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STARSPOT DETECTION FROM PLANETARY TRANSITS OBSERVED BY COROT

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RESUMEN

Las manchas solares son zonas más oscuras que el brillo promedio del disco solar, y su tamaño es comparable al de la Tierra. Cuando un planeta eclipsa a su estrella central es posible detectar fenómenos físicos que se manifiestan en la superficie estelar. Si se eclipsa parcial o totalmente una mancha estelar oscura en la superficie estelar, la luminosidad estelar integrada disminuirá ligeramente. Analizando la curva de luz medida durante un tránsito planetario es posible inferir las propiedades físicas de las manchas estelares, tales como tamaño, intensidad, posición y temperatura. Información adicional, como rotación estelar, rotación diferencial, y aún los ciclos de actividad magnética, pueden derivarse de observaciones realizadas en más de un tránsito. Observaciones del tránsito planetario en la estrella HD 209458 fueron utilizadas para probar el modelo. Discutiré como este modelo puede ser aplicado a los tránsitos planetarios detectados con CoRoT.

ABSTRACT

As a planet eclipses its parent star, features on the disk of the star may be detected. For example, sunspots on active regions are darker than the average disk of the Sun, and their sizes are comparable to that of the Earth. Hence, as the planet eclipses partially or totally a dark starspot on the surface of the star its integrated luminosity will increase slightly. Therefore, by analyzing the transit light curve it is possible to infer the physical properties of starspots, such as size, intensity, position, and temperature. Extra information, such as stellar rotation, differential rotation, and even magnetic activity cycles, may be obtained from observing features like these on more than one transit. Transit observations of HD 209458 were used as tests to the model and I will discuss how this model can be applied to the planetary transits detected by CoRoT.

Key Words: stars: spots — planetary systems

1. INTRODUCTION

On the visible disk of the Sun, small dark regions are seen commonly, these are called sunspots and were first observed by Galileo four centuries ago. These are regions of high concentration of magnetic fields and appear dark because they are cooler than the surrounding photosphere by about 1000 K. Sunspots are the most used indicators of solar activity and their number follows the 11 year cycle of the Sun being much more abundant during periods of high activity and almost completely disappearing from the disk of the Sun 5 to 6 years later.

Stars other than the Sun are also known to exhibit activity and some in fact have very large spots on their surface, maybe covering about a third of the stellar surface area. Currently it is not possible to detect, much less study the behavior of solar like spots on the surface of other stars, particularly due to their very small sizes. Nevertheless, I developed a new method for detecting and characterizing such small spots (Silva 2003).

This method for studying the physical characteristics of starspots is based on planetary transits. During one of its transits, an extra-solar planet may pass in front of a stellar group of spots. As of May 2007, 293 planets have been discovered (for an updated list of the planets detected see `http://exoplanet.eu`), among which 51 are transiting planets.

Several physical characteristics of the spots may be obtained, such as size, temperature, and position. And from its position during consecutive transits it is possible to estimate the stellar rotation and even differential rotation if the planet is large enough to cover a wide latitude span of the star.

The following section presents the model in detail, whereas the section after that describes how this model can be applied to the transits of HD209458. In § 4, the rotational period of a star is calculated by monitoring spots during consecutive transits. Finally, the conclusions are presented in the last section.

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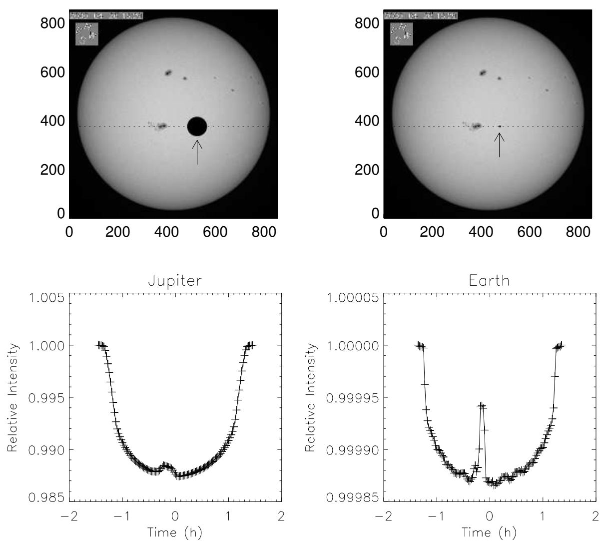

Fig. 1. Transit simulations in front of a spot from a Jupiter (left) and Earth (right) sized planet.

