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CONSTRAINING STELLAR MAGNETIC ACTIVITY WITH ASTEROSEISMOLOGY

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Abstract. Stellar magnetic activity results from the interaction between rotation, convection, and magnetic field. Unfortunately the detailed mechanism of this process is not completely understood. While there is a long history of spectroscopic surveys to tackle this problem, they only provide observables of the stellar surfaces. The fact that different manifestations of magnetic variability can be observed (either a regular cycle, a non-regular variability or no temporal variation) is linked to the internal properties of the stars and raises the following question: Which conditions and properties of the stars govern these different behaviors? To better understand the detailed mechanism driving solar and stellar magnetic activity and better constrain the 3D dynamo models, it is important to know the characteristics of their magnetic field, the property of the convection, and the rotation profile (internal and at the surface) of the stars. This is where asteroseismology has a key role. Indeed, with missions such as CoRoT and *Kepler*, we have access to high-precision photometric observations where asteroseismology puts strong constraints on the internal structure and dynamics of the stars. Here, I discuss what seismology brings to the big picture of stellar magnetic activity by presenting the recent results obtained with space missions such as CoRoT and *Kepler* with a focus on solar-like stars.

Keywords: Asteroseismology, stellar activity, rotation

1 Introduction

In the past, stellar magnetic activity studies were mostly based on spectroscopic observations. The Mount Wilson survey (Wilson 1978) was one of the first surveys that followed a few hundreds of stars for more than a decade allowing the detection of long magnetic activity cycles. In particular, this survey showed that stars can behave quite differently in terms of magnetic activity. Some stars have regular cycles like the Sun, others present a more chaotic variability while the last groups of stars have very flat magnetic activity (e.g. Baliunas et al. 1995). More surveys were led later with the Solar Stellar Spectrograph at the Lowell Observatory (Hall et al. 2007) or the Small and Moderate Aperture Research Telescope System at the Cerro Tololo Interamerican Observatory for instance(Metcalfe et al. 2010). While these surveys are based on the measurement of the CaHK line more recently the first big spectropolarimetric survey was led by the Bcool teams who studied 170 stars at the Telescope Bernard Lyot and the Canada-France-Hawaii Telescope (Marsden et al. 2013). These two methods are complementary as spectroscopic observations allow us to determine indirect magnetic proxies that measure the chromospheric emission, while spectropolarimetry provides measurement of the magnetic field and its mapping on the stellar surface. Moreover these surveys emphasized the existence of relationships between the surface rotation period and the magnetic cycle period. Indeed, fast rotators seem to have shorter cycle periods (Saar & Brandenburg 2002; Böhm-Vitense 2007).
For stars like the Sun, we know that magnetic activity results from the interaction of rotation, convection, and magnetic fields. The most common model is the $\alpha\Omega$ dynamo where the Ω effect is related to the distortion of the poloidal field lines due to the latitudinal differential rotation while the α effect is still under controversies. These dynamo models require information on the structure and dynamics of the stars: the depth of the convection zone, the rotation profile from the interior to the surface, and the strength of the magnetic field, which are illustrated in Figure 1.
However the detailed mechanisms of magnetic activity cycles, including the solar one, are not completely understood. For instance, we need to improve solar activity prediction (length, strength of cycles). We also need to understand what is the relation between rotation period, cycle period and properties of the stars (mass,

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structure...). Another question that needs to be addressed is: why do some stars show (regular) cycles and others don't? Magnetic activity is tightly related to deep layers of the Sun and the stars. To be able to go further into our theoretical understanding of stellar activity, we need to have a deeper knowledge of the internal structure and dynamics of the stars. This can be achieved thanks to asteroseismology that has been revolutionizing stellar physics for the past decade.

