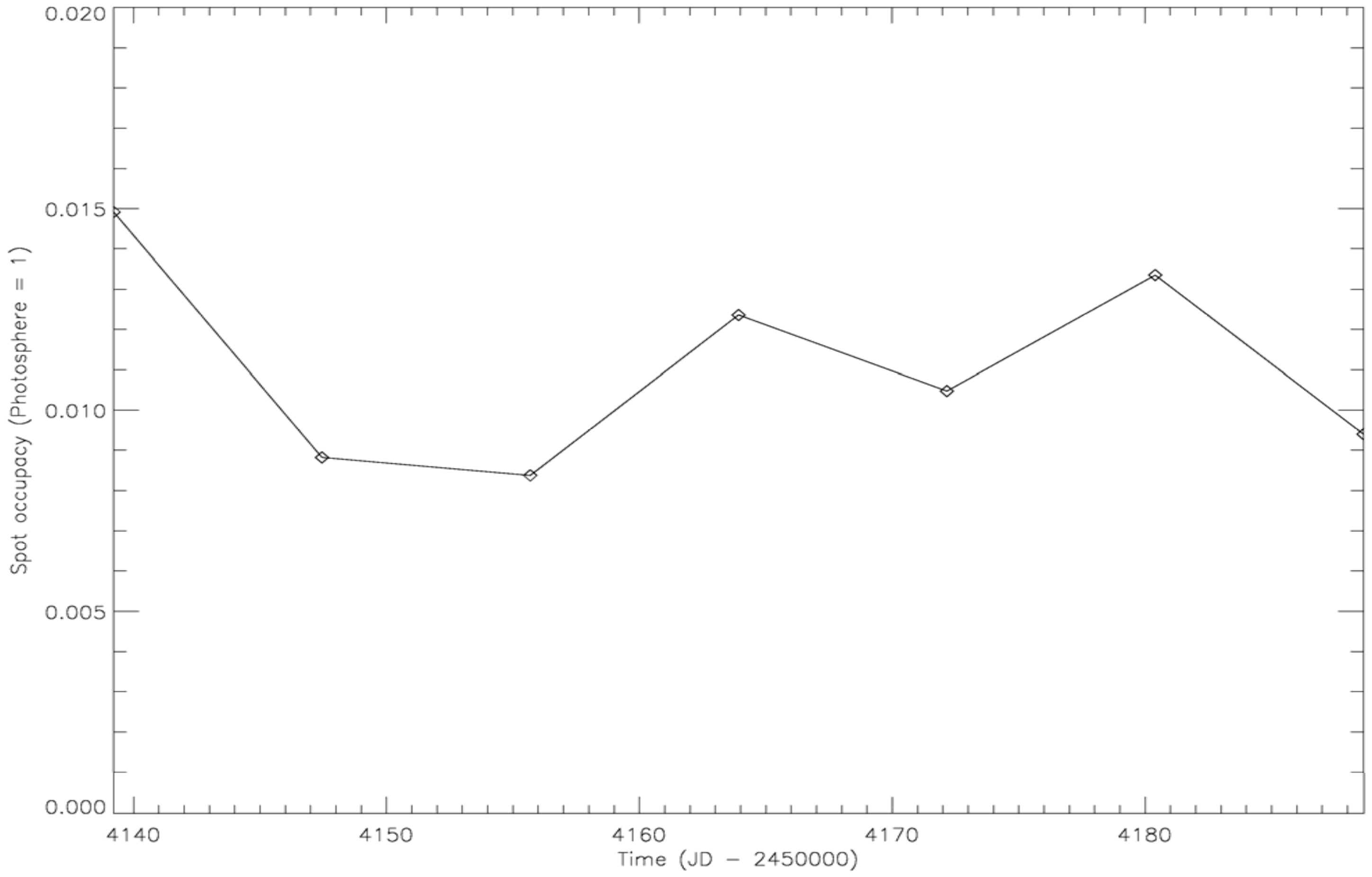
$$\Delta\Omega/\Omega = 0.056 \pm 0.015$$

Mean spotted area vs. longitude



Time average of the spotted area vs. longitude; models with Q=0 do not include faculae. The dotted line marks the subplanetary longitude.

Variation of the total spotted area



A facular component has been included with Q = 4.5

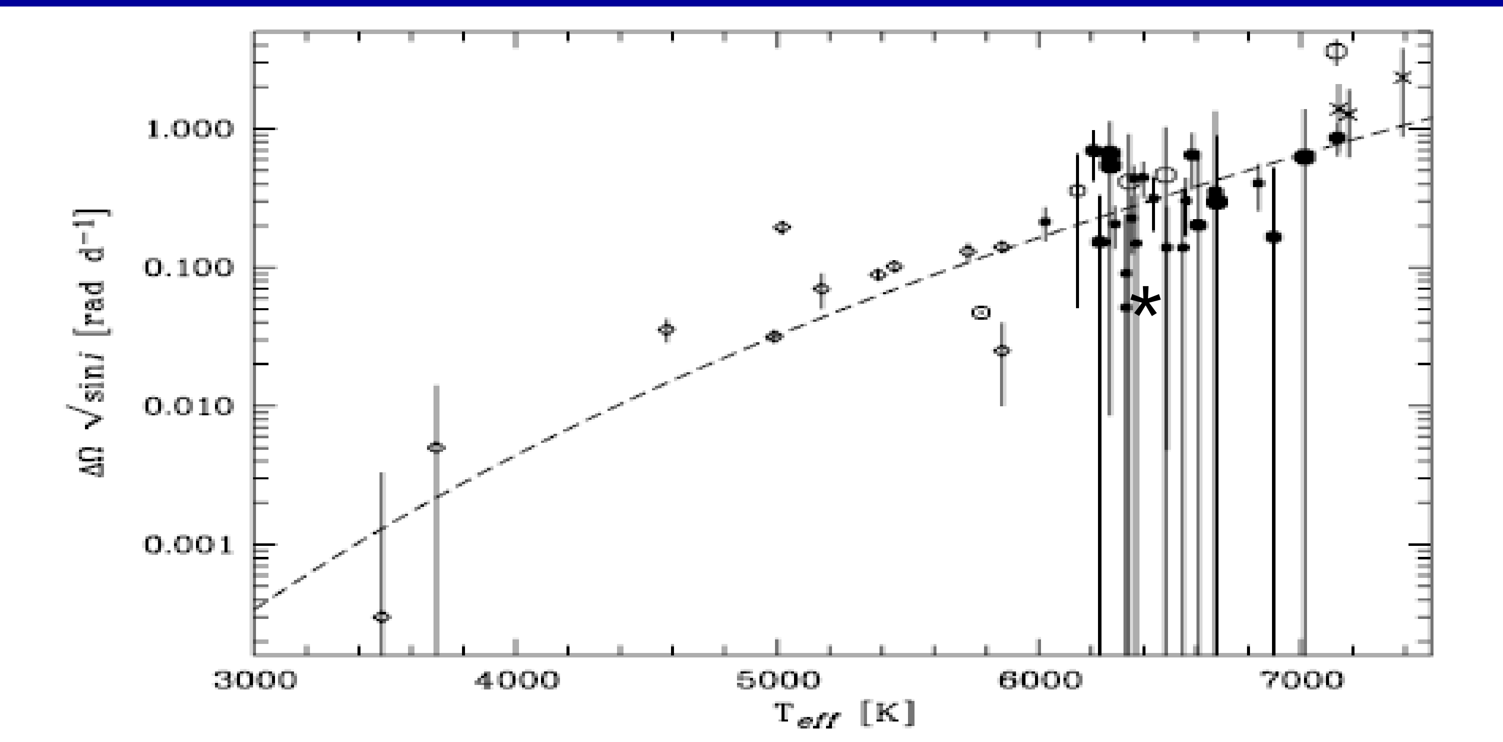
Differential rotation and possible star-planet interaction in CoRoT-Exo-4a

