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The solar-stellar connection: new insights from the Kepler mission

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Abstract. Magnetic fields appear to be ubiquitous in almost all types of stars although the underlying generation mechanism can be very different along the HR diagram. For instance, one of the most promising models of the solar activity cycle is based on the idea that the meridional circulation determines the period of the solar cycle if the eddy diffusivity is low enough. On the other hand, in massive stars the possibility of generating a dynamo action in radiative envelopes is still much debated. In this context the high-quality photometric data provided by the Kepler mission provide important information on the possible dynamo actions in young, fast-rotating, solar-type stars.

Key words. Sun: magnetic fields – Stars: magnetic fields – Stars: interior

1. Introduction

It is generally expected that most of solar-type stars should develops activity cycles, as the Sun. In fact, stars with a deep convective envelope and a radiative interior (late F, G, K and early M spectral type) are likely to produce a strong radial shear at the interface between the convective zone and the radiative interior. This powerful source of toroidal field via the so called Ω-effect guarantees the presence of a magnetic field in the tachocline which can then be subject to various instabilities. Moreover, the presence of a global non-zero helicity in the convective zone caused by the cyclonic turbulence provides a likely mechanism to close the dynamo loop by means of the the α-effect.

From the observational point of view, although new data are more and more available (Giampapa 2006) only with long term observing programs like the Mt.Wilson H&K survey (Wilson 1978) it is possible extract significant information on the presence of activity cycles in stars. However, although Baliunas et al. (1995) have collected and analyzed data on the the chromospheric activity of about 110 stars in the spectral range K to F the correlation between the cycle period $P_{\rm cyc}$ and the Rossby number $Ro = P_{\rm rot}/\tau$ - being τ the characteristic turnover time - is not very clear (Wright et al. 2004). In particular Saar & Brandenburg (1999) have argued that there are two branches in the distribution of $P_{\rm cyc}$ vs $P_{\rm rot}$ with $P_{\rm cyc} \propto P^{\beta}_{\rm rot}$ with the scaling exponent $\beta = 0.8$ for the active branch and $\beta = 1.15$ for the inactive branch.

A clear correlation between chromospheric emissions $\langle R_{\rm HK}\rangle$ and rotation rate appears instead in the activity-rotation relationship. In particular it turns out that $\langle R_{\rm HK}\rangle \sim Ro^{-1}$ with a clear saturation for small Ro, i.e. for fast ro-

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tating stars, a trend which is also present in the X-ray luminosities (Pizzolato et al. 2003).

In the saturated part of the activity-rotation diagram the following scenarios are possible: a) the filling-factor f is saturating, b) the field strength is suppressed via an α-quenching mechanism or c) at very smalls *Ro* a transition to small scale dynamo occurs. Unfortunately the exact scaling of the total magnetic flux is still a subject of debate (Schrijver et al. 2003) and it thus difficult to distinguish among these possibilities at the present time. From the theoretical point of view numerical simulations showed that that the dynamo action produces wreaths of strong toroidal magnetic field at low latitudes, often of opposite polarity in the two hemispheres (Nelson et al. 2011). On the other hand, theoretical models of generation of magnetic fields in fully convective pre-main sequence (PMS) stars argue that the basic process is an α^2 dynamo (Küker & Rüdiger 1999). In the small *Ro* regime, the differential rotation pattern is expected to be dictated by the Taylor-Proudman balance, so that the isocontour lines of the angular velocity are cylinder-shaped. Nevertheless, recent calculations of a 1-$M_\odot$ rapidly rotating main-sequence star with period $P_{\rm rot}$ = 1.33 days, predicts a value of 0.08 rad d^{-1}, surprisingly close to the Solar value despite there being a factor 20 between the average rotation rates (Küker et al. 2011). For instance, for (HD 171488), a young Sun with an equatorial rotation period of 1.33 days, values of differential rotation as high as 0.50 rad d^{-1} have already been found (Marsden et al. 2006; Jeffers and Donati 2008).