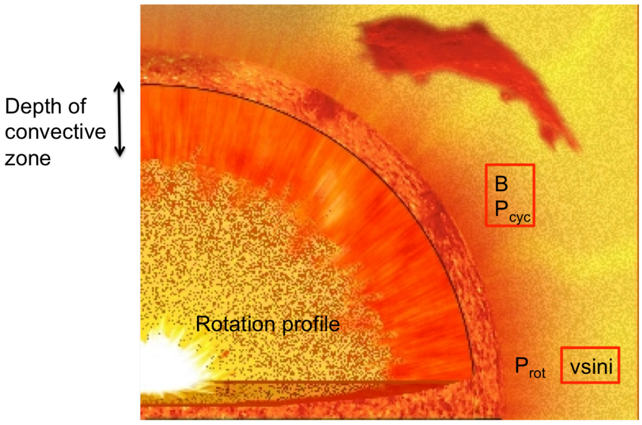

Fig. 1. Cut of a star like the Sun with the different ingredients needed in dynamo models: the depth of the convective zone, the internal rotation profile, the magnetic field, the surface rotation period, and the cycle period. The quantities in a red box are the ones spectroscopy has access to, though photometric data can also provide the latter. The other ones can be obtained with photometric data through asteroseismic studies. (Adapted from a photo courtesy of SoHO Consortium)

2 Constraints provided by seismology

Thanks to the exquisite photometric data collected by missions such as CoRoT (Baglin et al. 2006) and *Kepler* (Borucki et al. 2010), not only the panorama on the exoplanet side has changed by increasing the statistics and discovering smaller planet and new types of systems (e.g. Batalha et al. 2011; Lissauer et al. 2011; Barclay et al. 2013), but our knowledge of the stellar structure, dynamics and evolution has also tremendously improved (e.g. Bedding et al. 2011; Mosser et al. 2012b). We will see here what seismology can offer to better understanding stellar magnetic activity.

We briefly remind here the basis of asteroseismology but we refer to Aerts et al. (2010) for a deeper description. By measuring the brightness changes of the stars, we can study the different types of waves propagating in the stars. For a star like the Sun, acoustic waves (or p modes) are excited by the turbulent motions in the outer layers of the convection zone. Figure 2 (left panel) shows a power spectrum for a solar-like star. It shows a repeated pattern and the frequency of this repetition is called the mean large frequency separation (noted $\Delta\nu$), which is the frequency difference between two consecutive orders of the same degree modes. Another typical parameter that is easily measured in the power spectrum is the frequency of maximum power ($\nu_{\rm max}$) (e.g. Mathur et al. 2010).

By combining $\Delta\nu$ and $\nu_{\rm max}$ with the star effective temperature, we obtain a first determination of the mass and radius of the stars through scaling relations based on the Sun (e.g. Kjeldsen & Bedding 1995). We can even go further if we can detect individual acoustic modes frequencies and make use of stellar evolution models to fit both spectroscopic constraints and seismic observables. Different methods can be used to find the best-fit models: grid-based models (Chaplin et al. 2014), applying a genetic algorithm like the Asteroseismic Modeling Portal (AMP, Metcalfe et al. 2009), implementing Bayesian methods (Gruberbauer et al. 2013), Modules for Experiments in Stellar Astrophysics code (MESA, Paxton et al. 2013). Even though, we are aware that they are based on given physics implemented in the stellar evolution codes, they allow us to infer the internal structure of the stars and in particular have a first estimation of the depth of the convective zone, which is an important ingredient in dynamo models, that can be complemented by the measurement of the convective characteristic time scales (Mathur et al. 2011b). A large number of solar-like stars have already been modeled now using

