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How typical is the Solar magnetic cycle?

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Abstract. The 11-year activity cycle is a major continuous feature of the Sun. It is the result of a complex temporal evolution of the solar magnetic field intensity, which is controlled by dynamo, that is the physical process generating and maintaining solar magnetic field. The magnetic cycle has consequences in the variations of the Ca II H & K emission line cores and lower chromosphere heating. Long-term Ca II emission variability is also observed in other stars. Combining a star sample from HARPS planet-search program with high-precision Ca II chromospheric activity measurements we selected a large number of reliable Pcyc, and we revisit the relation between rotation periods $P_{\rm rot}$ and $P_{\rm cyc}$, and we discuss about the question of How typical is the Solar magnetic cycle.

Resumo. O ciclo de 11 anos de atividades magnética é uma das mais importantes características continua do Sol. É o resultado de uma complexa evolução temporal da intensidade do campo magnético solar, que é controlado pelo dínamo, que é o processo físico que gera e mantém o campo magnético solar. O ciclo magnético tem consequências nas variações dos núcleos das linha de emissão Ca II H & K e aquecimento da cromosfera inferior. A variabilidade de emissão de longo prazo também é observada em outras estrelas. Nese trabalho, combinando uma amostra de estrelas do programa HARPS de busca por planeta, para as quais fizemos as medidas da emissão de Ca IIreferente à atividade cromosférica associadas à um um grande número de estrelas selecionadas com Pcyc confiáveis, e revisados. Estudamos a relação entre períodos de rotação $P_{\rm rot}$ e $P_{\rm cyc}$, assim como discutimos neste artigo questões referentes a quão típico é o ciclo magnético solar.

Keywords. Stars: activity – Stars: rotation – Stars: solar-type

1. Introduction.

A milestone towards the spectroscopy study of chromospheric activity was given when Eberhard & Schwarzschild (1913) confirmed the presence of Ca II H&K absorption lines in the spectrum of several stars. The Ca II H&K flux became a very important parameter for the understanding stellar activity. Over three decades from the 1960 at the Mt. Wilson Observatory, and using the 100-inch Hooker telescope, Olin Wilson and his collaborators began a long-term program to monitoring Ca II line emission of 91 cool dwarf stars, included the Sun (Wilson 1978). This project became known as the "HK Project" and after 1978 was transferred to the Mount Wilson 60-inch telescope, which was dedicated entirely to study stellar chromospheric activity and variability, and has become identified with a particular methodology known as the *solar-stellar connection*. Along the decades, part of the raw data was lost, and thanks to the cooperative effort at the National Solar Observatory, a large amount was recovered in 2015. Now, a data set complete, calibrated, and self-consistent cover almost 2300 HK Project stars, from 1966 to mid-1995.

Another important step was taken by Skumanich et al. (1975) in established a correlation between the Ca II emission and solar magnetic fields. Today Ca II emission is a well-known proxy indicator for stellar magnetic activity. Long-term variations in the chromospheric Ca II emission can provide information on the nature and strength of magnetic activity. The Mt. Wilson monitoring programme (cf., Baliunas et al. 1995) was the longest-running program to monitor stellar activity cycles. This programme has been monitoring stars continuously since 1966 and demonstrated that the Sun is not the only star with a periodic activity cycle, but rather such periodic behavior is quite common, among the solar type stars. At the same time, for many other solar-like stars, was described an absence of activity or stars do not show any periodic activity cycles like. Wilson (1978); Baliunas & Vaughan (1985); Baliunas et al. (1995), and others have devoted major parts of their research efforts to study the variations of the Ca II emission and determine of $P_{\rm cyc}$ and $P_{\rm rot}$. Brandenburg et al. (1998) critically discussed the available data. Saar & Brandenburg (1999) judged the reliability of the available data and graded them accordingly. Saar & Baliunas (1992) have also studied the data from the extended Wilson survey and find that, while 10-15% of stars in the survey show no periodic variation.

