SF2A 2011
G. Alecian, K. Belkacem, R. Samadi and D. Valls-Gabaud (eds)

STELLAR ACTIVITY CYCLES AND ASTEROSEISMOLOGY

D. Salabert[1]

Abstract. The success of helioseismology is due to its capability to accurately measure the *p*-mode parameters of the solar eigenmode spectrum, which allow us to infer unique information about the internal structure and dynamics of the Sun from its surface all the way down to the core. It has contributed greatly to a clearer understanding of the Sun and provided insights into the complex solar magnetism, by means for instance of the variability of the characteristics of the *p*-mode spectrum. Indeed, variations in the mean strength of the solar magnetic field lead to significant shifts in the frequencies of even the lowest-degree p modes with high levels of correlation with solar surface activity proxies. These frequency shifts are explained to arise from structural changes in the outer layers of the Sun during the 11-year activity cycle, which is understood to be driven by a dynamo process. However, clear differences between *p*-mode frequencies and solar surface activity during the unusually extended minimum of cycle 23 were observed. The origin of the *p*-mode variability is thus far from being properly understood and a better comprehension of its relationship with solar and stellar activity cycles will help us in our understanding of the dynamo processes. Spectroscopic measurements of Ca H and K emission lines revealed magnetic activity variations in a large sample of solar-type stars with timescales ranging from 2.5 and 25 years. This broad range of cycle periods is thought to reflect differences in the rotational properties and the depths of the surface convection zones with various masses and ages. However, spectroscopic measurements are only good proxies of surface magnetic fields. The recent discovery of variations with magnetic activity in the *p*-mode oscillation frequencies of the solar-like star HD 49933 observed by CoRoT, with a frequency dependence comparable in shape to the one observed in the Sun, opens a new era in the study of the physical phenomena involved in the dynamo processes. Current and future asteroseismic observations will contribute to probe stellar cycles in a wide variety of solar-type stars.

Keywords: solar-type stars, activity, oscillations

1 Introduction

The Sun is a variable star with an 11-year cyclic variation of its magnetic activity. Signatures of its variability can be seen in several activity proxies, the most famous being the number of spots on the surface of the Sun. Other indices such as the 10.7-cm radio flux or the irradiance for instance also show this 11-year periodicity. The 11-year magnetic cycle is theoretically understood to be driven by a magnetic dynamo process located at the bottom of the convective zone (Svalgaard et al. 2005; Dikpati & Gilman 2006). Attempts have been made to provide prediction of the cycle properties based on dynamo models but these are not conclusive yet. Indeed, different conclusions were obtained for the new cycle 24, for which these models had not predicted the long and deep minimum of cycle 23.

Although spots on solar-type stars cannot be directly observed, stellar magnetic cycles have been already reported. Indeed, the associated areas of concentrated magnetic field produce strong emission in the Ca II H and K spectral lines, which were proven to be a good proxy of surface magnetic fields (Leighton 1959). Surveys from the Mount Wilson and Lowell Observatories (northern-hemisphere targets) along with long-term monitoring campaigns with SMARTS 1.5-m telescope at CTIO (southern-hemisphere targets) have revealed that many solar-type stars exhibit long-term cyclic variations in their Ca II H and K emission lines, analogous to the solar variations (Wilson 1978; Baliunas et al. 1995; Metcalfe et al. 2009). The complete sample includes cycle periods covering a range between 2.5 to 25 years. Recently, Metcalfe et al. (2010) discovered an even

[1] Université de Nice Sophia-Antipolis, CNRS UMR 6202, Observatoire de la Côte d'Azur, BP 4229, 06304 Nice Cedex 4, France

shorter activity cycle of 1.6 years in the exoplanet hosting F8V star HD 17051. Moreover, it has been observed that the periods of the activity cycles increase proportional to the stellar rotational periods along two distinct paths in main-sequence stars: the relatively young, active sequence, and the older, less active sequence (Saar & Brandenburg 1999; Böhm-Vitense 2007). Relations between mean level of magnetic activity, rotation rate, and periods of the observed activity cycle generally support a dynamo interpretation. However, spectroscopic measurements are only good proxies of surface magnetic fields.