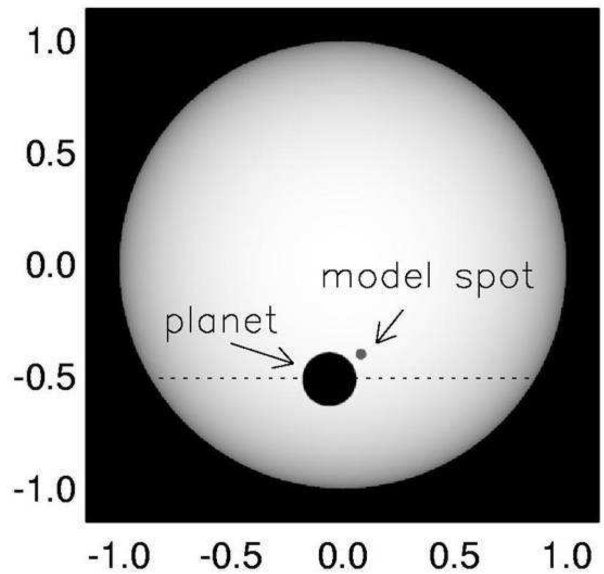

Fig. 2. Model of planetary transit in front of a starspot. The model star depicted here has a quadratic limb darkening.

2. THE MODEL

As described in Silva (2003), the model consists of using a white light image of the Sun for the star and modeling the planet as a dark disk with a radius relative to the "star" radius. However, a synthesized 2D image of the star can also be used instead. Then the position of the planet in its orbit is calculated for each desired time interval given its orbital parameters: a, the semi-major axis, and i, inclination angle. The orbit is considered to be circular, thus a is the radius of the orbit and is measured in stellar radii. Next, the planet is centered at a given position in its transit and the flux is calculated by summing up the intensity of all the pixels in the image. By estimating the flux at each time for different planetary position, a light curve is obtained.

An example of what the light curve of such a transit would look like is shown in Figure 1 where an image of the Sun was used to mimic the star. The left panels are for a Jupiter sized planet, $R_p/R_s = 0.1$, whereas the figures on the right represent the transit of a planet the size of Earth, $R_p/R_s = 0.009$, where R_p and R_s are the planet and star radii, respectively. The dark disks of the planets are indicated by arrows. As can be seen from the figure, the Jupiter transit is 1.2% deep, whereas the decrease in intensity of an earth-size planet would be only 0.013%. The influence of the spot, however, is much more evident in the small planet transit. Hopefully, it will be possible to detect such effects on the transit of Earth-like planets to be discovered by CoRoT.

Therefore, features like the ones in the bottom left panel of Figure 1 are searched for in the light curves of transiting planets. Such spot signatures were found in the light curves of HD209458 (Deeg et al. 2001; Brown et al. 2001) and TrES-1 (Charbonneau et al. 2007). In order to match the variations in the observed curves, spots are added to the modeled star and described by four parameters. The spot is modeled as a disk of a given (1) size (relative to the planet size), (2) latitude and (3) longitude of the star, and with a certain (4) intensity, relative to the maximum intensity of the star (that is the stellar central intensity). An example of a modeled spot can be seen in Figure 2.

For a given value of the spot parameters, the total intensity is calculated for each position of the planet along its transit (shown as the dotted line on Figure 2). Thus, the simulated light curve is the result of the intensity integration for each of the planet position, including its passage in front of the spot. The spot parameters are chosen such that the model light curve can reproduce the observations. However, since more than one combination of the parameter values can fit the data reasonably well, a search in parameter space was performed. The best values of the spot parameters are chosen by a least square method, and those with the smallest chi^2 are selected.

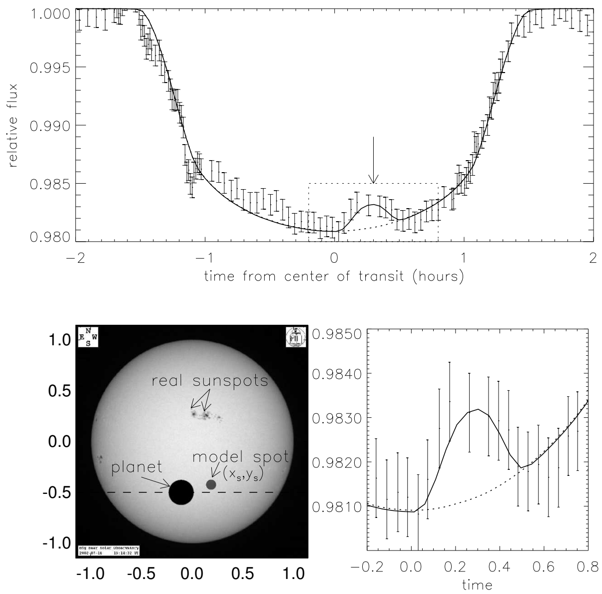

Fig. 3. Spot modeling of HD209458 applied by the observations performed by Deeg and collaborators (2001).