The "HK Project" has shown many interesting features. The quasi-regular cyclic activity demonstrated that many active solar-type stars do not behave cyclically and some exhibit solar-type cyclic behaviour, and other stars vary irregularly. The "HK Project" has shown that quasi-regular cyclic activity is by no means unique to the Sun, but it has also demonstrated that many active solar-type stars do not behave cyclically. A natural path at this point was to assume that by studying the different parameters of these stars (e.g. age, mass, luminosity, rotation periods, convective structure), it should be possible to identify which parameters control cyclic activity, and from that, understand the mechanism responsible for the stellar cycle. In this context, along the recent years, stellar activity surveys have been produced a huge quantity of Ca II H&K observations from the Doppler exoplanet programs and new studies have been conducted to investigate magnetic activity of solar-type stars (Santos et al. 2000; Wright et al. 2004; Hall et al. 2007). The merge of all these data brings a fundamental question: which of these stars are really similar to the Sun in terms of structure and evolution? The Mt. Wilson sample mainly consists of solar-type, main-sequence (MS) stars and the crucial point in this context is clearly found stars that can be considered comparable to the Sun from their mass, effective temperature, metallicity and rotation rate. From this early studies, it is almost clear the dependence of magnetic activity patterns on both rotation and convection, and

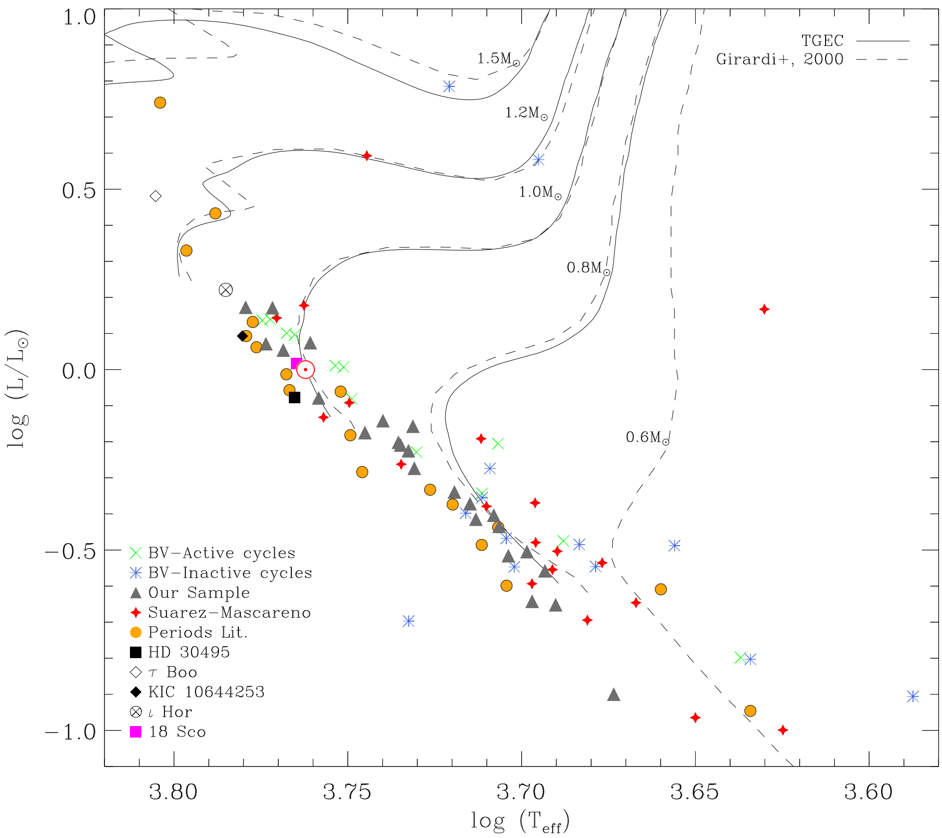

Figure 1. The distribution of the analog sample stars in the Hertzsprung-Russell diagram. Luminosities have been derived from the Hipparcos parallaxes. Evolutionary tracks at [Fe/H] = 0 are shown for stellar masses between $0.6M_{\odot}$ and $1.5M_{\odot}$. Crosses and asterixes indicate stars in Böhm-Vitense (2007) on the active and inactive sequences, respectively.