The recent discovery, using asteroseismic observations, of variations with magnetic activity in the p-mode oscillation frequencies of the solar-like F5V star HD 49933 (García et al. 2010), with a frequency dependence comparable in shape to the one observed in the Sun (Salabert et al. 2011), opens a new era in the study of the physical phenomena involved in the dynamo processes. Indeed, through the precise measurements of oscillation parameters, the seismic observables provide unique information about the interior of the stars and for the determination of key parameters for the study of stellar activity, such as the depth of the convection zone, the characteristic evolution time of the granulation, the differential rotation, or the sound-speed as a function of the star's radius (see the preliminary work on HD 49933 by Ceillier et al. 2011). All these new observables will impose new constraints to the theory (e.g. Chaplin et al. 2007a; Metcalfe et al. 2007). Long, high-quality photometric observations such as the ones collected by the space-based Convection, Rotation, and planetary Transits (CoRoT, Baglin et al. 2006) and *Kepler* (Koch et al. 2010) missions will contribute to probe stellar cycles in a wide variety of solar-type stars.

2 Variability of the oscillation parameters with solar magnetic activity

The success of helioseismology is due to its capability to accurately measure the p-mode parameters of the solar eigenmode spectrum, which allow us to infer unique information about the internal structure and dynamics of the Sun from its surface all the way down to the core. It has contributed greatly to a clearer understanding of the Sun and provided insights into the complex solar magnetism, by means for instance of the variability of the characteristics of the p-mode spectrum. Evidence of p-mode frequency changes with solar activity, first revealed by Woodard & Noyes (1985), were established by Pallé et al. (1989) with the analysis of helioseismic observations spanning the complete solar cycle 21 (1977–1988). As longer, higher quality, and continuous helioseismic observations became available, the solar p-mode frequencies proved to be very sensitive to the solar surface activity (e.g., Anguera Gubau et al. 1992; Régulo et al. 1994; Jiménez-Reyes et al. 2001; Gelly et al. 2002; Salabert et al. 2004; Chaplin et al. 2007b, and references therein) with high levels of correlation with solar surface activity proxies. The low-degree, p-mode frequencies change by about 0.4μHz between the minimum and the maximum of the solar cycle with correlation levels with surface activity proxies higher than 0.9. Moreover, Howe et al. (2002) showed that the p-mode frequencies are shifted in presence of surface magnetic activity, varying with close temporal and spatial distributions. However, clear differences were observed between the frequency shifts and the surface activity of the Sun during the unusually extended and deep minimum of cycle 23 (Howe et al. 2009; Salabert et al. 2009; Broomhall et al. 2009; Jain et al. 2011). Although the form and the dependence of the shifts indicate a near-surface phenomenon explained to arise from changes in the outer layers of the Sun, the origin of the frequency shifts is far from being properly understood. Moreover, a quasi-biennial signal in the solar frequencies was recently observed by Fletcher et al. (2010), indicating the possible action of a second dynamo seated near the bottom of the layer extending 5% below the solar surface.

The other p-mode oscillation parameters such as the amplitude, the lifetime, and the asymmetry, were also observed to vary with solar activity (Chaplin et al. 2000; Komm et al. 2002; Salabert et al. 2003; Salabert & Jiménez-Reyes 2006; Jiménez-Reyes et al. 2007). For example, the mode amplitudes decrease with increasing solar activity by about 40% from minimum to maximum of the 11-year cycle. The temporal variations between frequency and amplitude are therefore anticorrelated.

