*Comparative Magnetic Minima:*
*Characterizing quiet times in the Sun and stars*
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# Semi-empirical modelling of stellar magnetic activity

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**Abstract.** Since Galileo, for four hundred years, dark spots have been observed systematically on the surface of the Sun. The monitoring of the sunspot number has shown that their number varies periodically every 11 years. This is the well-known solar activity cycle that is caused by the periodic changes of the magnetic field of the Sun. Not only do spots vary in number on a timescale of a decade, but the total luminosity and other signatures of activity such as flares and coronal mass ejections also increase and decrease with the 11-year cycle. Still unexplained to the present date are periods of decades with almost an absence of activity, where the best known example is the Maunder Minimum. Other stars also exhibit signs of cyclic activity, however the level of activity is usually thousand times higher than the solar one. Obviously, this is due to the difficulty of observing activity at the solar level on most stars. Presently, a method has been developed to detect and study individual solar like spots on the surface of planet-harbouring stars. As the planet eclipses dark patches on the surface of the star, a detectable signature can be observed in the light curve of the star during the transit. The study of a different variety of stars allows for a better understanding of magnetic cycles and the evolution of stars.

**Keywords.** stars: activity, stars: spots, stars: rotation

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## 1. Introduction

Sunspots are regions of strong magnetic fields on the surface of the Sun, of the order of hundreds to a few thousands Gauss. The magnetic field suppresses the overturning motion of the convective cells and thus hampers the flow of energy from the stellar interior outwards to the surface. Therefore, the region becomes cooler than the surrounding photosphere and thus appears darker.

Very likely, all cool stars with a convective envelope like the Sun, or even fully convective, will have spots on their surfaces. This is not a new idea, in 1667, the French astronomer Ismael Boulliau (1605-1694) introduced the concept of a starspot to explain the periodic light variability of *Omicron Ceti*, which turned out to be a Mira variable star, but nevertheless the concept was introduced. In the 1940s, starspots were observed by Kron in the eclipsing binary AR Lacertae as a significant light variability outside the eclipse (Kron 1947). Starspots are observable tracers of the internal dynamo activity, and their study provides a glimpse into the complex internal stellar magnetic field.

As dark spots cross the stellar disk due to rotation they modulate the total brightness of the star. The periodic variation generally follows the rotational period of the star. There exists an observational bias toward young stars that are fast rotators (need less observing time) and are also more active. Moreover, their light curve variability is stronger. This is the case of CoRoT-2, the second star discovered by the CoRoT satellite to harbour a planet (Alonso *et al.* 2008).

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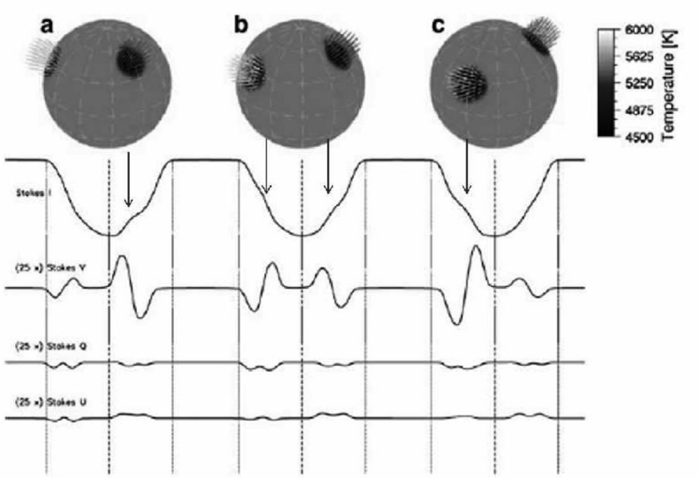


**Figure 1.** Zeeman-Doppler imaging: cool spots cause reduced line absorption at the wavelengths that are proportional to the Doppler velocity at their respective surface location.

The goal here is to spatially resolve the stellar disk and trace individual spots, just as Galileo, Scheiner, and others have done for the Sun 400 years ago. This type of study provides information on: i) stellar rotation and differential rotation; ii) spots location and physical characteristics such as size, temperature, and magnetic field intensity; and iii) magnetic cycles.