this suggests the presence of some kind of dynamo action, but it is still a challenger explain a few number of hypothesis, as for example those tars that are completely inactive, or those stars with extremely irregular activity. Using new cycle lengths of stellar activity from Mt. Wilson and HARPS FGK high-precision sample (Udry et al. 2000; Lovis et al. 2011) which include some stars nearly indistinguishable from the Sun (Cayrel de Strobel 1996), call solar twins, we can study how typical is the Sun's magnetic cycle length.

2. Evolutionary status and mass

In this sections, we discuss about the sample evolutionary status and some specific observational characteristics of stars used in this study. Part of our data and analysis is based on the high-quality data as selected by Saar & Brandenburg (1999); Lorente & Montesinos (2005); Lovis et al. (2011) and collected by do Nascimento et al. (2015). The Fig.1 shows the HR diagram with the evolutionary tracks computed for different metallicity values ([Fe/H] = 0.15, 0.0, -0.20, and -0.40), and presented here only for [Fe/H] = 0.0, which encompasses most of the stars contained in the present working sample. For comparison raisons, we presenting TGEC models (do Nascimento et al. 2009) and those from (Girardi et al. 2000). The work sample is composed for stars with masses between $0.6M_{\odot}$ and $1.5M_{\odot}$. Crosses indicate stars on the active sequence, and asterisks indicate stars on the Inactive sequence as in Böhm-Vitense (2007). The bright star 18 Sco (HD 146233, HIP 79672, HR 6060) is represented by a square and was the first star identified as a solar twin by Porto de Mello & da Silva (1997). 18 Sco has been observed for chromospheric activity (e.g. Hall et al. 2007), magnetic fields (Petit et al. 2008). 18 Sco which has physical characteristics similar to solar, a lithium abundance about three times solar (Meléndez & Ramírez 2007), a younger age (Baumann et al. 2010), $P_{\rm rot}$ of 22.7 days (Petit et al. 2008) and a Sun-like activity cycle of 7 years (Hall et al. 2007), is found here that along border line of the inactive sequence.

3. Rotation Periods and Cycle Lengths of Stellar Activity relation

In Fig. 2 we present the lengths of the activity cycles, $P_{\rm cyc}$ in years as a function of the rotation periods in days as originally published by Böhm-Vitense (2007). In Fig. 3 we present an updated version of this Fig. 2. Here we use the same observational data as used by Saar & Brandenburg (1999) and Lorente & Montesinos (2005), but with new $P_{\rm cyc}$ and $P_{\rm rot}$ from Lovis et al. (2011). We from found a distinct segregation of active and inactive stars into two approximately parallel bands A(active) and I (inactive) sequences and a remarkable scattering of points. Crosses indicate stars on the A sequence, and asterisks indicate stars on the I sequence from Böhm-Vitense (2007). Squares