3 Signatures of stellar magnetic activity using asteroseismic observations

The solar-like F5V star HD 49933 observed by the CoRoT satellite (Appourchaux et al. 2008; Benomar et al. 2009) is the first star after the Sun for which variability of the p-mode parameters with magnetic activity was observed (García et al. 2010). Indeed, the p-mode frequencies and amplitudes vary with time with a clear anti-correlation between both parameters as observed in the Sun (e.g. Salabert et al. 2003). These temporal variations suggest a cycle period of at least 120 days. Preliminary spectroscopic measurements with of the Ca II H and K emission lines had shown that HD 49933 is an active star, with a Mount Wilson S-index of 0.3. Followup long-term monitoring confirms the existence of a short activity cycle (T. Metcalfe, private communication, 2011). Incoming observations (both asteroseismic and spectroscopic) will help us to determine more accurately the period and the properties of this magnetic activity cycle. Salabert et al. (2011) showed that the frequency shifts measured in HD 49933 present a frequency dependence with a clear increase with frequency, reaching a maximal shift of about 2μHz around 2100μHz, which shows a similar pattern as in the Sun. That indicates then the presence of similar physical phenomena driving the frequency shifts of the oscillation modes as the ones taking place in the Sun, which are understood to reflect structural changes in and just below the photosphere with stellar activity if we suppose similar mechanisms as in the Sun (e.g., Goldreich et al. 1991). However, the frequency shift measured in HD 49933 is at least five times larger than in the Sun, which reaches about 0.5μHz at 3700μHz between the maximum and the minimum of the 11-year solar cycle (e.g. Salabert et al. 2004). This observation supports the scaling proposed by Metcalfe et al. (2007), who predicted that stars hotter and more evolved than the Sun (like HD 49933) should have larger frequency shifts than in the Sun. Preliminary structure models of HD 49933 were computed by Ceillier et al. (2011) in order to study the effects of sound-speed perturbations in the near surface layers on the p-mode frequencies. This will provide for instance insights on the properties of the convective zone of HD 49933 and on the depth at which the magnetic field perturbs the modes.

Three other solar-like stars observed by CoRoT have been studied, for which spectropolarimetric measurements from the NARVAL instrument (Aurière 2003) located at the Pic du Midi Observatory are available: HD 181420 (Barban et al. 2009), HD 49385 (Deheuvels et al. 2010), and HD 52265 (Ballot et al. 2011). Although HD 181420 and HD 49385 seem to be in a quiescence state, HD 52265 shows small temporal variations of the p-mode parameters, suggesting a modest increase of magnetic activity, also indicated by the spectroscopic observations (Mathur et al. 2011).

4 Conclusions

Asteroseismology provides not only invaluable information to infer the structure and the dynamics of the interior of the stars but also key parameters for the study of stellar magnetic activity cycles in a wide variety of solar-type stars imposing new observational constraints to the theory. Studies of stellar activity cycles will bring important inferences for the modeling of dynamo processes and will put the Sun and its 11-year activity cycle into context. The solar-like F star, HD 49933, is the first star after the Sun for which variations of the oscillation parameters with magnetic activity have been observed. Although these changes follow analogous patterns as in the Sun, they suggest a short cycle period, which is confirmed by spectroscopic observations. They also support that stars hotter and more evolved than the Sun should have larger frequency shifts. This is important for CoRoT and *Kepler* when searching for similar frequency shifts as it suggests that the shifts should be easier to detect in the F stars. Also, as short activity cycles seem to be more common than expected, the CoRoT and *Kepler* (and future) missions should potentially be able to observe a large number of full cycles. Such studies will also provide inputs to explore the impacts of magnetic activity on possible planets hosted by these stars.

The author acknowledges the financial support from the Centre National d'Etudes Spatiales (CNES).

References

Anguera Gubau, M., Pallé, P. L., Pérez Hernandez, F., Régulo, C., & Roca Cortés, T. 1992, A&A, 255, 363

Appourchaux, T., Michel, E., Auvergne, M., et al. 2008, A&A, 488, 705

Aurière, M. 2003, in Proceedings of the conference Magnetism and Activity of the Sun and Stars, ed. J. Arnaud & N. Meunier (EAS Publications Series, Vol. 9) 105

Baglin, A., Michel, E., Auvergne, M., & The CoRoT Team 2006, in Proceedings of SOHO 18/GONG 2006/HELAS I, Beyond the spherical Sun, ESA SP-624, ed. K. Fletcher, & M. Thompson (ESA Special Publication, Noordwijk), 34

