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Asteroseismic signatures of magnetic activity variations in solar-type stars

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Abstract. Observations of magnetic activity cycles in other stars provide a broader context for our understanding of the 11-year sunspot cycle. The discovery of short activity cycles in a few stars, and the recognition of analogous variability in the Sun, suggest that there may be two distinct dynamos operating in different regions of the interior. Consequently, there is a natural link between studies of magnetic activity and asteroseismology, which can characterize some of the internal properties that are relevant to dynamos. I provide a brief historical overview of the connection between these two fields (including prescient work by Wojtek Dziembowski in 2007), and I highlight some exciting results that are beginning to emerge from the *Kepler* mission.

Keywords. stars: activity, stars: interiors, stars: magnetic fields, stars: oscillations

1. Background

In early 2005, I attended a seminar given by David Salabert in which he described his work documenting subtle shifts in the solar oscillation frequencies throughout the 11-year sunspot cycle (Salabert *et al.* 2004). The measurements relied on data from the IRIS network, and they clearly showed that even the low-degree ($l \leqslant 3$) solar oscillation frequencies were shifted by a few tenths of a μHz between magnetic minimum and maximum. If such frequency shifts were detectable in the Sun observed as a star, I realized that it might be possible to see similar behavior in other stars.

The high-degree oscillation frequency shifts in the Sun through the solar cycle were first characterized by Libbrecht & Woodard (1990). Using the thousands of oscillation modes then available from helioseismology they showed that the magnitude of the shift depended on both the geometry (spherical degree, l) and the frequency of the oscillation, with the largest shifts observed for higher degrees and at higher frequencies. The initial interpretation of these observations was given by Goldreich *et al.* (1991), who matched the frequency dependence of the shifts by considering a direct magnetic perturbation to the near-surface propagation speed of the acoustic waves.

Dziembowski & Goode (2005) developed a similar formalism to explain modern space-based observations of the solar acoustic oscillations (p modes) as well as the surface gravity waves (f modes). They identified some secondary effects that were needed to explain the shifts observed in both sets of modes: a decrease in the radial component of the turbulent velocity, and the associated changes in temperature. Shortly after this work was published, I contacted Wojtek Dziembowski to ask whether I could use his code to calculate the expected shifts in low-degree p modes for other solar-type stars.

At the time there were very few stars with detections of solar-like oscillations, but Fletcher *et al.* (2006) would soon publish evidence of a marginally significant shift in the p-mode frequencies of α Cen A by comparing ground-based observations with earlier data from the *WIRE* satellite, and Bedding *et al.* (2007) would see a similar (but statistically

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insignificant) shift when comparing two ground-based asteroseismology campaigns on β Hyi. Wojtek happily sent me a copy of his code, and with his help I spent more than a year trying to figure out how to adapt it for other stars before he generously invited me to come to Warsaw for a week and work on it together. During that week we kick-started a project on β Hyi, and we submitted the paper six months later (Metcalfe *et al.* 2007).

2. Predictions

As the activity level of the Sun rises from minimum to maximum, the p-mode oscillations are gradually shifted to higher frequencies. The magnitude of the shift is proportional to the change in activity level, so the simplest prediction for other stars is to assume that the mean shift in the p-mode frequencies scales with activity level. In other words, the largest shifts would be expected in the most active stars. This was the approach taken by Chaplin *et al.* (2007), who were working contemporaneously.

Wojtek took a slightly different approach to predicting the frequency shifts in other stars. He parametrized the shifts as $\Delta\nu \propto A_0\ [R/M]\ Q_j(D_c)$, where A_0 scales with the activity level as in Chaplin *et al.* (2007), R and M are the radius and mass, and Q_j is a function of D_c which is the depth of the source of the perturbation below the photosphere. He demonstrated that this parametrization could remove all of the dependence on spherical degree and most of the frequency dependence in MDI data of the Sun with D_c fixed at 0.3 Mm. To extend the relation to other stars, he assumed that D_c would scale with the pressure scale height H_p in the outer layers: $D_c \propto H_p \propto L^{1/4}R^{3/2}/M$, which can be expressed in terms of the luminosity L, radius and mass.

At the time we were doing this work, β Hyi was the only star with a known activity cycle and multiple asteroseismic observing campaigns. The activity cycle had been observed in the Mg II h and k lines by the *IUE* satellite, and several years of additional observations were available in the archive after the initial characterization by Dravins *et al.* (1993). Phil Judge did a complete reanalysis of the *IUE* data, and determined a cycle period of 12 years with a maximum at 1986.9. Marty Snow produced a comparable record of solar Mg II h and k flux so we could scale the observed change in β Hyi to predict a mean shift in the oscillation frequencies. Just by luck, β Hyi was near magnetic maximum during the first detection of solar-like oscillations by Bedding *et al.* (2001), and close to magnetic minimum during the subsequent asteroseismic campaign by Bedding *et al.* (2007). The ground-based data were insufficient for a quantitative test, but Wojtek's relation qualitatively reproduced the observed shifts (Metcalfe *et al.* 2007).