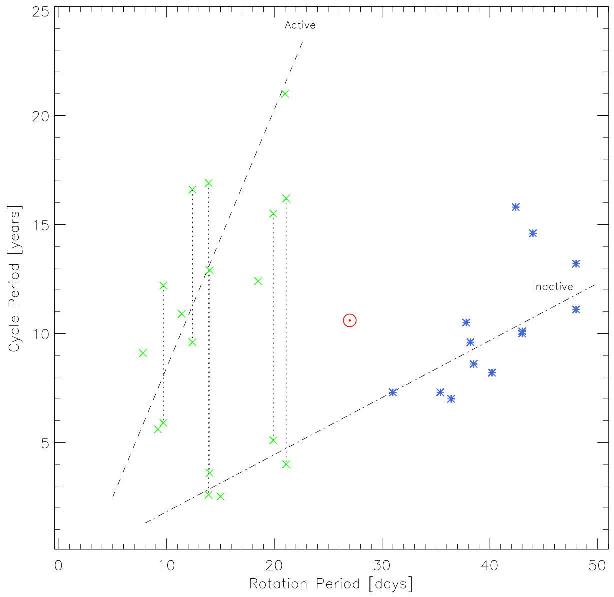

Figure 2. Relation between rotation periods P_{rot} (in days) and cycle Lengths P_{cyc} (in years) of stellar Activity as suggested by Böhm-Vitense (2007). Two sequences are defined by Böhm-Vitense (2007) as relatively young, active A sequence (dashed line) and the older, less active I sequences (dash-dotted line). The solar point is represented by the usual symbol $\odot$.

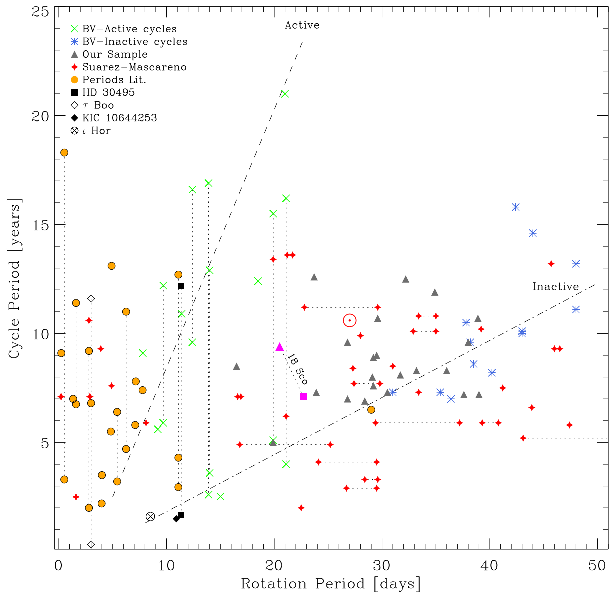

Figure 3. Updated version of the Figure 2, presented originally presented by Böhm-Vitense (2007). Squares around the crosses show stars with $(B-V) < 0.62$. Gold points are cycles from Saar (2011) and more recent data for other single dwarfs seen in HK and photometry, gathered since Saar & Brandenburg (1999) & Brandenburg (1999) represented by green and blue symbols. We also included data from Hall et al. (2007); Metcalfe et al. (2010, 2013); Egeland et al. (2015); Suárez Mascareño et al. (2016); Salabert et al. (2016). Triangles indicate secondary periods for some stars on the A sequence. The vertical lines connect multiple cycles observed for the same star, while the horizontal lines connect multiple P_{rot} observed for the same star. The shaded area indicates the variation of the solar period of rotation caused by differential rotation. The solar twin 18 Sco is represented by the a magenta symbol. For 18 Sco the triangles indicate activity cycles and rotation periods values range.

around the crosses show stars with $(B-V) < 0.62$. Triangles indicate secondary periods for some stars on the A sequence. The Sun position on this diagram is represented by the usual symbol. Inactive I sequence, as defined by Böhm-Vitense (2007) are composed by cooler and more slowly rotating stars. We need to highlight a particular star in this plot, the star 18 Sco. This object it is a solar twin, that is defined as stars nearly spectroscopic indistinguishable from the Sun (Cayrel de Strobel 1996). This target was first identified as a solar twin by Porto de Mello & da Silva (1997). 18 Sco chromospheric activity has been measured for decades (e.g. Hall et al. 2007; Petit et al. 2008). For 18 Sco, authors obtain an age of 2.89 ± 1.09 Gyr, using Li abundances and stellar parameters from high S/N spectroscopy. The mass derived is $1.04 \pm 0.02\ M_{\odot}$. 18 Sco has physical characteristics really close to solar. A lithium abundance about three times the solar (Meléndez & Ramírez 2007), a younger age (Baumann et al. 2010), P_{rot} of 22.7 days (Petit et al. 2008) and a Sun-like activity cycle of 7 years determined by Hall et al. (2007). This solar twin is found here at the border line of the inactive sequence. From the Fig. 4 we can see a clear 7 years cycle for 18 Sco, but possibilities of a longer cycle exist, and further observation of 18 Sco is needed.