The different migration rates of the active longitudes allow us to estimate a relative differential rotation amplitude of $\approx 0.060 \pm 0.015$ (actually, it is a *lower limit*);

There is an indication for a persistent spot activity at the subplanetary longitude, suggesting a possible star-planet interaction (see Lanza 2008 for conjectures on the origin of the phenomenon);

The total spotted area does not show significant oscillations during the 57 days of the observations.

SDR in other F-type stars



Conclusions

he unprecedented continuity and accuracy of CoRoT ime series open a new era for stellar activity studies using pot modelling techniques;

CoRoT light curves can be modelled to derive maps of the ongitude distribution of the photospheric ARs on stars accompanied by transiting planets; this allows us to study:

– stellar active longitudes;
– short-term spot cycles;
– stellar rotation and differential rotation;
– possible star-planet magnetic interactions (Lanza 2008; Shkolnik et al. 2008; Walker et al. 2008).

ferences: Lanza et al. 2009a, A&A 493, 193; Lanza et al. 2009b, A&A,

Thank you very much for your attention

Additional material

Parameters of Exo-2a and its planet

Star:

- effective temperature: 5625 ± 120 K;
- mass: 0.97 ± 0.06 solar masses;
- radius: 0.90 ± 0.02 solar radii;
- v sin i = 11.85 ± 0.50 km/s;
- i = 88 ± 7 deg (from the Rossiter-McLaughlin effect);
- estimated age: 0.3-1.0 Gyr;

Planet:

- mass: 3.31 ± 0.16 Jupiter masses;
- radius: 1.46 ± 0.03 Jupiter radii;
- orbital semi-major axis: 0.0281 AU;

Spot modelling

Our main interest is in studying stellar rotation and magnetic activity as traced by photospheric active regions; we also look for a possible magnetic star-planet interaction;

We fit the CoRoT light curve with the model of Lanza et al. (2007); it includes the effects of cool *spots* and bright solar-like *faculae*; and uses a *Maximum Entropy* approach to select a unique and stable solution;

From the modelling we derive :

- the longitude distribution of the spotted area vs. time;
- the variation of the total spotted area vs. time

Out-of-transit light curve of CoRoT-Exo-2a

The original chromatic N2-level data are summed up to get white light fluxes;

he effects of hot pixels, pointing jitter and outliers are emoved (see Lanza et al. 2008);

Transits are removed by means of the ephemeris of Alonso et al. (2008);

The out-of-transit light curve is binned in 1-orbital period 6184 s) intervals, obtaining a time series consisting of 945 normal points along 142.006 days;

Search for the rotation period

The out-of-transit light curve is binned in 1-orbital period intervals, obtaining a time series of 142.006 d consisting of 1945 normal points;

we apply the Lomb-Scargle periodogram to extract the rotation period from the light modulation;

we find: $P_{rot} = 4.52 \pm 0.14$ d.

Spot modelling

Ve adopted the Maximum Entropy spot model of Lanza et al. (2007, \&A 464, 741);

he surface of the star is divided into pixels of 18° x 18° and a mixture of spotted and unspotted photosphere is assumed within each pixel;

he fraction of the area covered by the spots is the pixel filling factor f_i

solar-like facular component, co-spatial with spots, can be included; s area is assumed to be a fixed multiple of the spotted area in each ixel, i.e., $Q \equiv A_{fac}/A_{spot}$; in other words, the facular filling factor is Qf_i in he i-th pixel;

single map is derived out of virtually infinite solutions by means of he ME regularization, i.e., optimizing the functional:

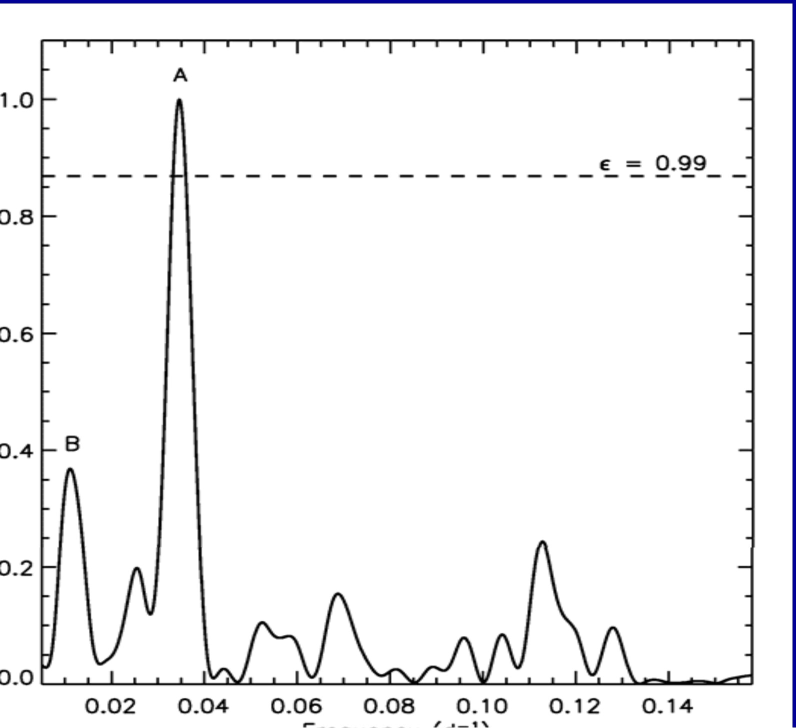
$$\Theta = \chi^2(f) - \lambda S(f),$$

Parameters adopted for the spot modelling of CoRoT-Exo-2a

Parameter		Ref.[a]
Star Mass ($M_\odot$)	0.97	A08
Star Radius ($R_\odot$)	0.90	A08
$T_{\rm eff}$ (K)	5625	B08
Limb darkening $u_{\rm a}$	0.41	A08
Limb darkening $u_{\rm b}$	0.06	A08
$P_{\rm rot}$ (d)	4.5221	L08
ϵ	2.48×10^{-4}	L08
Inclination (deg)	87.84	A08
$c_{\rm s}$	0.665	L08
$c_{\rm f}$	0.115	L04
Q	0.0, 1.5	L08
$\Delta t_{\rm f}$ (d)	3.15611	L08

[a] References: A08: Alonso et al. (2008); B08: Bouchy et al. (2008);

Periodogram of the variation of the total spotted area



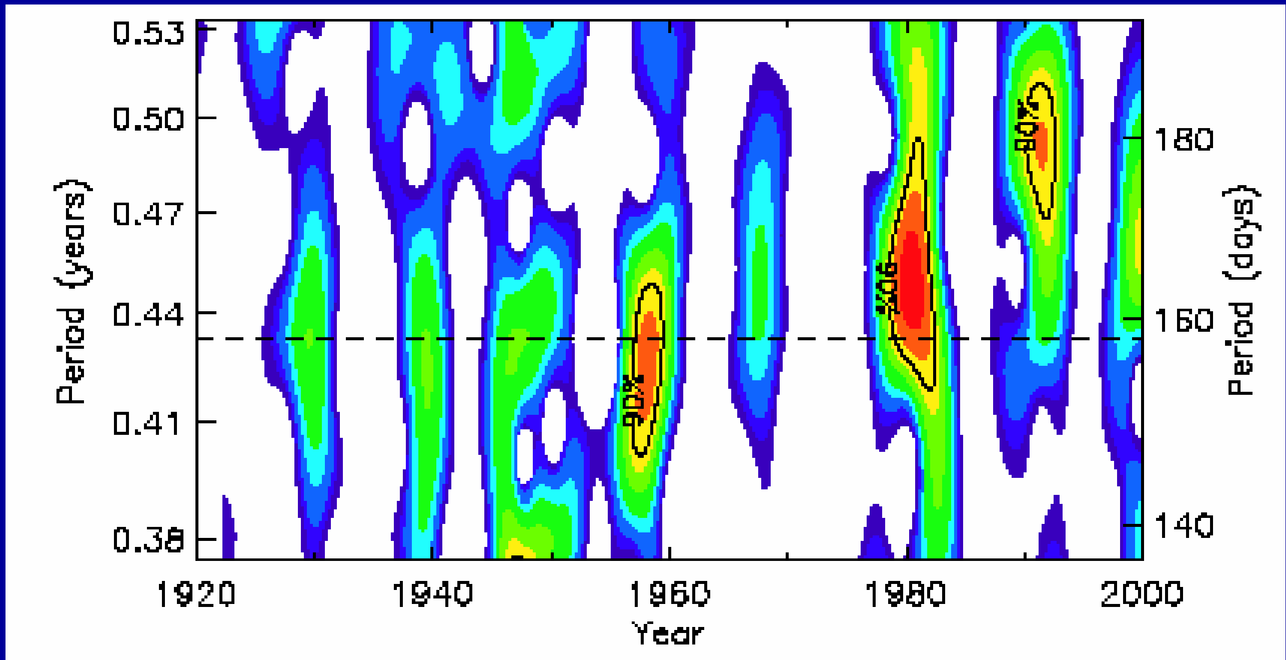
Scargle-Lomb periodogram of the variation of the spotted area (Q = 0);

a) principal periodicity (A):
P_A = 28.9 d, ε_A = 0.997;

b) secondary periodicity (B):
P_B = 86.5 d, ε_B = 0.783.

Rieger sunspot cycles

riods of about 150-180 days are sometimes apparent in e variation of sunspot area (e.g., Oliver, Ballester & udin 1998; Krivova & Solanki 2002);



Parameters adopted for the spot modelling of CoRoT-Exo-4a

Parameter		Ref.[a]
Star Mass ($M_\odot$)	1.16	A08
Star Radius ($R_\odot$)	1.17	A08
$T_{\rm eff}$ (K)	6190	M08
Limb darkening $u_{\rm a}$	0.275	L08
Limb darkening $u_{\rm b}$	0.381	L08
$P_{\rm rot}$ (d)	9.20205	A08
ϵ	1.10×10^{-4}	L08
Inclination (deg)	90.0	A08
$c_{\rm s}$	0.681	L08
$c_{\rm f}$	0.115	L04
Q	4.5	L08
$\Delta t_{\rm f}$ (d)	8.24037	L08

Parameters of Exo-4a and its planet

Star:

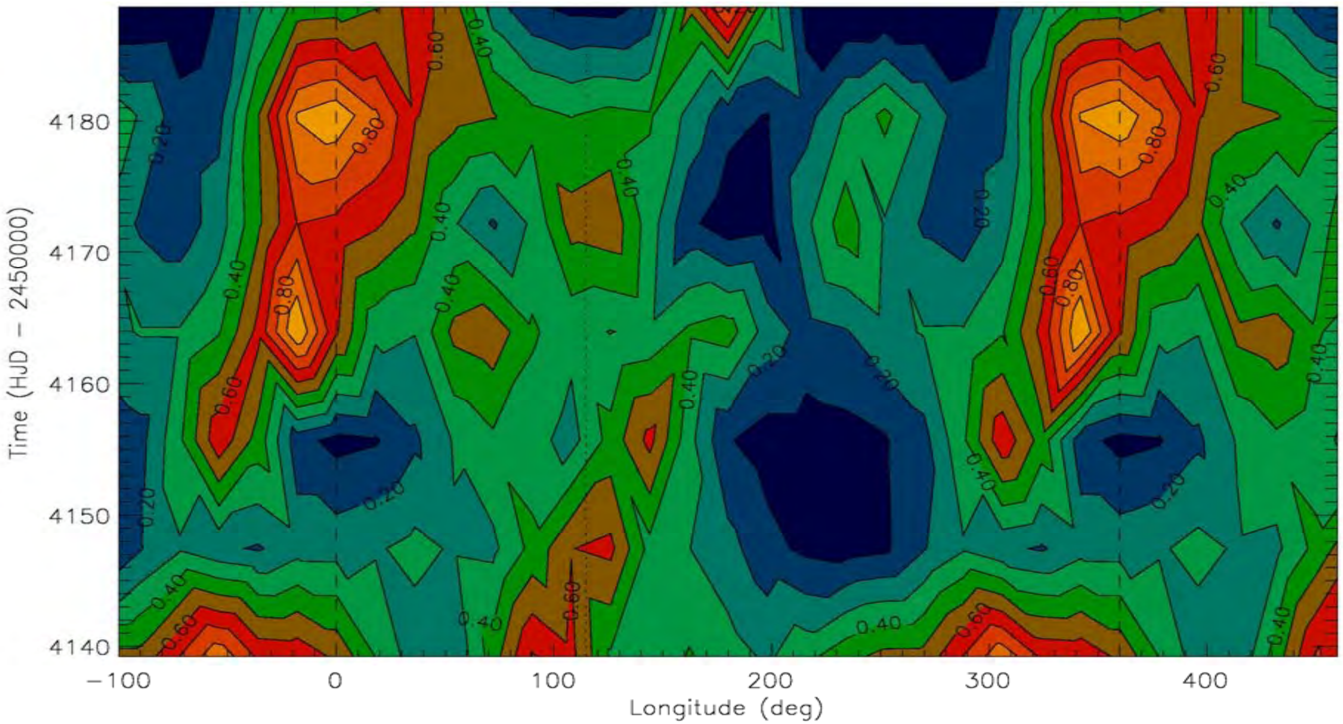
- effective temperature: 6190 ± 60 K;
- mass: 1.16 ± 0.03 solar masses;
- radius: 1.13 ± 0.02 solar radii;
- rotation period: 9.2 ± 0.4 days (synchronized with the planetary orbit);
- v sin i = 6.4 ± 1.0 km/s;
- estimated age: 0.5-3 Gyr;

Planet:

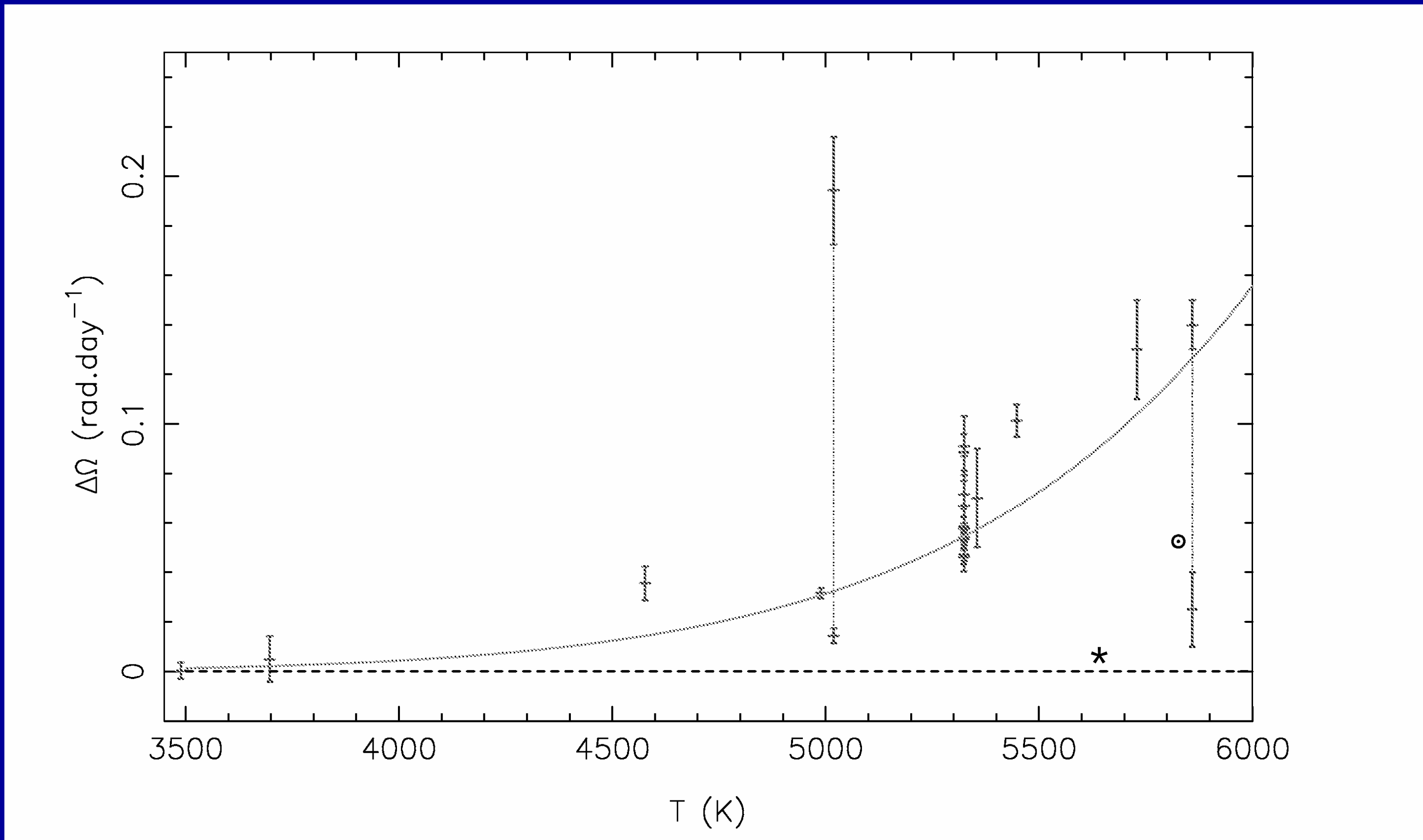
- mass: 0.72 ± 0.08 Jupiter masses;
- radius: 1.19 ± 0.06 Jupiter radii;
- orbital semi-major axis: 0.09 AU;

