Effect of line-of-sight inclinations on the observation of solar activity cycle: Lessons for CoRoT & Kepler

H. Vázquez Ramió¹,², S. Mathur³, C Régulo¹,², R A García⁴

¹ Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain
² Dept. de Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain
³ High Altitude Observatory, 3080 Center Green Drive, Boulder, CO, 80302, USA
⁴ Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot; CEA, IRFU, SAP, F-91191, Gif-sur-Yvette, France

E-mail: hvr@iac.es, savita@ucar.edu, crr@iac.es, rgarcia@cea.fr

Abstract. CoRoT and Kepler missions are collecting data of solar-like oscillating stars of unprecedented quality. Moreover, thanks to the length of the time series, we are able to study their seismic variability. In this work we use numerical simulations based on the last 3 solar cycles to analyze the light curves as a function of the line-of-sight inclination angle. These preliminary results showed that the direct observation of the light curve can induce some bias in the position of the maximum of the cycle.

1. Introduction

The structure of the stars can be perturbed by their magnetic fields. The interaction of convection, rotation and magnetic fields induces the development of dynamos that can be observed as cyclic modulations in several parameters. Several surveys done on magnetically sensitive absorption lines (Ca H and K) have shown a high number of stars in our vicinity showing such cycles [e.g. 1]. In the case of the Sun, the cyclic variation of the sunspots are well known, as well as for many other parameters. In particular, frequencies and amplitudes of the acoustic modes propagating inside the Sun react to the magnetic field and show an 11 year modulation [e.g. 2]. Long and high-quality asteroseismic data are now being collected on solar-like stars thanks to the new satellites such as CoRoT and Kepler [e.g. 3, 4, 5, 6, 7, 8] or the ground-based campaigns [e.g. 9]. The recent discovery of an activity cycle in HD49933 [10] —using seismic analysis of the two observed runs performed by CoRoT [11, 12]— opens such studies to asteroseismology. However, a shift in the position of the maximum of the cycle was found between the inferences obtained from seismology indicators and from the light curve.

In the present work we will check the effect of the inclination angle of the star on the light curve as we know that it has an important effect on other parameters like the visibility of the modes [13, 14]. The visibility of the spots is utterly related to the active latitudes of the star and to the spots migration process. Thus, at a specific moment of observation, depending on the inclination angle, we can see or not these spots on the visible disk.
Figure 1. Examples of the numerical simulation of the same day with an inclination angle of 90 and 15 degrees, left and right panels respectively. The solar pole is indicated by a cross in each image.

2. Numerical Simulation
To explore the influence of the line-of-sight inclination angle coupled with the active latitudes of the star during the evolution of the cycle, we perform a numerical simulation of a Sun in which we change the inclination angle from 90° (the real Sun) till 0° by increments of 5°. The model was designed to simulate different solar photospheric patterns such as granulation, supergranulation and sunspots [15]. The spots areas and their positions on the solar disk have been taken from the Solar Geophysical Data Centre (http://www.ngdc.noaa.gov/). Every sunspot is considered to be circular with an area equivalent to the total of the reported sunspot group. Data from 1980 to 2004 were employed, covering two minima and three maxima of the solar activity cycle. Some samples of the numerical simulation are shown in Fig.1: from left to right angles 90° and 15°.

3. Analyses and Results
To analyze the light curves we use two methods: the first one consists of applying wavelet tools [16] to obtain the evolution of the sunspots with time [17]. We also build a sunspots proxy by computing the standard deviation of the light curves in subseries of 365 days, 50% overlapping (following [10]).