Baliunas, S.L., Donahue, R.A., Soon, W.H., et al. 1995, ApJ, 438, 269

Ballot, J., Gizon, L., Samadi, R., et al. 2011, A&A, 530, A97

Barban, C., Deheuvels, S., Baudin, F., et al. 2009, A&A, 506, 51

Benomar, O., Baudin, F., Campante, T. L., et al. 2009, A&A, 507, L13

Böhm-Vitense, E. 2007, ApJ, 657, 486

Broomhall, A.-M., Chaplin, W. J., Elsworth, Y., Fletcher, S. T., & New, R. 2009, ApJ, 700, L162

Ceillier, T., Ballot, J., García, R. A., et al. 2011, in Proceedings of the 2^{nd} CoRoT symposium, Transiting planets, vibrating stars, and their connection, ed. A. Baglin, M. Deleuil, E. Michel, & C. Moutou, to be published
Chaplin, W. J., Elsworth, Y., Isaak, G. R., Miller, B. A., & New, R. 2000, MNRAS, 313, 32
Chaplin, W. J., Elsworth, Y., Houdek, G., & New, R. 2007a, MNRAS, 377, 17
Chaplin, W. J., Elsworth, Y., Miller, B. A., Verner, G. A., & New, R. 2007b, ApJ, 659, 1749
Deheuvels, S., Bruntt, H., Michel, E., et al. 2010, A&A, 515, A87
Dikpati, M., & Gilman, P. A. 2006, ApJ, 649, 498
Fletcher, S. T., Broomhall, A.-M., Salabert, D., et al. 2010, ApJ, 718, L19
García, R. A., Mathur, S., Salabert, D., et al. 2010, Science, 329, 1032
Gelly, B., Lazrek, M., Grec, G., et al. 2002, A&A, 394, 285
Goldreich, P., Murray, N., & Willette, G. 1991, ApJ, 370, 752
Howe, R., Komm, R. W., & Hill, F. 2002, ApJ, 580, 1172
Howe, R., Christensen-Dalsgaard, J., Hill, F., et al. 2009, ApJ, 701, L87
Jain, K., Tripathy, S. C., & Hill, F. 2011, ApJ, 739, 6
Jiménez-Reyes, S. J., Corbard, T., Pallé, P. L., Roca Cortés, T., & Tomczyk, S. 2001, A&A, 379, 622
Jiménez-Reyes, S.J., Chaplin, W.J., Elsworth, Y., et al. 2007, ApJ, 654, 1135
Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJ, 713, L79
Komm, R., Howe, R., & Hill, F. 2002, ApJ, 572, 663
Leighton, R. B. 1959, ApJ, 130, 366
Mathur, S. et al. 2011, Submitted to A&A
Metcalfe, T. S., Dziembowski, W. A., Judge, P. G., & Snow, M. 2007, MNRAS, 379, L16
Metcalfe, T. S., Judge, P. G., Basu, S., et al. 2009, arXiv:0909.5464
Metcalfe, T. S., Basu, S., Henry, T. J., et al. 2010, ApJ, 723, L213
Pallé, P. L., Régulo, C., & Roca Cortés, T. 1989, A&A, 224, 253
Régulo, C., Jiménez, A., Pallé, P. L., Pérez Hernandez, F., & Roca Cortés, T. 1994, ApJ, 434, 384
Saar, S.H., & Brandenburg, A. 1999, ApJ, 524, 295
Salabert, D., Jiménez-Reyes, S. J., & Tomczyk, S. 2003, A&A, 408, 729
Salabert, D., Fossat, E., Gelly, B., et al. 2004, A&A, 413, 1135
Salabert, D., & Jiménez-Reyes, S. J. 2006, ApJ, 650, 451
Salabert, D., García, R. A., Pallé, P. L., & Jiménez-Reyes, S. J. 2009, A&A, 504, L1
Salabert, D., Régulo, C., Ballot, J., García, R. A., & Mathur, S. 2011, A&A, 530, A127
Svalgaard, L., Cliver, E. W., & Kamide, Y. 2005, Geophys. Res. Lett., 32, 1104
Wilson, O. C. 1978, ApJ, 226, 379
Woodard, M. F., & Noyes, R. W. 1985, Nature, 318, 449