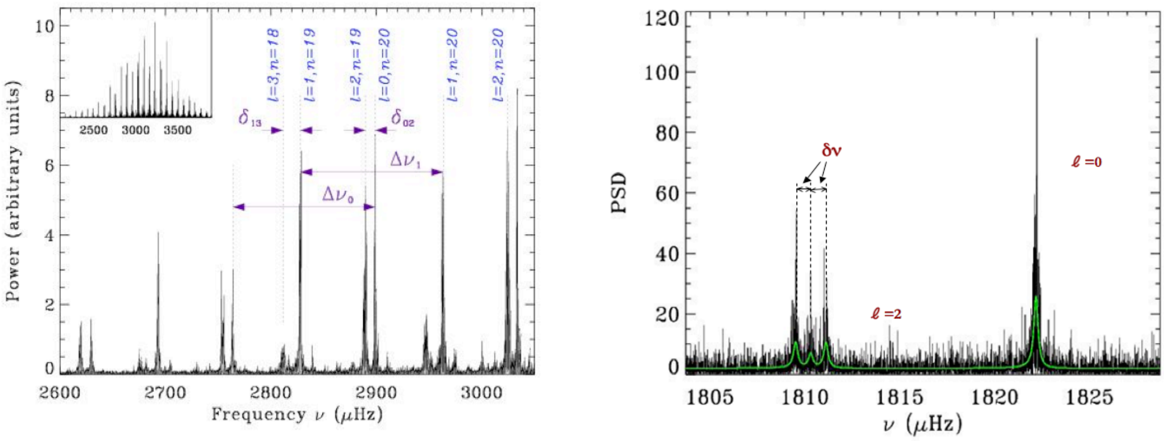

Fig. 2. Left panel: Power density spectrum of the light curve of the Sun obtained with SoHO, revealing a rich spectrum of nearly equidistant peaks. The frequencies and their spacings provide direct access to the mass, radius and age of the stars. Right panel: lifting of the degeneracy of the m components with rotation. Three components (m=-2,0,2) are visible for the ℓ=2 mode.

either grid-based models (Chaplin et al. 2014) or AMP (Mathur et al. 2012; Metcalfe et al. 2014), whenever individual modes can be characterized (Appourchaux et al. 2012).

Furthermore, the rotation affects the modes by lifting the degeneracy of modes of degree ℓ larger than 1. As shown in Figure 2 (right panel), the mode ℓ=1 is split and the distance between the two components is proportional to the rotation rate of the star in the layers probed by the mode and to the inclination angle of the star (Ballot et al. 2006). For the Sun, the measurement of several thousands of modes splittings allowed us to determine quite precisely the rotation profile of the Sun down to 0.2$R_\odot$ (García et al. 2008b). In order to go further down, we need to detect the splittings of gravity modes (Mathur et al. 2008) that live most of their time in the radiative zone and are evanescent in the convection zone, making them very difficult to detect (García et al. 2007, 2008a). However, for more evolved stars, because of the coupling between the g-mode cavity and the p-mode cavity it is possible to detect the mixed modes (Beck et al. 2011; Mosser et al. 2011). Their detection in sub giants and red giants along with their splittings led to very interesting results regarding the core rotation of these evolved stars (Beck et al. 2012; Deheuvels et al. 2012; Mosser et al. 2012a; Deheuvels et al. 2014), which rotates more than 5 times faster than the rest of the radiative zone.

Finally, magnetic activity has also an impact on the modes. Indeed we know for the Sun that there is a relationship between the magnetic activity and the p-mode parameters. When magnetic activity increases the amplitude of the modes decreases and the frequencies shift towards higher frequencies. This behavior has also been observed in the CoRoT target solar-like stars, HD49933 (García et al. 2010; Salabert et al. 2011). Chaplin et al. (2011) also confirmed using a larger *Kepler* sample that the p-mode amplitudes are lower for more active stars, suggesting that magnetic activity suppresses the modes.

3 Photometric data

The photometric data provide some additional information on the surface variability. The presence of spots creates a modulation in the light curves that is related to the surface rotation of the star (e.g. García et al. 2009; Mathur et al. 2011a) that can be measured using spot modeling techniques (Mosser et al. 2009; Fröhlich et al. 2012; Lanza et al. 2014). Hence, we can study the low-frequency part of the power spectrum to estimate the surface rotation rate. Different techniques can be used: periodogram (Nielsen et al. 2013), auto-correlation function(McQuillan et al. 2014), or time-frequency analysis (Ceillier et al. 2014). With the periodogram technique we have to be very careful as the harmonic could be detected instead of the fundamental one. The other two methods are more robust against this issue. These methods have been applied to a large sample of *Kepler* targets now allowing to study the transport of angular momentum along the evolution stage but also as a function of the mass. Another application is the study of age-rotation relationships in particular for main-sequence stars (do Nascimento et al. 2014). For instance, Garcia et al. (2014) who studied a sample of solar-like stars with detected solar-like oscillations and thus with asteroseismic ages showed that relationships derived in the past by Skumanich (1972) or Barnes (2003) still hold for field stars observed by *Kepler*.