## 2. Starspot modelling

There are basically three methods for modelling starspots:

- Analysis of Doppler imaging from spectral lines.
- Light curve modulation: both considering a small number of spots (usually three) and the Maximum Entropy Method.
- Planetary transit mapping.

Doppler imaging is a tomographic technique based on high-resolution spectroscopy. It is applicable only to fast rotators, that is, $v\sin(i) \geqslant 20 - 25$ km/s. Cool spots on the stellar surface generate clearly detectable distortions in the profile of the absorption lines. These distortions move from blue to red wavelengths across the line profile as the spots rotate across the visible hemisphere due to the stellar rotation (see Figure 1). The span of migration within the line profile reveals the feature latitude. Thus, by detecting spots on different latitudes it is possible to determine the stellar differential rotation if any. Strassmeier has mapped the surface of 79 stars this way (Strassmeier 2009).

For slow rotators, such as solar analogues, the modelling of the irradiance variations is based on the information of the location and area of the active regions provided by the rotational modulation of the stellar flux. The assumption here is that the active regions do not change during their transit across the disk, thus the variability of the optical flux is due to the modulation of the visibility of the active regions. The quantities derived by the model are: i) the longitudinal distribution of the filling factor of active regions and ii) the variation of total area of active regions.

One of the caveats of this method is that the reconstruction of the stellar surface map is an ill-posed problem because of the non-uniqueness of the solution and its instability. Moreover, the rotational modulation of the flux is a function of the varia-

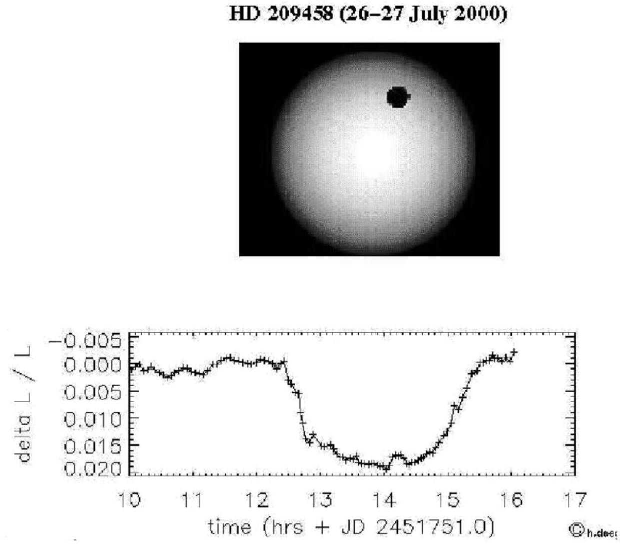


**Figure 2.** Example of the variation ("bump") caused by the occultation of a spot during a planetary transit.

tion of the surface brightness versus longitude, with no information on the latitude. Furthermore, the contrast of the surface brightness inhomogeneities must be assumed, that is the spot temperature cannot be derived from measurements in a single spectral band.

Earlier rotational modulation models were based on just two circular spots, where the coordinates and radii of the spots were adjusted to fit the light curve rotational modulation (Rodono *et al.* 1986). Later, a model with three active regions containing cool spots and bright faculae in a fixed proportion was applied by Lanza *et al.* (2003, 2004) to fit the total as well as the spectral solar irradiance variations. A total of 11 free parameters were needed to describe the model. However, very often the longitudinal distribution of the real active regions was too complex to be described with only three active regions, resulting in a poor agreement between the model and the observations.

The Maximum Entropy method is a regularization technique applied to a continuous spot distribution (Lanza *et al.* 2007). It yields better agreement with the Doppler imaging maps. In this case, the surface of the star is subdivided into 200 squared elements (each with 18° in latitude) with varying filling factors to reproduce the rotational modulation of the star. The downside is that there are a large number of free parameters (about 200) and the stellar rotation period is fixed, and not estimated by the method. The ratio between the area of faculae and of sunspots is also fixed. The regularized solutions are computed by minimizing a function that is a linear combination of the reduced $\chi^2$ and a regularizing function that accounts for the a priori assumptions on the filling factor map of the spots. Lanza and collaborators applied this model to many stars, among them CoRoT-2, 4, 6, and 7.