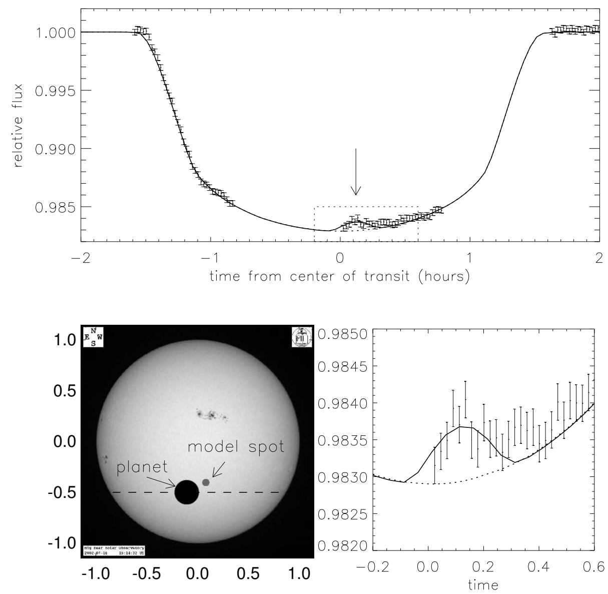

Fig. 4. Same as Figure 3 for the HST data taken by Brown et al. (2001).

3. SPOTS ON HD209458

The model described in the previous section was applied to observations of HD 209458 (Brown et al. 2001; Deeg et al. 2001). These observations are shown in Figures 3 and 4. The small increase in the intensity during the flat part of the transit due to spots are indicated by arrows in both figures. These variations in the light curves are presumably caused by the planet occultation of a dark feature on the stellar surface, similar to a sunspot. Since spots are cooler and therefore darker than the surrounding stellar photosphere, their occultation will cause an increase in the intensity during a short period of the transit. This happens because the intensity decrement is smaller when the planet eclipses a dark region of the stellar surface (the spot) than when it blocks a brighter region of the star that has no spots.

Both the orbital and planet parameters were taken from the literature (Henry et al. 2000; Brown et al. 2001). The planet in considered to be in a circular orbit around HD 209458 with a period of 3.5247 days, major semi-axis of 0.0467 AU, and inclination angle of 86.68. This is equivalent to the planet crossing the star at a latitude of 30.45°. The planet radius was taken as 1.347 $R_{\rm Jup}$, whereas the stellar radius is 1.146 $R_{\rm Sun}$. The planet position is calculated at two minutes time interval, when all the pixels values in the image are summed, yielding the light curve.

For the modeling of the Deeg et al. (2001) observations, a white light image of the Sun was used. However, the more precise HST data (Brown et al. 2001) are not well fit by the model, indicating that the limb darkening of HD209458 is not a linear function of μ, as that of the Sun, instead it is best described by a quadratic function ($\mu = \cos\theta$)

$$\frac{I(\mu)}{I(1)} = 1 - w_1(1-\mu) - w_2(1-\mu)^2 \,, \qquad (1)$$

where $w_1 = 0.2925$ and $w_2 = 0.3475$ (Brown et al. 2001).

Thus, a synthesized 2D image was constructed with the appropriate limb darkening (see Figure 2). A search in parameter space for the spot physical characteristics (size, intensity, and position) was performed and the values are listed on Table 1 of Silva (2003). Since the variation of the light curve of the HD209458 observation taken on April 25, 2000 (Brown et al. 2001) was smaller, the resulting sizes are smaller and the intensities larger.

In summary, the resulting spot sizes, in units of planet radius, were 0.4–0.6 and 0.3–0.4 for the July 26, 2000 (Deeg et al. 2001) and April 25, 2000 (Brown et al. 2001) observations, respectively. The acceptable intensities varied from 0.4–0.6 and 0.5–0.7 of the central maximum intensity for both sets of data. The perpendicular distance to the transit line, in units of planet radius, ranged from 0.5–0.8 and 0.7–0.9, respectively for the Deeg et al. (2001) and Brown et al. (2001) data.