Important insights on the above questions can be obtained from NASA *Kepler Mission* (Borucki 2010). Although the main goal of the mission is the detection of exoplanets, the high-precision quality of the photometry ($\sim$ 20 ppm in one hour of integration time for m_V = 12) provides us with important information either from spot-modelling (for the photospheric fields) or from asteroseismology (for the internal structure). For instance, in this latter case, it has recently been shown (Creevey et al. 2012) that it is possible to determine radius, mass and age with a precision of 2 − 5%, 7 − 11% and 35% respectively on *Kepler* stars combining 8 months of short cadence (30 min) Kepler data with ground based spectroscopic observations. Once the precise evolutionary status of the star is known it is then possible to model the internal differential rotation and meridional circulation, as it has been shown in the case of Procyon A for instance (Bonanno et al. 2007). Once the above ingredients are then known it is possible to use mean field theory to discuss the occurrence of activity cycles, for instance, or make predictions on the strength on photospheric fields.

2. Mean-field dynamo models in solar-like stars

In the framework of mean field theory it is possible to classify the dynamo mechanism by means of the dimensionless numbers

$$C_\Omega = \frac{R^2\,\Omega}{\eta}, \qquad C_\alpha = \frac{R\,\alpha_0}{\eta}, \qquad C_u = \frac{R\,U}{\eta} \tag{1}$$

where R is the stellar radius, Ω is the angular velocity, U is the strength of the meridional circulation at the surface, and η is the eddy diffusivity. Here α_0 is strength of the pseudo-scalar α which characterizes the contribution to the mean turbulent force $\mathcal{E} = \alpha\mathbf{B} + \cdots$ due to rotating turbulence and it represents the most important term in the study of solar and stellar magnetic fields (Parker 1955). A dynamo action characterized by $C_u \ll 1$ is generically called $\alpha^2\Omega$ and, depending on the ratio C_Ω/C_α, it ranges from an α^2 regime (with negligible differential rotation, $C_\Omega \sim 0$) to the pure $\alpha\Omega$ regime, where $C_\Omega \gg C_\alpha$. In this case the essential ingredients are the α-effect and the differential rotation. While the latter can be constrained by observations (helioseismology in the case of the Sun, spectroscopy or photometry for stars) for the former it has often been assumed that the most suitable location for this effect (Parker 1993; Steenbeck et al. 1966) is just beneath the convection zone where a strong radial shear is produced in the so called tachocline (Spiegel & Zahn 1992).

The source of the turbulent helicity producing the α-effect can be attributed to various mechanisms. The most promising one is the tachocline instability proposed by Dikpati