Presently nearly 800 extrasolar planets have been discovered orbiting other stars. More than 200 (about 30%) of them transit their host star. During one of these transits, the planet may pass in front of a spot group and cause a detectable signal in the light curve of the stars, shown in Figure 2.

## 3. Spotted star with planetary transit

### 3.1. *Method*

The method discussed in this section simulates planetary transits, using the planet as a probe to study starspots (Silva 2003). This technique yields the individual spots physical characteristics such as:

• Size, or surface area coverage.

• Intensity, that can be converted to temperature assuming black body emission. This can be further translated to an estimate of the magnetic field provided that a solar model is used.

• Location, both the longitude and latitude of the spots.

Also, from observation of successive transits, presuming that the same spot is detected a few times on different transits, the stellar properties can be inferred such as:

• Rotation period.

• Differential rotation, if a mean period is known.

• Activity cycle, provided that a long enough observational time series is obtained.

The model creates a 2-D synthesized image of a star with a given limb darkening (linear or quadratic), whereas the planet is an opaque disk of radius $r/R_s$, where $R_s$ is the stellar radius. The orbit is assumed to be circular and the orbital axis and stellar spin axis are parallel. Every 2 minutes (or a desired time interval), the planet is centred at its calculated position in a circular orbit (with semi-major axis $a/R_s$ and inclination angle $i$). The light curve flux at every instant in time is the sum of all pixels in the image. The input parameters for the transit simulation are the orbital period, semi-major axis, inclination angle, and the ratio of the planet and stellar radii. The Southern hemisphere projection of the transit was arbitrarily chosen. The main program and auxiliary routines of this model can be found in www.craam.mackenzie.br/∼avalio/research.html.

The interesting feature of this model is to allow for the presence of sunspots on the stellar photosphere. The spots are considered circular and with a constant brightness. Also the foreshortenning effect of the spots close to the stellar limb is taken into account. Each spot is characterized by three parameters: radius (in units of planetary radius), intensity (measured with respect to the stellar central intensity), and location (longitude and latitude). To decrease the number of free parameters, so far I have only considered the latitude of the spots to be on the projected transit cord.

The spotted star with transiting planet model was applied to five stars observed by the CoRoT satellite: CoRoT-2 (Silva-Valio *et al.* 2010; Silva-Valio & Lanza 2011), CoRoT-4 and 6 (Valio & Lanza 2012), CoRoT-5, and CoRoT-8. The parameters of the star and its orbiting planet are given in Table 1 (where $P_{rot}$ means the stellar rotation period). Images of the synthesized stars and the modelled spots during the first transit, with their respective planet at mid transit (depicted as a black circle) are shown in Figure 3.

### 3.2. *Results*

The number of transits observed varies from star to star, depending on the orbital period of the transiting planet. CoRoT-2 is the star with the larger number of transits, 77, because the planets orbits its host star every 1.743 d. Being a very young star, less than half a billion year, it is also very active, with a total of 392 spots detected, or an average detection of 5 spots per transit. CoRoT-4 was observed during a short run of less than 60 days, thus only 6 transits were detected and a total o 12 spots modelled. The other stars were detected during the long runs of 140 days, however not all transit observations are usable for the model. Therefore, 89, 71, and 33 spots were modelled for the stars CoRoT-5, CoRoT-6, and CoRoT-8, respectively.

**Table 1.** Stellar and planetary parameters

| Star | CoRoT-2[1] | CoRoT-4[2] | CoRoT-5[3] | CoRoT-6[4] | CoRoT-8[5] |
|---|---|---|---|---|---|
| Spectral type | G7V | F8V | F9V | F9V | K1V |
| Mass ($M_{sun}$) | 0.97 | 1.10 | 1.0 | 1.055 | 0.88 |
| Radius ($R_{sun}$) | 0.902 | 1.17 | 1.19 | 1.025 | 0.77 |
| Teff (K) | 5625 | 6190 | 6100 | 6090 | 5080 |
| Prot (d) | 4.54 | 8.87 | 26.6 | 6.35 | 21.7 |
| Age (Gyr) | 0.13-0.5 | 0.7-2.0 | 5.5-8.3 | 1.0-3.3 | 2.0-3.0 |
| Mass ($M_{jup}$) | 3.31 | 0.72 | 0.467 | 2.96 | 0.22 |
| Radius ($R_{jup}$) | 0.172 | 0.107 | 0.467 | 2.96 | 0.22 |
| Orbital period (d) | 1.743 | 9.203 | 4.038 | 8.886 | 6.212 |
| Semi-major axis ($Rstar$) | 6.7 | 17.47 | 9.877 | 17.95 | 17.61 |
| Latitude (°) | -14.6 | 0 | -47.2 | -16.4 | -29.4 |