From its relative intensity, the starspot temperature, T_s, can be estimated if one considers its emission to be of blackbody type, as well as the emission of the star. Assuming an effective photospheric temperature T_e of 6000±50 K (Mazeh et al. 2000) for the star, the spot temperature can be estimated from:

$$\frac{I_{\rm spot}}{I_{\rm star}} = \frac{\exp\left(\frac{h\nu}{KT_s}\right) - 1}{\exp\left(\frac{h\nu}{KT_e}\right) - 1} \,. \tag{2}$$

Values of $I_{\rm spot}/I_{\rm star}$ of 0.4 to 0.7 obtained from the modeled spots implied spot temperatures between 4900-5500 K. These temperatures are hotter than regular sunspots (3800–4400K), however the 6000 K surface temperature of HD 209458 is also hotter than that of the Sun (5780K). Nevertheless, the sunspots seen in the white light image of the Sun (Figure 1) are also about 0.4–0.7 of the solar disk center intensity, similarly to what was obtained from the model.

The spot size ranges from 0.3 to 0.6 planet radius, which being 9.4×10^4 km, implies sizes of $3-6 \times 10^4$ km. It appears that the spots on HD209458 are larger than regular sunspots, usually of the order of 11,000 km. However, the variation in the light curves of HD209458 may have been caused by a group of sunspots, similar to those in solar active regions.

4. STELLAR ROTATION

It has been almost four centuries since the first observations of sunspots, some time between 1610 and 1612, took place. Today a controversy still remains about who was the first person to observe sunspots, whether it was Galileo, Johannes Fabricius, Harriot or Scheiner (Tassoul 2000).

In 1871, Vogel, with the help of a spectroscope, made the first measurements of solar rotation from Doppler shifts of spectral lines observed on both limbs of the solar disk. These observations showed that the east limb was approaching Earth while the west limb receded. Abney was the first to realize that stellar rotation could be inferred from the broadening of spectral lines.

Today, stellar rotation can also be measured from periodic variations of the light curve due to the presence of dark and bright features on the surface of some stars. However, this can only be done for very active stars, which surface is significantly occupied by spots.

Here I propose a new way of estimating the stellar rotation by using planetary transits. If during a transit the planet passes in front of a starspot as

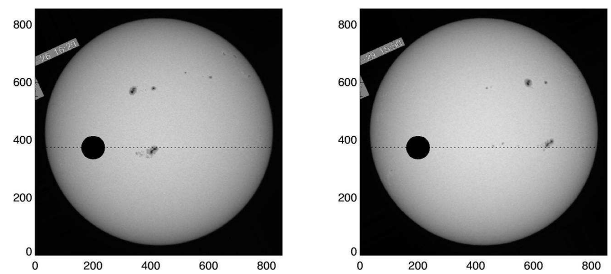

Fig. 5. White light images of the Sun taken three days apart on April 26 and 29, 2000.

discussed in the previous sections, and if the configuration is such that this same spot is again occulted in a consecutive transit, then it is possible to estimate the stellar rotation by measuring the spot longitudinal displacement, as it was done for the Sun four centuries ago. Since the spot model yields the longitude of the spot, by comparing the longitude of the spot on the two consecutive transits it is possible to determine the stellar rotation.

In order to exemplify this method, I will use two white light images of the Sun from Big Bear Solar Observatory, taken three days apart on April 26 and 29, 2000, shown in Figure 5. Light curves for both days were obtained by considering the transit of a Jupiter size planet ($R_p/R_s = 0.1$) that intercepts the sunspot group near the solar equator on both days. The circular orbit considered in this simulation has a semi-major axis of 10 R_s and an inclination angle of 89.4°. The resulting light curves are shown in the upper panel of Figure 6 for 2000 April 26 (black line) and 29 (gray line).

By subtracting the light curve of April 26 from that taken three days later, the variations due to spot crossing on both days are enhanced. The difference in phase position of these intensity variations is caused because the longitude of the spot has changed due to the rotation of the star. Thus, the rotation of the star can be obtained by measuring the phase difference, Δf. An approximate expression for the period is given by

$$P_s = \frac{\Delta t}{\Delta f \left(\frac{a}{R_s}\right)} \,, \tag{3}$$

where Δt is the elapsed time between the two observations, and a/R_s is the orbit radius in units of stellar radii. Using the measured value of $\Delta f = 0.1$, a period of 27.6 is obtained for the Sun.