3.1. Observations at 90°: The Sun
In Figure 2 (Left) we can see the synthetic light curve (top) based on the last three solar cycles observed with an observation line-of-sight inclination of 90 degrees. The global wavelet power spectrum (middle panel) presents clear signatures of the 11-year activity cycle. A surface rotation is confirmed by doing a collapsogram in the temporal direction (middle right panel) obtaining a periodicity of 25 days. The second harmonic of the rotation rate is also visible between 0.90 and 0.95 µHz (between 12 and 13 days). In both cases the peak is above the limit of 90% confidence level. The collapsogram in the frequency direction—corresponding to periods in a range between 20 and 30 days (bottom panel)—shows a similar behavior than the light curve, which means that this is another way to compute a starspots proxy.
Figure 2. Analysis of the light curves from simulations with inclination angles 90 and 15 degrees (left and right respectively) using wavelet techniques. In the top panels the absolute value of the light curves obtained with both inclinations are shown in ppm. The middle panels are the global wavelet power spectrum. The bottom panels are the collapsograms of the wavelet power spectrum along in the vertical axis. The right small panels are the collapsograms in the time domain.

The magnetic activity proxy (Fig. 3) –built from the standard deviation of the light curve– is similar to the collapsogram of the vertical axis of the wavelets periodogram (see Fig. 2 bottom panels) and shows clearly the presence of the maximum activity as well as the periods of minima. The ascending and descending phases of the cycle are well determined thanks to the high signal-to-noise ratio.

3.2. Observations at 15°: similar to HD49933
When the angle is small –as in the case of HD49933 (estimated by [12] to be $17^\circ \pm 7^\circ$)– the shape of the activity cycle from the analyses of the light curve is different. The inferred rotation periodicity is still correct but there is no signature of the second harmonic of the rotation. Moreover, the maximum of the activity cycles is shifted compared to the observations at 90 degrees (See Fig 2 and 3 right panels) and is lower in amplitude than in the previous case. Finally, the ascending and descending phases are not so well defined.

4. Conclusions
In the present work we have developed a numerical simulation of the variations induced in the light curves due to starspots crossing the visible disk of a star. To build such a simulation we have used real solar data measured after more than 30 years of solar observations. We have shown that the activity cycle inferred from the light curve is heavily influenced by the inclination
angle under which the star is observed. Beside, the maximum of the cycle changes as well as the ascending and descending phases of the cycle.

Acknowledgments
The CoRoT (Convection, Rotation and planetary Transits) space mission has been developed and is operated by CNES, with the contribution of Austria, Belgium, Brazil, ESA (RSSD and Science Program), Germany and Spain. This work has been partially supported by the CNES/GOLF grant at the SAp CEA-Saclay and by the French PNPS program.

References
[1] Baliunas S L, Donahue R A, Soon W H et al. 1995 ApJ 438 269
[2] Charbonneau P 2005 Living Reviews in Solar Physics 2
[3] Barban C, Deheuvels S, Baudin F et al. 2009 A&A 506 51
[4] García R A, Régulo C, Samadi R et al. 2009 A&A 506 41
[5] Bedding T R, Huber D, Stello D et al. 2010 ApJ 713 L176
[6] Chaplin W J, Appourchaux T, Elsworth Y et al. 2010 ApJ 713 L169
[7] Deheuvels S, Brunt H, Michel E et al. 2010 A&A 515 A87
[8] Mathur S, García R A, Catala C et al. 2010 Astron. & Astroph. 518 A53
[9] Arentoft T, Kjeldsen H, Bedding T R et al. 2008 ApJ 687 1180
[10] García R A, Mathur S, Salabert D, et al. 2010 Science 329 1032
[11] Appourchaux T, Michel E, Auvergne M. et al. 2008 A&A 488 705
[12] Benomar O, Baudin F, Campante T L et al. 2009, A&A 507 L13
[13] Gizon L and Solanki S K 2003 ApJ 589 1009
[14] Ballot J, García R A and Lambert P 2006 A&A 369 1281
[15] Vázquez Ramió H, Régulo C and Roca Cortés T 2006 Proceedings ESA-SP 624 69
[16] Torrence C and Compo G P 1998 Bull. of the Amer. Met. Soc. 79 61
[17] Mathur S, García R A, Régulo C et al. 2010 Astron. & Astroph. 511 46