4. Summary and discussions

As seen in Fig. 3 the observed relation between rotation periods and lengths of activity cycles for main-sequence G and K stars based on recent P_{cyc} and P_{rot} also shows an intermediate scattering (new branch?), besides the two mainly sequences, which Saar & Brandenburg called the active, A, and the inactive, I, sequences. We suggested a "new branch", that it may be a splitting of the Inactive branch. As a main result, we conclude that the Sun is not anomalous, when compared to the magnetic cycles that have been seen in other stars, but potentially a member of a new intermediate branch. An important next step will be evaluated this new P_{cyc} and determined how reliable they are. 18 Sco shows a cycle close to to the lower sequence, however further observation of 18 Sco is needed to confirm (or not) an existence of a longer cycle for this solar twin. A critical analysis on the cycle "quality" is urgently needed.

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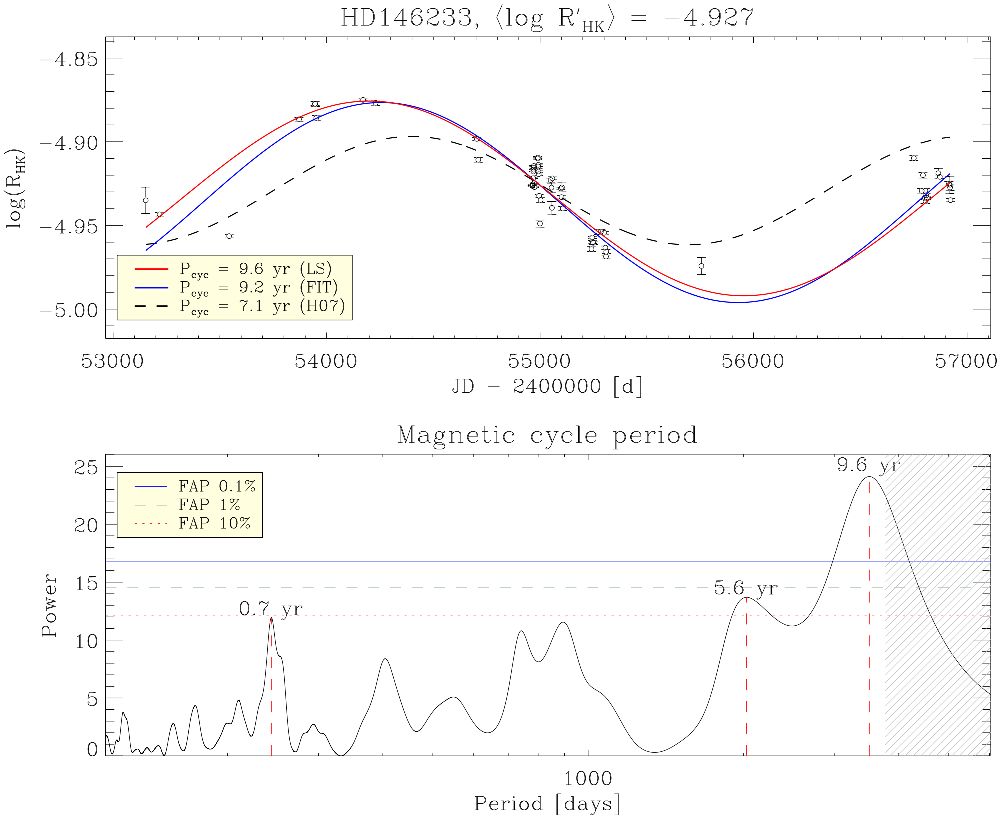

FIGURE 4. HARPS $log(R_{HK})$ measurements and periodogram for 18 Sco (HD146233).

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