(Aigrain et al. 2008; Moutou et al. 2008)

pot area vs. longitude and time

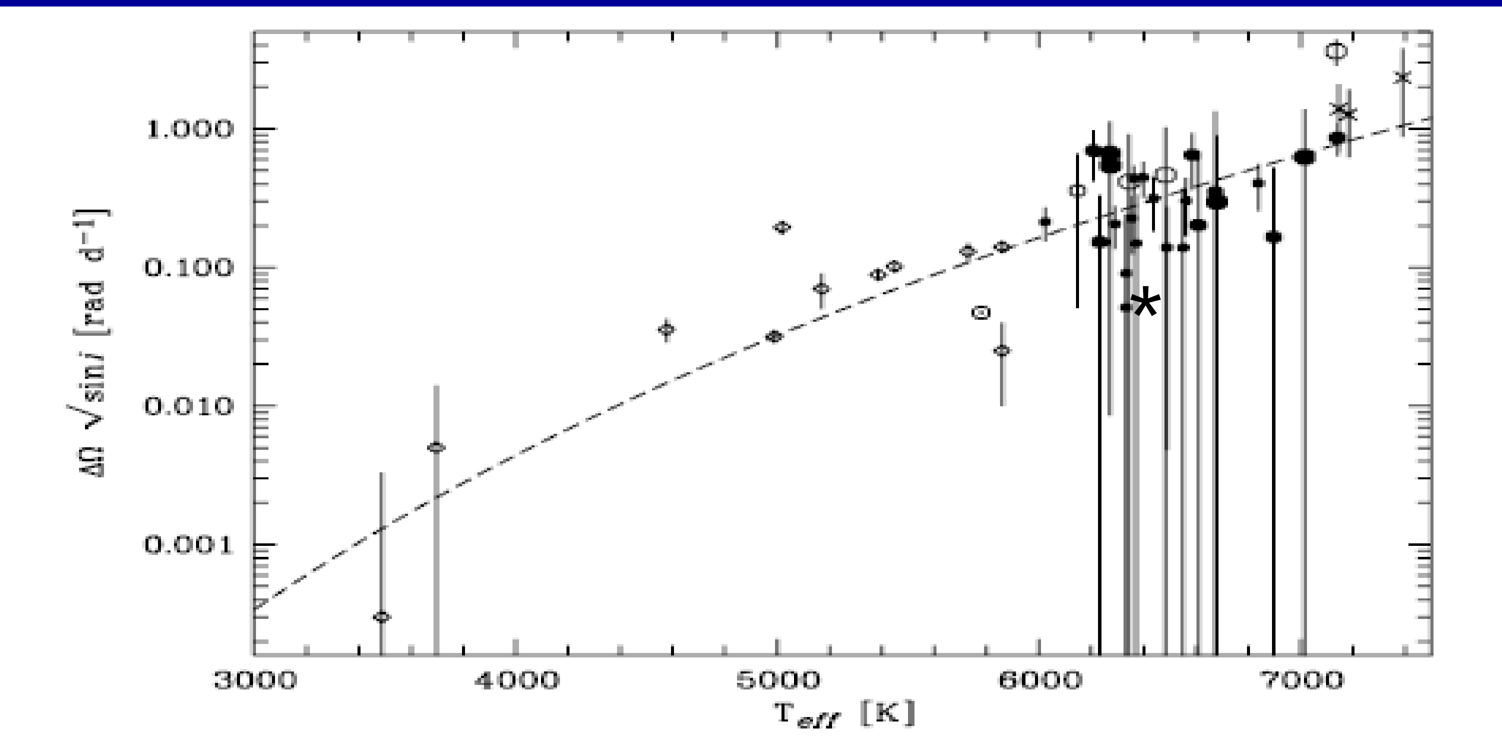


Comparison with other late-type stars



Note that $\Delta\Omega$ is the *total shear* from the equator to the pole; the

SDR in other stars



pplications and future perspective

Photospheric boundary conditions for a modelling of the stellar coronal field (cf. Catala et al. 2007; Donati et al. 2008);

Differential rotation => dynamo parameter;

Time variability of the stellar magnetic flux;