*Notes:*
[1] Alonso *et al.* (2008)
[2] Aigrain *et al.* (2008)
[3] Rauer *et al.* (2009)
[4] Fridlund *et al.* (2010)
[5] Borde *et al.* (2010)

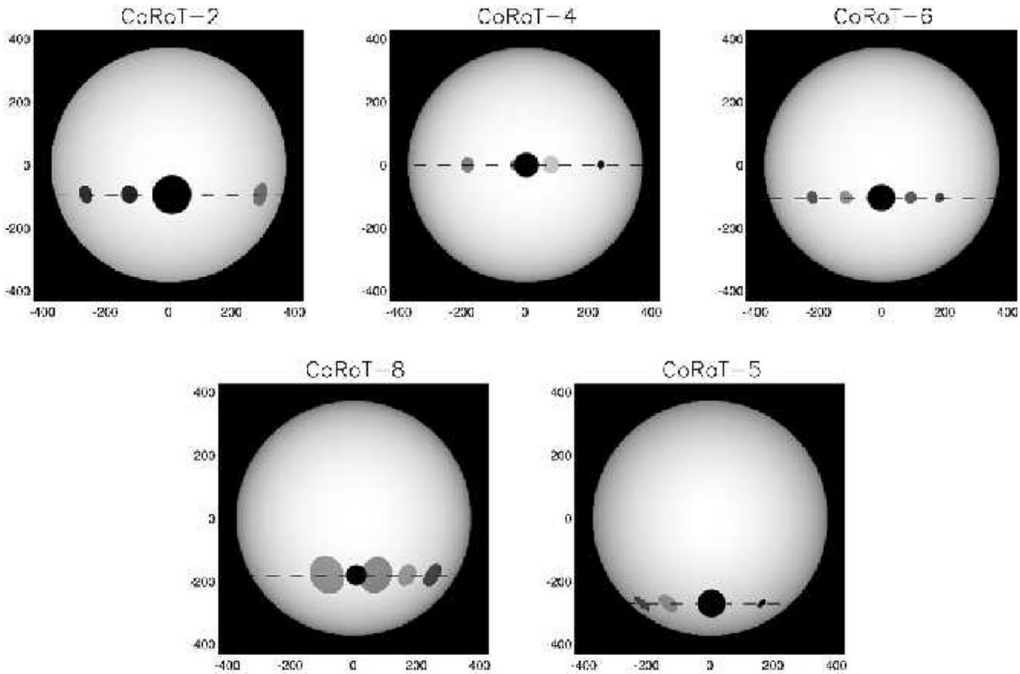


**Figure 3.** Five CoRoT stars with their transiting planet (black disk in the centre of the transit).

The average value of the radii of the spots and contrast with the rms are listed in Table 2, for all five stars. The last column displays the average values of the Sun for comparison. Assuming that the emission of both the surrounding photosphere and of the spot are black body emissions, the temperature of the spot may be estimated. These are the average temperatures values displayed in Table 2. Also, the 2-D histograms of the radius and contrast of the spots on each star are shown in Figure 4.