A way to estimate the uncertainty in the period is by considering several simulations, where all parameters are kept constant except for the inclina-

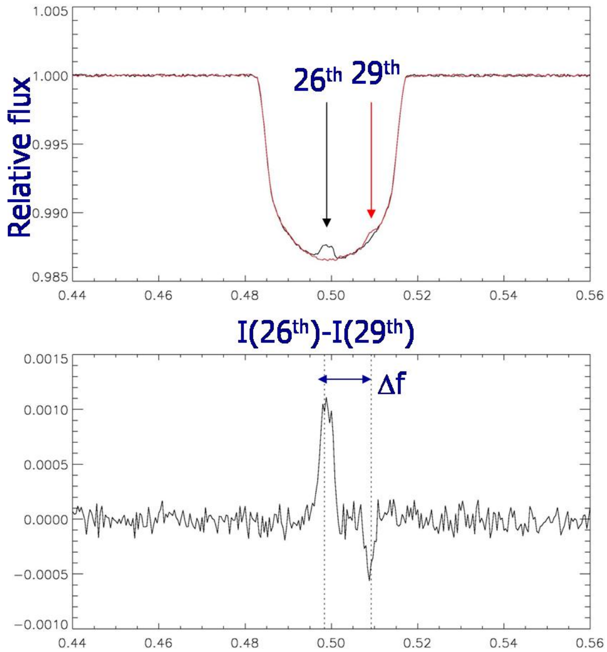

Fig. 6. Top: Light curve intensity as a function of phase for the simulated transit of a Jupiter size planet in front of the Sun for the days of April 26 (black line) and 29 (gray line), 2000. Bottom: Difference of the light curves of the transit simulation on April 26 and 29, 2000.

tion angle. Only for small variations in the inclination angle that the planetary transit still eclipses the sunspot group. Each simulation yield a slightly different value for the rotation period, and the two extreme values of the period were considered for determining the uncertainty.

This "stellar" rotation period inferred from this equation is 27 ± 1 days, which agrees quite well with the known value of the solar rotation, that for this latitude is about 26 days.

This method can be applied to real transit observations, as long as the variations in consecutive light curves supposedly produced by spots are detected. This method was applied to the four transits observed by HST (Brown et al. 2001) and the resulting period of approximately 11 days is in agreement with that obtained from line velocities observations. The model and results are described in detail in Silva-Válio (2008).

5. CONCLUSIONS

The method described above (Silva 2003) provides the physical parameters of spots such as size, intensity/temperature, and their location (latitude and longitude) on the surface of the star. To test the proposed method, two observations of planetary transits in front of HD209458 were analyzed. These observations showed small variations in the bottom part of the transit seen in the light curve, which were assumed to be due to the spots, supposedly present on the stellar photosphere.

The spots on HD209458 were found to have radii of $3 - 6 \times 10^4$ km, considering a planet radius of 1.347 $R_{\rm Jup}$. These are probably a group of starspots instead of a single spot, similar to those found in active regions on the Sun. The spot temperature can be inferred from their modeled intensity and for this star ranges from 4900 to 5500 K, making them hotter than sunspots which have temperatures between 3800 and 4400 K. Notice, however, that HD209458 is hotter than the Sun, with an effective temperature of $T_e = 6000$ K (Mazeh et al. 2000).

Another interesting information about the star, which can be obtained as described in § 4, is the stellar rotation. This is done by detecting the same spot on consecutive transits and calculating how much its longitude has changed in the time elapsed between the two planetary orbits. As an example of the model, I used images of the Sun taken three days apart. The resulting period of 27 ± 1 is in good agreement with the real period of the Sun, which is about 26 for regions close to the equator. By careful monitoring of successive planetary transits, it might also be possible (if the conditions are favorable) to gather information about the spot evolution.

Application of this method to observations from the CoRoT satellite (Michel et al. 2000), designed for detecting planetary transits, will definitely enhance our understanding of the magnetic activity on stars other than our Sun. Besides sensibility, one important characteristic of CoRoT is to observe a certain region of the sky for a long uninterrupted period of 150 days. This is an excellent opportunity to analyze starspots. The first data studied were the transits of CoRoT-Exo-2, which has an orbital period 1.743 days, a=0.028 A.U., inclination angle of 88° and planet radius of 0.17 R_s (Alonso et al. 2008).

There are high temporal resolution data for 78 transits for CoRoT-Exo-2 spanning a total of 135 days. CoRoT-Exo-2 is an active star with many spots on its surface at any given time. The study of the transits provides information on the temporal evolution of spots and their mean lifetime, as well as size and temperature distributions (Silva-Válio, Alonso & Barge, in preparation).

In summary, planetary transits in front of a reasonably active star allows the determination of starspot characteristics such as size, temperature, and location. Other results which may be explored by the analyses of many consecutive transits are stellar rotation, the existence or not of differential rotation, and maybe hint at stellar activity cycles, for short cycles. One may also obtain information on the temperature gradient of the stellar photosphere by the measurement of the limb darkening. As shown by Figure 1, once Earth size planets are detected to transit their host star, the structure of starpost may be unraveled.

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