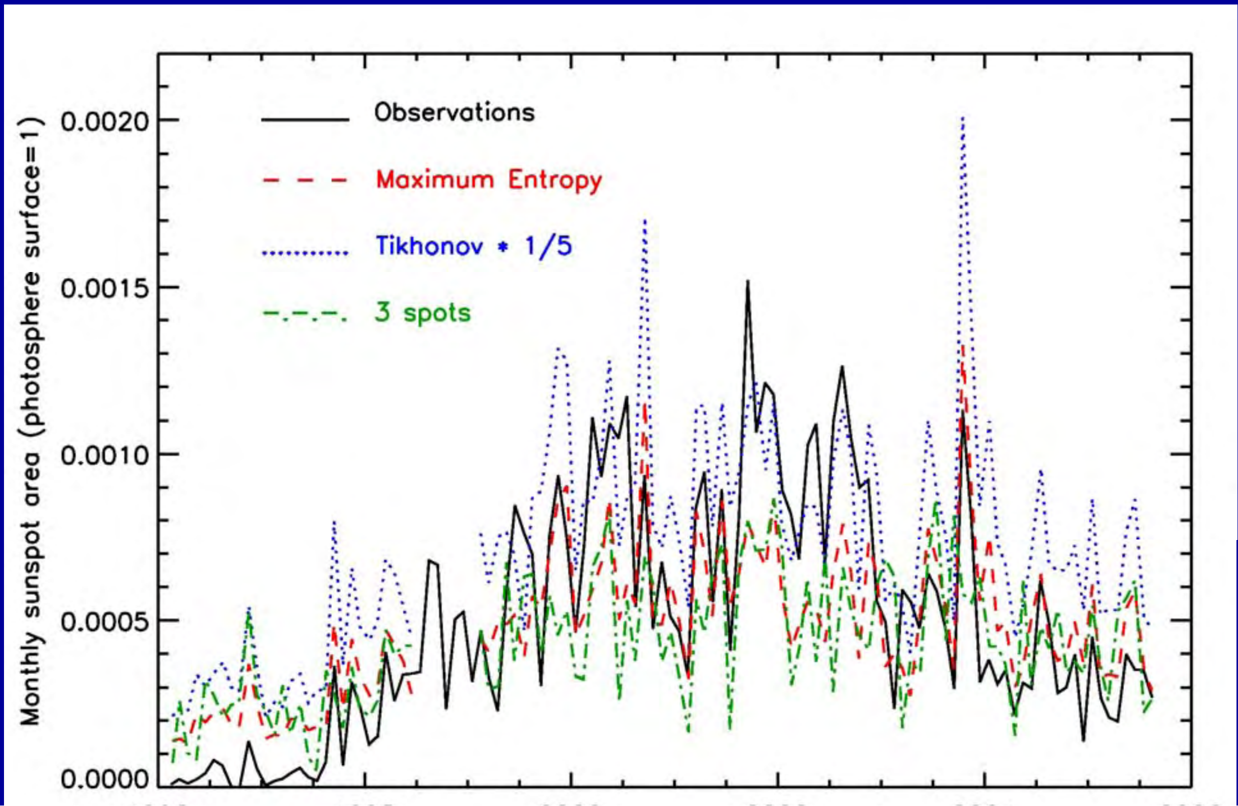
Activity in young solar analogues (*The Sun in ime*);

Spot modelling of the Sun

We can compare the modelled active region areas and longitudes with those of the sunspot groups actually seen on the Sun;

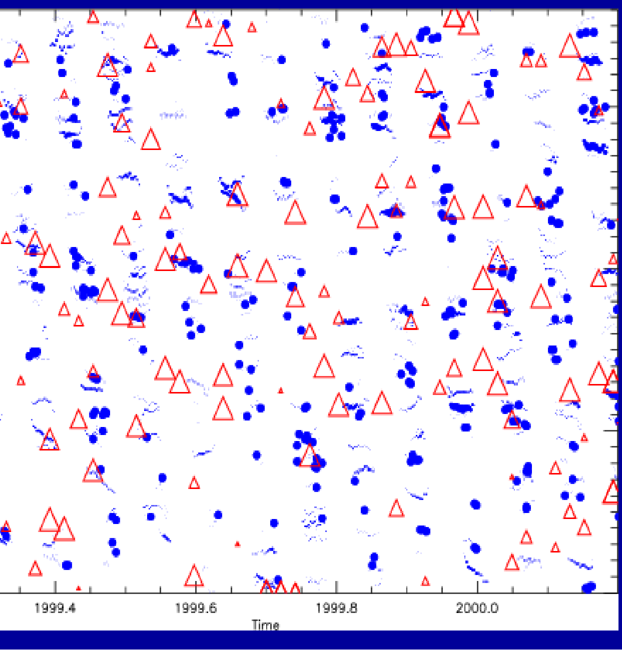
a detailed test of our modelling approach (see Lanza et al. 2003 and 2007).