For each transit it is possible to estimate the area of the stellar surface covered by the spots, as has been done for CoRoT-2 (Silva-Valio *et al.* 2010), only within the latitude band obscured by the passage of the planet. The average total area of the spots in each

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**Table 2.** Spots physical characteristics

| Star | CoRoT-2 | CoRoT-4 | CoRoT-5 | CoRoT-6 | CoRoT-8 | Sun |
|---|---|---|---|---|---|---|
| Radius ($\times 10^6$ m) | $55 \pm 19$ | $51 \pm 14$ | $75 \pm 17$ | $48 \pm 14$ | $82 \pm 21$ | $12 \pm 10$ |
| Area (%) | $13 \pm 5$ | $6.0 \pm 1.5$ | $13 \pm 3$ | $8.2 \pm 2.0$ | $29 \pm 10$ | $< 1$ |
| Contrast ($I_c$) | $0.45 \pm 0.25$ | $0.73 \pm 0.14$ | $0.48 \pm 0.19$ | $0.49 \pm 0.18$ | $0.52 \pm 0.22$ | $0.46 \pm 0.19$ |
| $T_{spot}$ (K) | $4600 \pm 700$ | $5300 \pm 500$ | $5100 \pm 600$ | $5100 \pm 500$ | $4400 \pm 600$ | $4800 \pm 400$ |

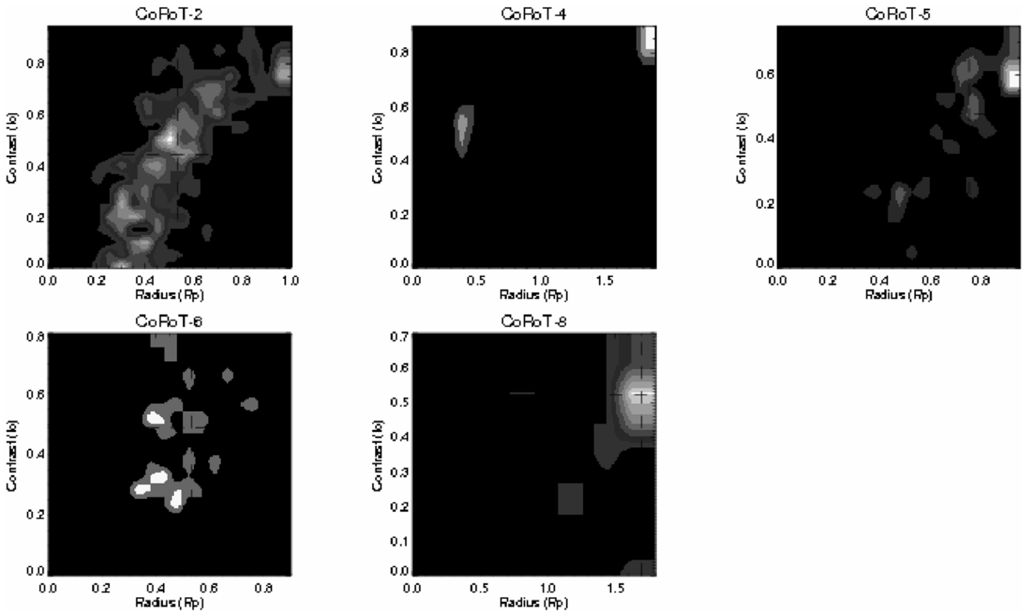


**Figure 4.** 2-D distributions of the radius and contrast of the spots for the five CoRoT stars.

transit is listed in Table 2 and shown, as a function of time in Figure 5. The star with the surface most covered by spots is CoRoT-8, with almost 30% coverage, note that this occurs at high latitudes (−29°).

Figure 6 presents the spotted stellar area as a function of the rotation period of the star (top right panel), orbital period (bottom left panel) and semi-major axis (bottom right panel) of the planet. The top left panel shows the rotation period of the star as a function of the orbital period, except for CoRoT-2 (with the closest hot Jupiter) there appears to be an anti-correlation between both periods.

A way to visualize how the spots are distributed on the stellar surface, restricted to the latitude bands covered by the planetary transit, of course, is to stack the longitude position of the spots on successive transits forming a “map” of the stellar surface. This was initially done considering the position of the spot as viewed from Earth. These are known as the topocentric longitude, and are limited to ±90°, where zero longitude corresponds to the line-of-sight at the the time of mid transit. Such maps for the 5 stars are shown in Figure 7, where the size of the circles are proportional to the modelled spot radius.

