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A LANDSCAPE OF MAIN SEQUENCE COOL STARS ACTIVITY THOUGHT PHOTOMETRIC OBSERVATIONS

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Abstract. The magnetic activity of stars presents a large diversity that is still poorly understood. With the recent discovery of a massive number of exoplanets has emerged the need to better characterize their interactions with their host stars. Therefore, we need to better understand their internal and external magnetism. Using Kepler, we computed the Fourier spectra of the data and used an analytical description of spot transits in light-curves to look at global trends. We thus recovered two proxies to identify activity regimes: a proxy which estimates the lifetime of the spots and a second which estimates the activity, in terms of surface coverage and light contrast of the spots on the stellar disk.Using these proxies, we propose a distribution of low-mass stars into four different activity regimes.

Keywords: Stars: activity, low-mass stars, magnetic field

1 Introduction

Stellar activity is a direct consequence of the internal and external magnetism of stars and is characterized by the appearance of magnetic structure like dark spots on the surface of stars, and their destabilization which can lead to flares and therefore massive release of energy. There are several methods used to study this activity: one can look at the coronal X-rays emission (Wright et al. 2011; Reinhold et al. 2019) or to the CaII K or Hα lines (West et al. 2008) which are related to variations respectively in the corona or the chromosphere. Photometric variability can also provide information on stellar activity (Mathur et al. 2014; García et al. 2010) since the transit of spots on the surface of the star induces a temporary drop in its luminosity.Thanks to space missions, increasingly precise photometric data such as Kepler can provide information on the properties of these spots, which are a direct expression of magnetic activity. The study of photometric variability in the temporal domain to determine properties of spots has unfortunately highlighted the degeneracy of this problem (position of the spots on the disk, their sizes, their temperatures, inclination of the star, possible rotation differential...).

However, the Fourier domain makes it possible to extract global trends about spots. Harvey (1985) has shown that the impact of activity in photometric data could be seen in low frequencies and could be approximated by a pseudo-Lorentzian. Later, Aigrain et al. (2004) suggested that the parameters of this function can be related to spots properties like their characteristic lifetime.

The aim of this work is to build on this concept and go beyond with a new analytical approach and apply it on the large sample of stars provided by McQuillan et al. (2014).

2 Method

This section gives a analytical description of the signature and mean properties of spots as seen in the Fourier spectrum of the light curves analyzed. This description is based on Harvey (1985), Harvey et al. (1993) and Aigrain et al. (2004).

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2.1 Model

We consider a single spot transiting on a star with a rotation period P_{rot}, which is characterized by an area S_{spot} and a temperature T_{spot}. This spot is assumed to always rotate at the same rotation period and to remain at the same latitude. Its transits on the stellar disk can be described using three normalized components:

- Ш_{Prot}: a Dirac comb with a spacing of one rotation period which represents the periodicity of the transit,
- $T_{transit}(t)$: the mean shape of the transit, it is associated to the characteristic time τ_{tr}, proportional to $P_{rot}/2$. The shape of the transit can vary depending on the inclination of the star relative to the line of sight and its position on the disk, but we consider here an average transit shape,
- $E_{life}(t)$: the intrinsic evolution with time of the spot, with a characteristic time τ_{life} which represents the spot lifetime. This function reflects the possible variations of the size and temperature of the spot during its lifetime.

By combining these three components, the impact of the spot in the light curve (Eq. 2.1) can be reproduced: coevolving Ш_{Prot} and $T_{transit}(t)$ replicates the repetition of the spot transit. Then, multiplying by $E_{life}(t)$ represents the intrinsic evolution of the spot during its lifetime:

$$S_0(t) = [\text{Ш}_{Prot} * T_{transit}(t)] \times E_{life}(t) \tag{2.1}$$

The transit photometric depth is given by $A(T_{spot}, S_{spot})$ which depends on the temperature contrast and the area of the spot. Therefore: $S(t) = A(T_{spot}, S_{spot}) \cdot S_0(t)$.

Two types of spots can be distinguished: if $\tau_{life} > P_{rot}$, the spot shows multiple transits, it is then categorized as *long spots*; if $\tau_{life} < P_{rot}$, the spot shows only one transit, it is then the **short spot** case.