odel vs. observed sunspot group area variations

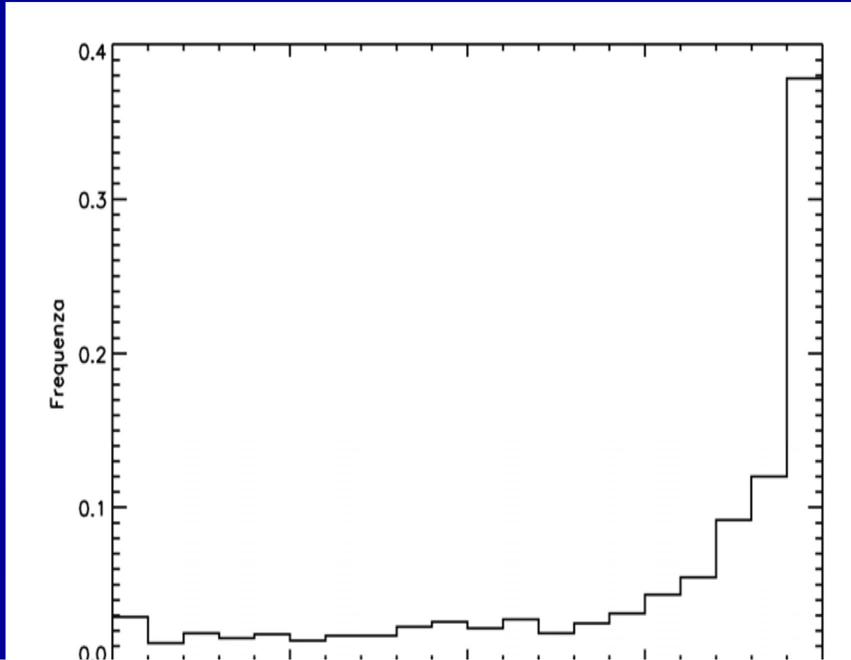


Active region longitudes

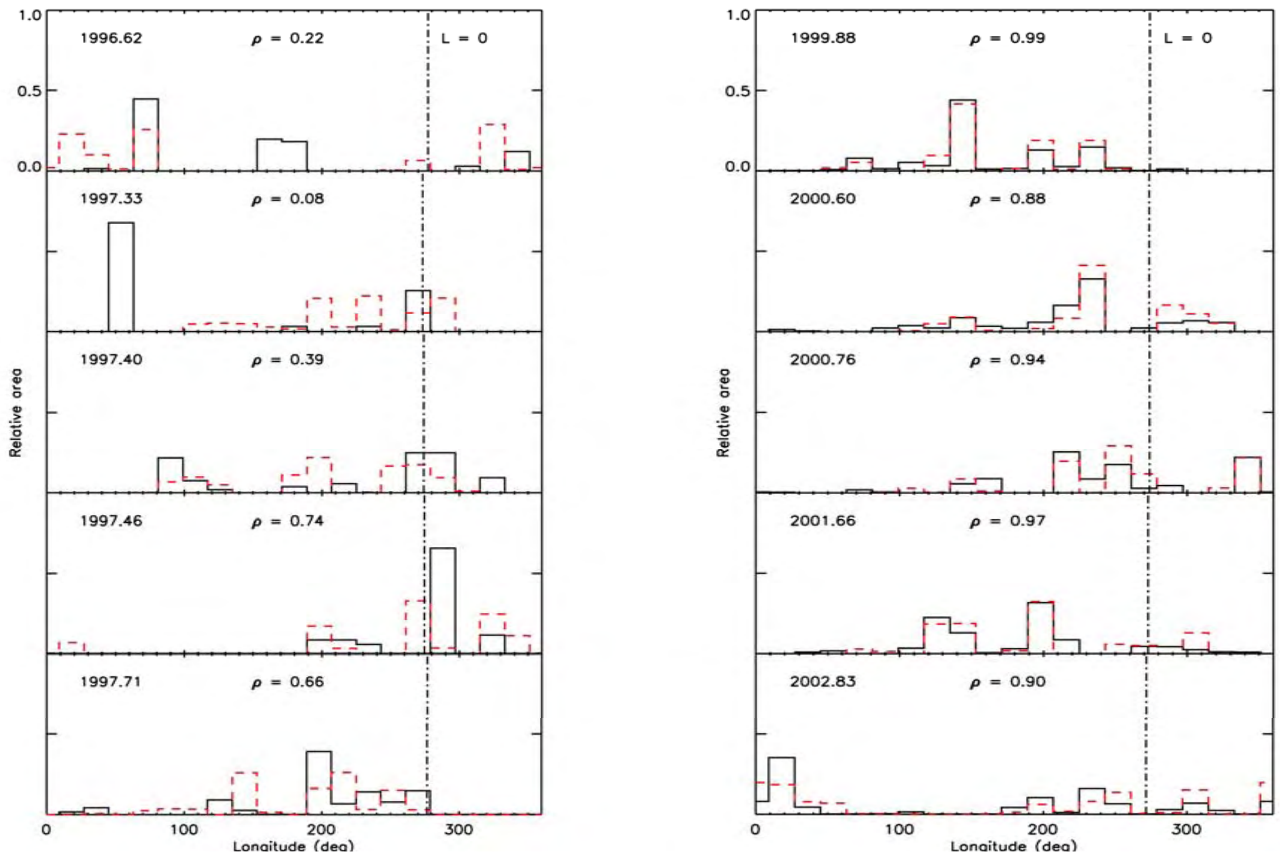
tudes of observed sunspot
s (blue dots) and longitudes
e ARs of our 3-spot model
triangles) for the period
2000



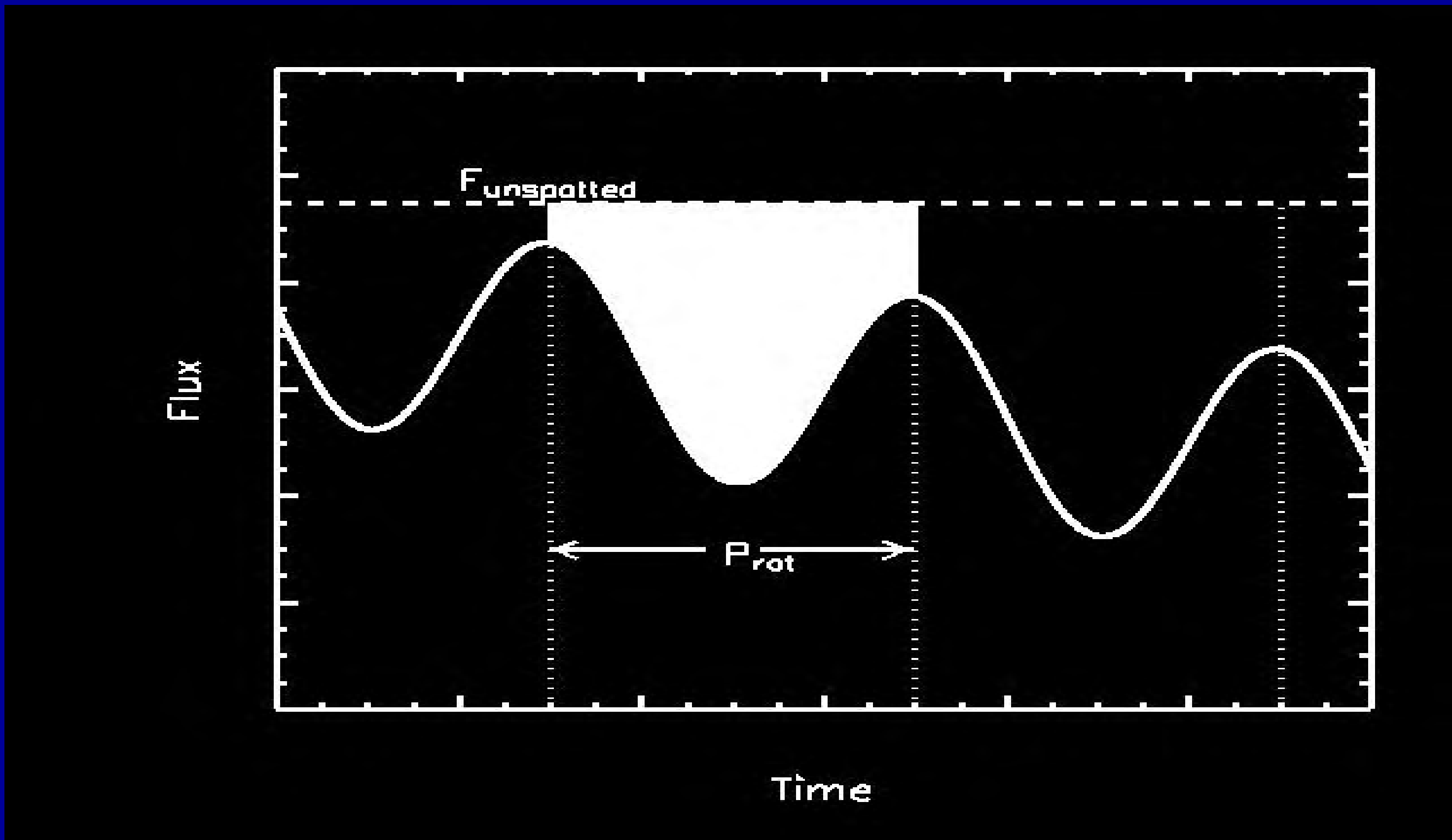
Distribution of the angle between the observed mean sunspot longitude and the mean longitude of the 3 ARs our spot model from the best fit to the 26-yr time series of TSI