It is more interesting to know the position of the spots in a reference frame that rotates with the star that is called the rotational longitude. The conversion between topocentric

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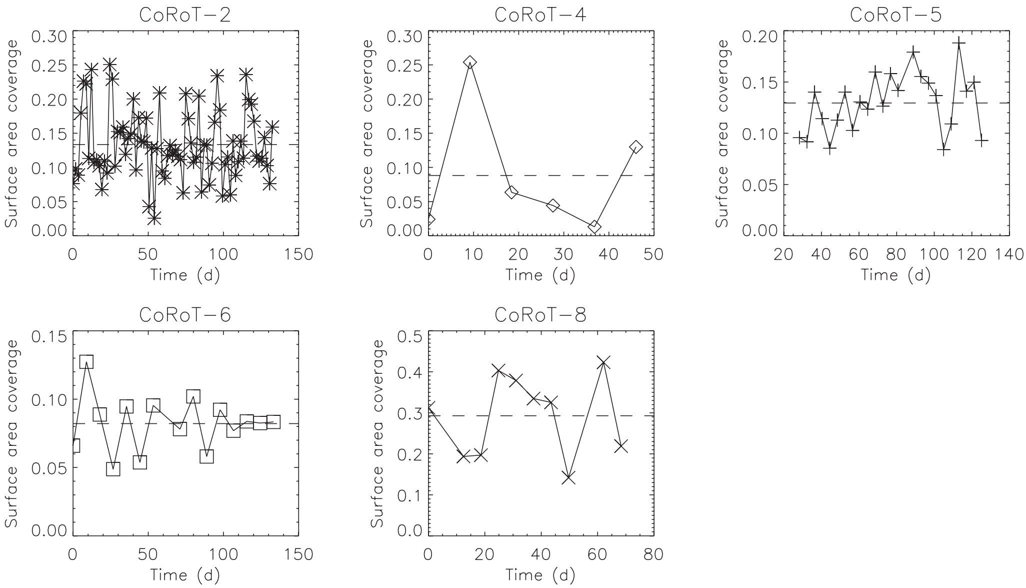


**Figure 5.** Spotted area coverage within the transit band latitudes as a function of time for the five CoroT stars.

and rotational longitudes is given by:

$$\beta_{rot} = \beta_{topo} - 360^\circ \frac{nP_{orb}}{P_{star}} \tag{3.1}$$

where $P_{orb}$ is the orbital period (d), $n$ is the transit number, and $P_{star}$ is the stellar rotation period. The spotted surface maps of the five stars are displayed on Figure 8. The values on the top of each panel correspond to the rotation period of the star in days.

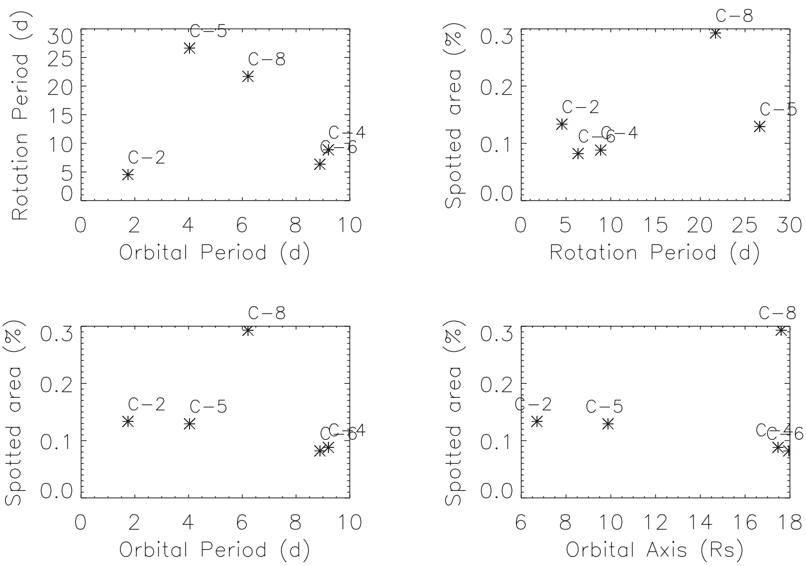


**Figure 6.** For the five CoroT stars: (top left) Stellar rotation period versus orbital period. (top right) Spotted surface area versus stellar rotation period. (bottom left) Spotted surface area versus planet orbital period and axis (bottom right).