When shifting to the Fourier domain, we obtain:

$$\widehat{S_0}(\nu) = [\frac{\text{Ш}_{1/P_{rot}}}{P_{rot}} \times \widehat{T_{transit}}] * \widehat{E_{life}}(\nu); \tag{2.2}$$

The convolution between the Fourier comb $\text{Ш}_{1/P_{rot}}$ and the Fourier transform of E_{life} yields the rotation peaks that are seen in the light curve spectrum. These peaks are multiplied by the Fourier transform of the transit component, $T_{transit}$, giving the final shape of the spectrum. The information about the spot lifetime, τ_{life}, appears thus in the rotation peaks whereas the width of the spectrum part just above the zero frequency, described by a pseudo-lorentzian in Harvey et al. (1993), provides information on the transit time, τ_{tr}. In the case of short spots ($\tau_{life} < \tau_{tr}$), the peaks are wider than the rest of the profile and overlap each other. As a result, the rotation peaks disappear and the spectrum corresponds to the description of Harvey (1985) and (1993) for the solar case.

In summary, three proxies linked directly with the spots physical properties can be extracted from the spectra of a light curve:

1. The *transit proxy*, τ_{tr}: the inverse of the width of the very low frequency part of the spectrum. It is the characteristic time of the transit and is thus proportional to $P_{rot}/2$,
2. The *lifetime proxy*, τ_{life}: the inverse of the width of the rotation peaks. It gives an information about the mean lifetime of the spots transiting on the stellar disk,
3. The *coverage proxy*, A: the amplitude of the spectrum. This proxy gives an information about the spot coverage of the stellar disk but is linked to two spot properties: their surface and their temperature. This gives degenerate information about whether the spots are cold or hot, small or large, and provides only an estimate of the global activity of the star over the duration of the observation.

3 Application to Kepler data

The data used here are the sample of 34 040 stars from McQuillan et al. (2014). This sample is composed of main sequence stars observed by the Kepler mission, with an effective temperature below 6500 K. There are no binary stars or stars with exoplanets visible in the light curves in this sample. McQuillan et al. (2014) also give an estimate of the rotation period and the mass of these stars. After removing the data where the fit has not converged, the sampling used here is made of 33 200 stars.

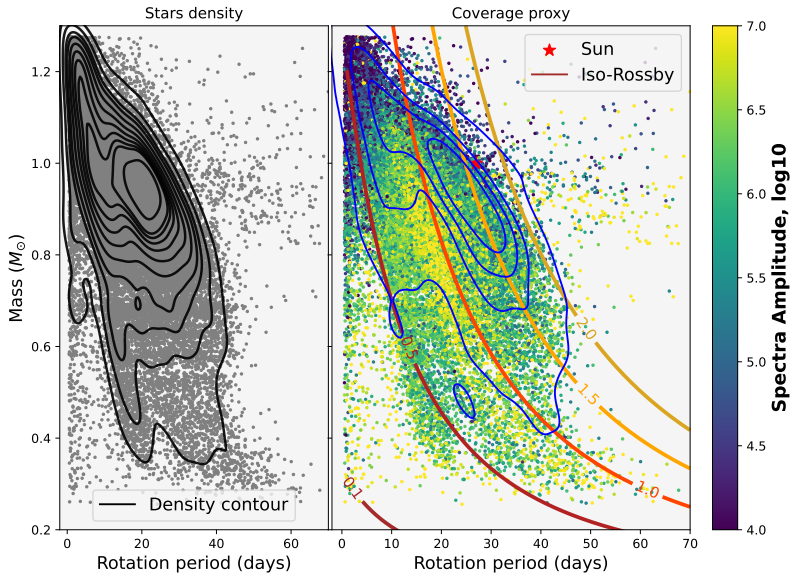

Fig. 1. The left figure show the density of stars in the diagram. Right : All of the star sample as a function of mass and rotation period. The color scale shows the surface proxy: yellow is for a large spot coverage (active stars), blue for low spot coverage (less active stars). The colored lines show iso-Rossby values. The red star symbol indicates the position of the Sun in this diagram. Blue lines represent the density of point from the short spots stars sample (ie. $\tau_{life} < P_{rot}$) from the fig. 2.

3.1 Coverage proxy

The results of the estimate of the coverage proxy are shown in Figure 1. The colored lines in hot colored with values from 0.1 to 2 are iso-Rossby lines, computed from the turn-over time estimated with the mass dependent relation from Wright et al. (2011) (Ro = P_{rot} / $\tau_{turnovertime}$). We can see a first regime of intense activity around Ro = 1: we can see a banana-shaped cloud for which the proxy is the highest. A second regime is emerging for high mass stars (top of the diagram): here the proxy coverage is relatively weak (dark purple area). This corresponds to fairly low activity, which is in line with current theory: the most massive stars have a weaker convective zone and therefore less magnetic activity (Berdyugina 2005). Finally, on either side of the Ro = 1 regime, stars show a similar activity (green areas).