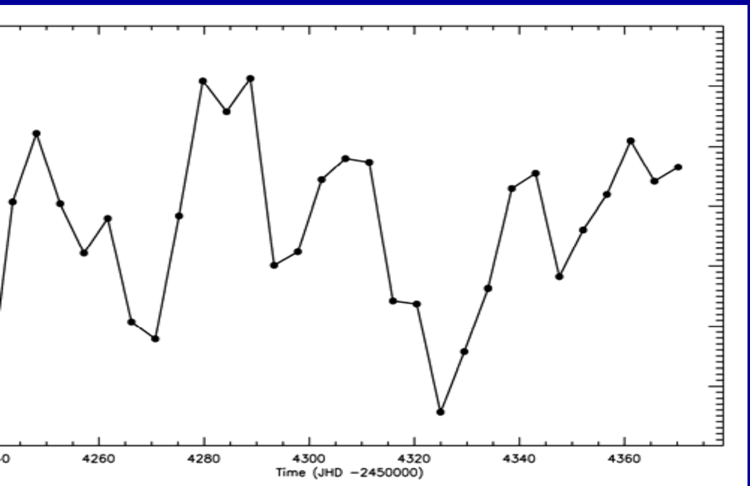
Maximum entropy longitude distributions at different epochs along solar cycle 23:



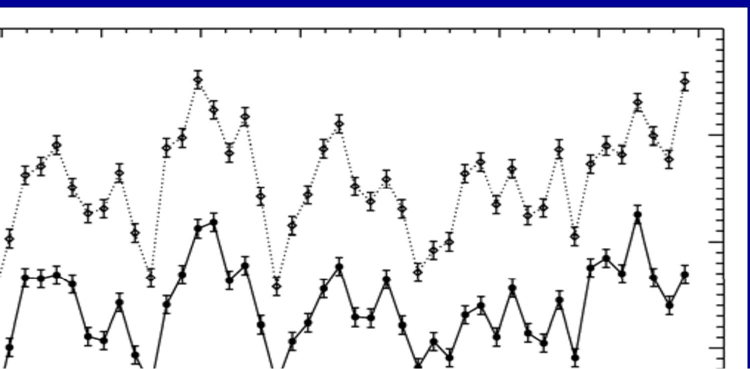
Estimating the relative spot area variation from the integrated flux deficit



Comparison of the two methods for CoRoT-Exo-2a

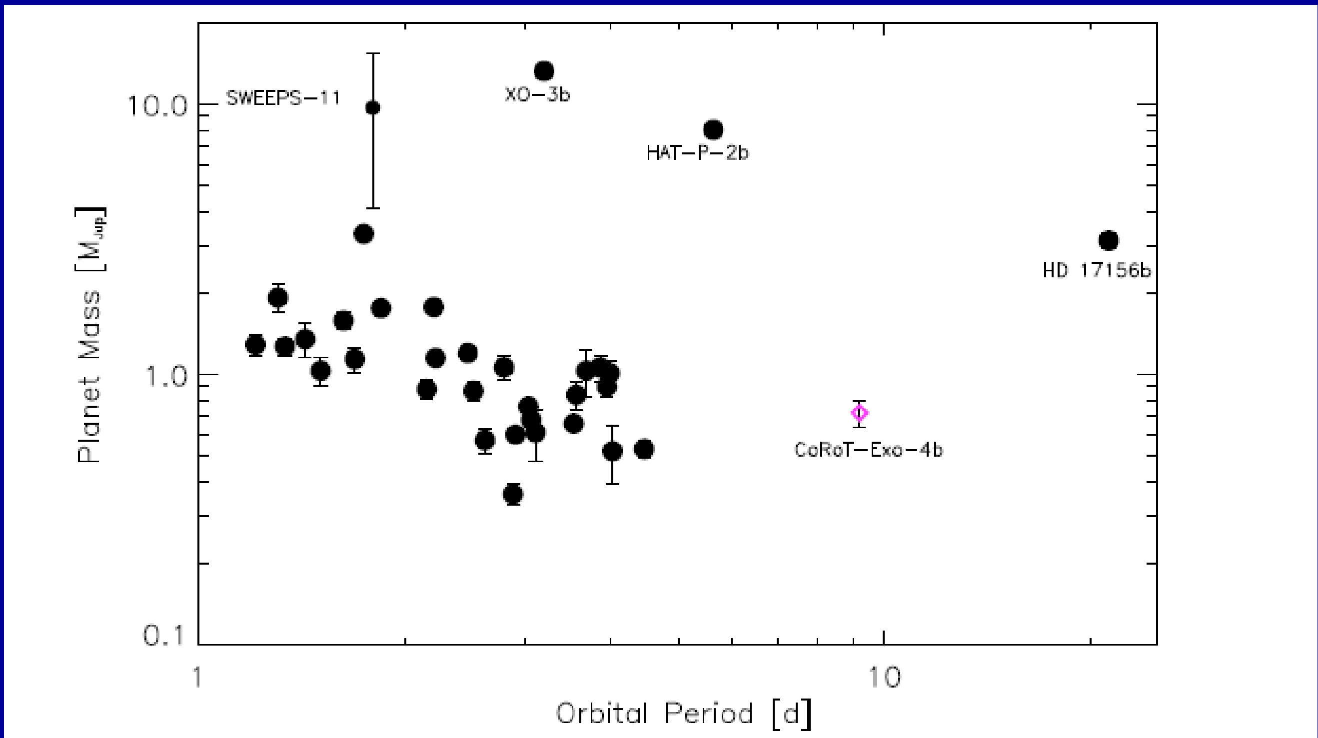


Spot area from the flux deficit integrated along successive rotation cycles (P_{rot} = 4.52 days)



Spot area from ME spot modelling (with and without solar-like faculae)

Mass-period relationship for transiting exo-planets



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