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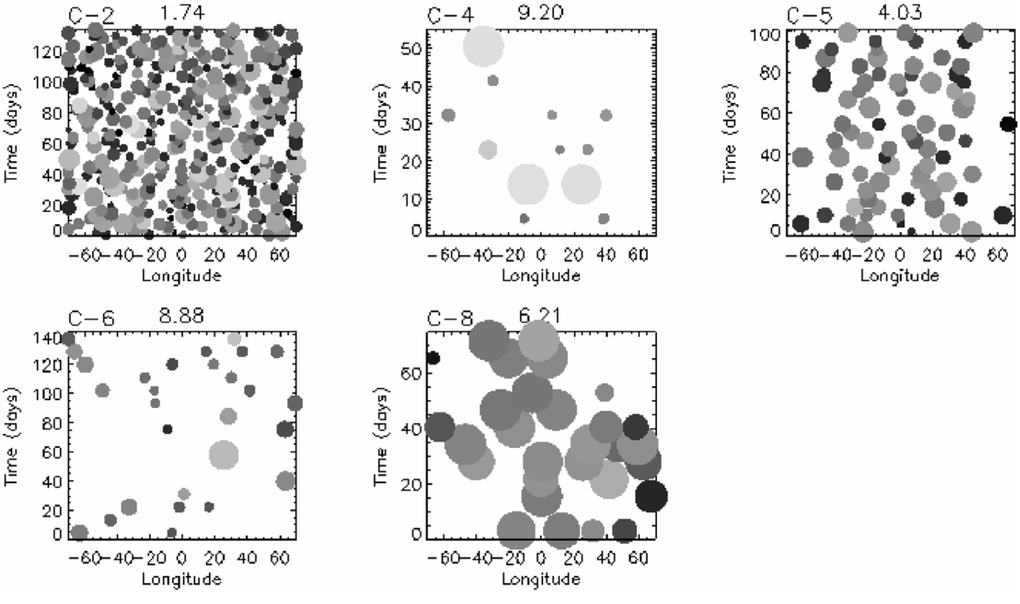


**Figure 7.** Surface maps of the spots for the five CoRoT stars as a function of their topocentric longitudes.

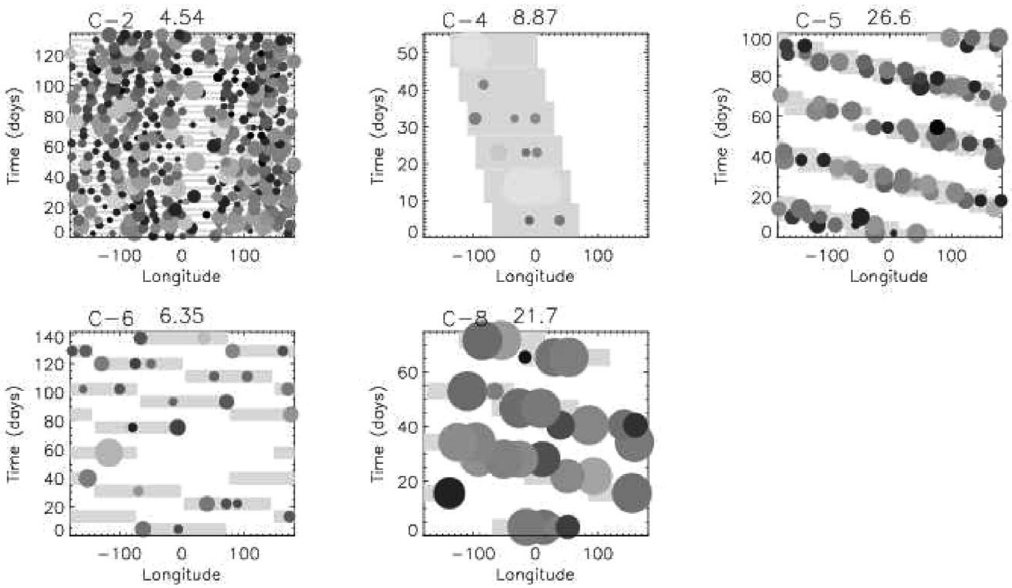


**Figure 8.** Same as Figure 7 but for the rotation longitudes of the spots.

As a last calculation, it is demonstrated how a magnetic activity cycle, similar to the 11 year solar cycle, may be inferred from the spotted surface area coverage for the star CoroT-2, reproduced again on the left panel of Figure 9. A running mean every 20 points is shown as the solid grey (red in the colour version) line. The power spectrum of the spotted area was calculated using the Scargle routine and is shown in the right panel. Several periods are identified with the orbital period, the stellar rotation, a 18 d periodicity observed in the spots coverage that is approximately equal to 10 times the