Since the light curves contain the information of the presence of star spots, we can compute photometric indexes of magnetic activity by taking the standard deviation of the time series. Because of the link between rotation and magnetic activity, we can use our knowledge of the surface rotation of the stars to compute a new magnetic index based on subseries of length proportional to $P_{\rm rot}$. This ensures that we measure a variability related to the magnetic activity. This has been measured for around 300 solar-like stars by Garcia et al. (2014). They showed in particular that the Sun is not a particular star in terms of magnetic index. But we have to keep in mind that these indexes represent the average magnetic activity during the four years of the *Kepler* observations so if the cycle length is much longer, this index could be biased.

We can also use the time-frequency analysis based on the wavelets to study the magnetic activity of the stars. Figure 3 (top panel) shows the light curve of an F star observed by *Kepler*. The Wavelet power spectrum (middle panel) provides a rotation period around 9 days for this star. By projecting this wavelet power spectrum on the x-axis we obtain a magnetic proxy similar to the sunspots number. We detect some variability for this star but no cycle is firmly detected. This analysis was done for 22 F stars (Mathur et al. 2014b) and M dwarfs (Mathur et al. 2014c) and a few candidates for magnetic activity cycles detected have been outlined.

4 Conclusions

To conclude, seismology provides a large number of constraints for understanding the stellar magnetic activity processes: internal structure of the stars, internal rotation profile and changes due to magnetic activity. Photometric data also provides crucial information on the surface rotation and the surface magnetic activity. It is still important to complement these measurements with spectroscopy and spectropolarimetry to have a full view of the magnetism processes (Mathur et al. 2013). The next step is to test the current dynamo models on these observations, which we are starting to do now (Mathur et al. 2014a).

These studies are also important to characterize the magnetic activity of planet host stars as it impacts the definition of their habitability zones. With the large amount of data already collected by the *Kepler* mission, we are now starting to study the surface rotation and the magnetic activity of red giants (Ceillier et al. in prep.). Kepler gave us a unique opportunity with 4 year long continuous observations. The PLATO mission(PLAnetary Transits and Oscillations of stars Rauer et al. 2014) selected by ESA is the next mission that will provide similar long time series for a large portion of the sky enabling us to study magnetic variability.

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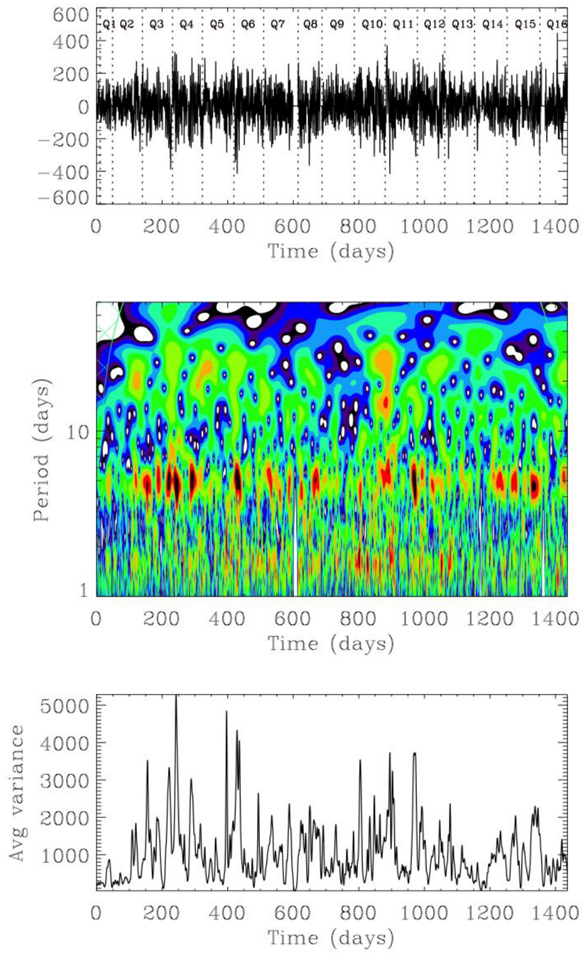

Fig. 3. Wavelet analysis of KIC 10016239. Top panel: temporal variation of the flux after the corrections applied as in (García et al. 2011) and rebinned to 2 h. Middle panel: wavelet power spectrum as a function of time and period. The green grid represents the cone of influence that provided reliable region in the WPS. Red and dark colours correspond to strong power while blue corresponds to weak power. Bottom upper panel: projection of the WPS on the time axis between periods of 6 and 8 days. Extracted from Mathur et al. (2014b).

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