Two years later, Christoffer Karoff led a project to define an optimal sample of asteroseismic targets in the *Kepler* field that would also be monitored for stellar activity variations from ground-based Ca II H and K measurements obtained throughout the mission (Karoff *et al.* 2009, 2013). When trying to determine which stars would show the largest frequency shifts, he was confronted with two conflicting predictions (see Fig. 1). The relation proposed by Chaplin *et al.* (2007) suggested that the largest shifts would be expected in the young active K stars. Wojtek's relation in Metcalfe *et al.* (2007) predicted that the hotter F stars would exhibit the largest shifts, which would grow even larger as the stars evolved. To be safe, the sample covered the full range of temperatures.

3. Confirmation

At the Beijing SONG workshop in March 2010, I gave a contributed talk on monitoring stellar magnetic activity cycles with SONG. During the coffee break Rafa García told me about some asteroseismic observations of the F star HD 49933, and he invited me to participate. The activity level of the star was not known, so I added it to a time-domain

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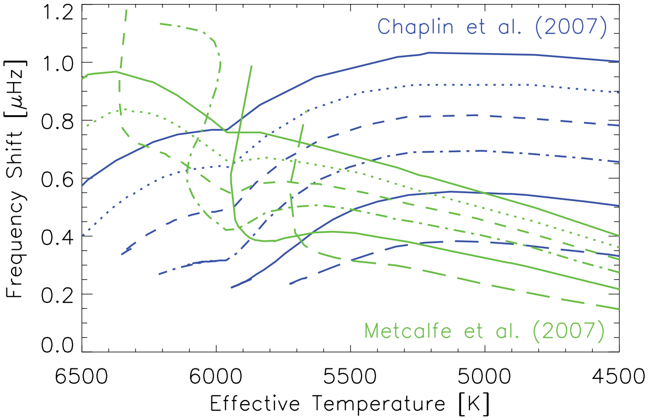

Figure 1. Predictions of the cycle-induced frequency shift as a function of effective temperature and age, with the scaling proposed by Chaplin *et al.* (2007) shown in blue and that proposed by Metcalfe *et al.* (2007) shown in green. Solid lines are Padova isochrones at an age of 1 Gyr, and the sets of dashed lines show progressively older isochrones at 1.6, 2.5, 4, 6.3, and 10 Gyr (adapted from Karoff *et al.* 2009).

survey of Ca II H and K emission that I was conducting for a sample of bright stars in the southern hemisphere (Metcalfe *et al.* 2009).

García *et al.* (2010) discovered anti-correlated changes in the frequencies and amplitudes of the oscillations in HD 49933 during 150 days of continuous monitoring by *CoRoT*. The frequency shifts were positive, and passed through a minimum while the amplitudes increased and passed through a maximum—the same pattern of changes that occurs in the Sun as it passes through a magnetic minimum. Convection stochastically excites and intrinsically damps solar-like oscillations. Magnetic fields inhibit convection, suppressing the oscillation amplitudes while simultaneously shifting the frequencies.

Salabert *et al.* (2011) pushed the analysis further, and examined the frequency dependence of the shifts. Just as in the Sun, the shifts grew steadily larger toward higher frequencies. It seemed clear that *CoRoT* had made the first asteroseismic detection of a stellar magnetic cycle, but there was one striking difference between HD 49933 and the Sun. The frequency shifts observed in this ∼2 Gyr-old F star at 6600 K were 4 − 5 times larger than solar, providing the first confirmation of Wojtek's relation.

4. Future prospects

The archive of *Kepler* data represents an unprecedented opportunity to study the short-period magnetic cycles that have been observed in some rapidly rotating F stars. The high precision time-series photometry collected every 30 minutes over the past four years can be used to measure rotation periods from spot modulation and to monitor the longer-term brightness changes associated with the stellar cycle. Furthermore, for targets that have been observed in short cadence (1-minute sampling), asteroseismology allows a characterization of the star including key dynamo ingredients such as the depth of the surface convection zone (Mazumdar *et al.* 2012) and radial differential rotation (Deheuvels *et al.* 2012). The asteroseismic data can also be used to monitor the solar-like oscillations over time, allowing a search for the same pattern of changes that have been seen for the Sun and HD 49933 in response to their magnetic cycles. Rapidly rotating F stars are the ideal targets because they show the shortest cycle periods (Metcalfe *et al.* 2010), and the frequency shifts are significantly larger than in the Sun (see Fig. 1). Young,

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rapidly rotating K stars can also show relatively short cycles (Metcalfe *et al.* 2013), but the asteroseismic signatures are expected to be smaller.

Mathur *et al.* (2013) recently examined the archive of *Kepler* observations for a sample of 22 rapidly rotating F stars. Wavelet analysis of the long light curves revealed clear signatures of latitudinal differential rotation and evidence for short magnetic cycles in a few stars. The best target in the sample has three years of continuous asteroseismic data spanning what appears to be a complete magnetic cycle, so additional tests of Wojtek's relation should soon be possible.

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