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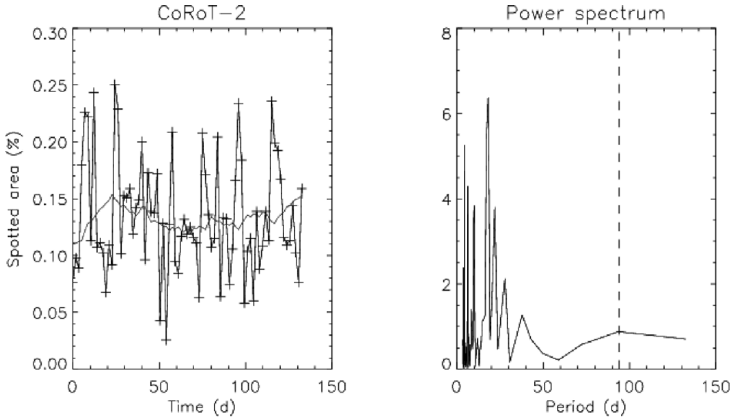


**Figure 9.** Left: Spotted surface area coverage of the spots on CoRoT-2 as a function of time for the 77 transits. Right: Power spectrum of the spotted area coverage.

orbital period, and the longest peak at around 94 days (dashed line). If this series was long enough such as to cover a significant fraction of the magnetic cycle of CoRoT-2, it would be detectable in the spotted area coverage of the star.

## 4. Discussion and conclusions

A technique that models the spots on the surface of a star by fitting the "bumps" detected on the transit light curve of stars with transiting planets was applied to five stars observed by the CoRoT satellite. This technique allows to determine the individual spots physical characteristics such as size and contrast.

The starspots modelled here are 4 to 7 times larger than regular sunspots, this happens probably due to the planet large size, and because spot groups are being detected (i.e., active regions) and not individual spots. The area covered by spots within the transit band of the star varies from 7 to 30%, on average. Moreover, there does not seem to be any correlation between the spotted area on the stellar photosphere and the rotation of the star, neither with the orbital parameters of the planet.

In conclusion, the modelling of small variations observed in the transit light curves yields:

- From single transits: Spots physical characteristics (size, temperature, location active longitudes, evolution/lifetime, surface area coverage, magnetic fields) (Silva 2003);
- From multiple transits: Stellar rotation (Silva-Valio 2008) and stellar differential rotation (Silva-Valio *et al.* 2010; Silva-Valio & Lanza 2011); and
- For longer observing period: Stellar activity cycles.

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## Discussion

Axel Brandenburg: If you say 4-7 times larger starspots than sunspots, one would like to know about selection effects?

Adriana Valio: The main selection effect is that these are planet hosting stars but solar type. The inferred starspot size is big because the probe, the planet - a hot Jupiter, is big. We are probably detecting the whole active region or sunspot group. Once I start analyzing transits of smaller planets, these values should decrease as we may identify individual spots.

Katja Poppenhager: You only constructed spots in the transit path (in line with the planet). What about spots at other latitudes? Are you planning to do some work including this in your model?

Adriana Valio: Presently, I don't model the spots on the stellar disk outside the transit latitude bands. But, as the spots don't change during transits (a few hours) and the light curve is normalized, that should not affect the results.

Francesco Zuccarello: How do you determine the stellar latitude where the planet transits in front of the star?

Adriana Valio: It is a geometric calculation from the semi-major axis and inclination angle of the planetary orbit.

Pablo Mauas: You could have spots just because of the interaction between the planet and the magnetosphere of the star. Perhaps the spots would not be there if it wasn't for the planet.

Adriana Valio: That may be true because there definitely is a planet-star interaction. This is clearly seen in the CoRoT-4 data, where an active longitude is observed at -30 deg. or 30 deg. from the sub-planetary point.