3.2 Lifetime proxy

Figure 2 shows the results for the lifetime proxy. The density lines in black highlight two points of accumulation in this diagram: the short spots stars, below a lifetime of $\tau_{life} < 10$ days (in dark blue), and the long spots stars (in yellow). The sample of long spots stars represent 77 % of the initial sample. Most of these stars have higher coverage proxy than the short spot stars, and are thus more active. However, a small group of stars with a short spot lifetime shows a higher coverage proxy than the rest of the sample (bottom of the diagram).

4 Discussion and conclusion

Figure 1 highlight two regimes: one made of very active stars at Ro = 1 and another made of low active stars. By superposing the samples of short-lived stars in Figure 1 (blue contour lines) we can observe that they correspond to the massive stars from the low activity regime and the stars above the high activity regime. When we compile all of these results together, we can therefore identify four activity regimes:

- A high activity regime at Ro = 1 with long spots, corresponding to the elongated shape in Figure 1,
- A low activity regime with short spots, for the more massive stars,

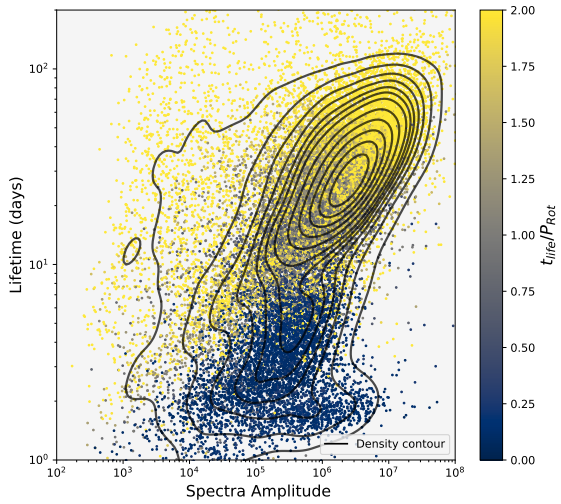

Fig. 2. The star sample shown as a function of the lifetime proxy and the coverage proxy. The color scale shows the ratio between the rotation periods estimated by McQuillan et al. (2014) and the lifetime proxy. Blue is for short spots ($\tau_{life} < P_{rot}$) and the yellow for long spots. The black lines represent the density of stars in this figure.

- A regime of intermediate activity with long spots, corresponding to the iso-Rossby Ro = 0.5 ,
- A second intermediate regime activity with short spots above the one of high intensity.

However, there remains a number of biases that can influence these results such as differential rotation and the appearance of faculae or plages . These biases will be discussed in more detail in a futur publication. This work can alredy be put into perspective with the results found by Reinhold et al. (2019) who suggest the existence of spotdominated stars and faculaedominated stars. The two regimes of stars with long spots may correspond to regions with spot-dominated stars and the two other regimes to stars dominated by faculae, like the Sun, which reinforces the idea of several types of activity linked to different types of magnetism at the surface of the star.

Looking at the global characteristics of the spots using the Fourier domain thus makes it possible to highlight different types of stellar activity, which will eventually provide information on the magnetism of stars such as stellar dynamo. More results and interpretations are coming !

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References

Aigrain, S., Favata, F., & Gilmore, G. 2004, A&A, 414, 1139

Berdyugina, S. V. 2005, Living Reviews in Solar Physics, 2, 8

García, R. A., Mathur, S., Salabert, D., et al. 2010, Science, 329, 1032

Harvey, J. 1985, in ESA Special Publication, Vol. 235, Future Missions in Solar, Heliospheric & Space Plasma Physics, ed. E. Rolfe & B. Battrick, 199

Harvey, J. W., Duvall, T. L., J., Jefferies, S. M., & Pomerantz, M. A. 1993, in Astronomical Society of the Pacific Conference Series, Vol. 42, GONG 1992. Seismic Investigation of the Sun and Stars, ed. T. M. Brown, 111

Mathur, S., Salabert, D., García, R. A., & Ceillier, T. 2014, Journal of Space Weather and Space Climate, 4, A15

McQuillan, A., Mazeh, T., & Aigrain, S. 2014, ApJS, 211, 24

Reinhold, T., Bell, K. J., Kuszlewicz, J., Hekker, S., & Shapiro, A. I. 2019, A&A, 621, A21

West, A. A., Hawley, S. L., Bochanski, J. J., et al. 2008, AJ, 135, 785

Wright, N. J., Drake, J. J., Mamajek, E. E., & Henry, G. W. 2011, ApJ, 743, 48