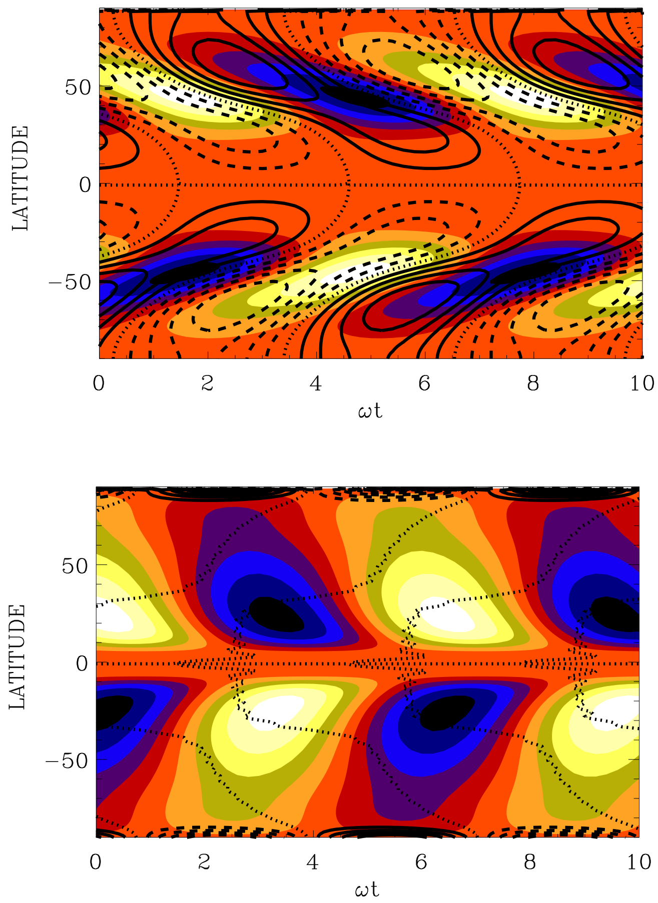

Fig. 1. Upper panel: Butterfly diagram and phase relation for a overshoot dynamo solution with no meridional circulation and a solar-like rotation law, $C_\alpha = 19.34$, $C_\Omega = 3000$. The solid and dashed lines represent the radial field at the surface (solid for negative B_r), and blue is for negative toroidal field, while ω is the frequency of the dynamo wave. Lower panel: butterfly diagram and phase relation for a solution with $C_u = 400$, $C_\alpha = 19.34$, $C_\Omega = 30000$. The period of about 20 yrs and a flow of 27 m s^{-1} at the surface.

& Gilman (2001) although in recent investigations another appealing possibility is provided by a current-helicity generated α-effect (Gellert et al. 2011) due to kink and quasi-interchange instabilities in stably stratified plasmas. This latter mechanism can be operating at the bottom of the convection zone because it has been shown that the presence of combined poloidal and toroidal field produce instabilities with arbitrarily large azimuthal wave numbers (Bonanno & Urpin 2011). However, as it is well known, differential rotation and α-effect alone cannot explain various features of the solar dynamo because the helioseismically derived rotation law predicts a negative shear at high latitude and a positive shear at low latitude that does not lead to the correct butterfly diagram (Dikpati & Charbonneau 1999; Bonanno et al. 2002, 2006; Guerrero & de Gouveia Dal Pino 2008). An example of this phenomenon can be seen in the left panel of Fig. 1 in the case of an overshoot dynamo, where it is clear that, due to the fact that $\partial\Omega/\partial r < 0$ at high latitude, the dynamo wave produces a strong polar field which can only partially migrate towards the equator because the migration is halted around the latitude where $\partial\Omega/\partial r \approx 0$.

In recent years it has been realized that a flux-transport dynamo, characterized by the hierarchy $C_u \gg C_\alpha$ in (1) is a promising mechanism to explain several properties of the solar activity cycle. The basic observation behind this process is that in the presence of a low eddy diffusivity η the magnetic Reynolds number becomes very large and the dynamics of the mean-field flow becomes an essential ingredient of the dynamo process. In this regime the advection produced by the meridional circulation dominates the diffusion of the magnetic field which is then "transported" by the meridional circulation at lower latitude. A typical butterfly diagram for a G star like the Sun is depicted in the right panel of Fig. 1.

Can this mechanism be extended to other solar-like stars? In principle yes, but it would be necessary to know the strength of the meridional circulation for various spectral classes as in flux-transport dynamo the $P_{\rm cyc}$ is basically determined by the strength of the return flow at the base of the convection zone, a quantity which is very difficult to estimate, even for the Sun. An attempt to fit the $P_{\rm cyc}$ vs $P_{\rm rot}$ relation in Mt.Wilson data with this type of dynamo has been carried out by Jouve et al. (2008), but the results seem to depend more on the topological structure of the meridional flow than on its strength.

3. Magnetic fields in radiative zones

Most probably a dynamo action cannot operate in stellar radiation zones because it requires strong magnetohydrodynamic flows to generate a global magnetic field which are not available in the internal radiation zones. On the other hand, a weak fossil field with non-vanishing poloidal component will quickly wrap up into a predominantly toroidal configuration, under the action of differential rotation. Such configuration can be generated if $|\nabla\Omega| > \eta/r^3$ where Ω and η are the angular velocity and magnetic diffusivity, respectively, so that the magnetic Reynolds number of the flow is greater than one. The toroidal field resulting from these processes cannot grow without bound because of various magnetic instabilities that can be triggered by magnetic pressure and tension.

For this reason much attention has been devoted to the instabilities that may affect the toroidal magnetic field in stably stratified radiation zones. The magnetic field in a radiation zone can be subject to various instabilities such as the magnetic buoyancy (Gilman 1970; Acheson 1978) or magnetorotational instability (Velikhov 1959; Balbus & Hawley 1991). Most probably the most efficient instabilities are caused by electric currents maintaining the magnetic configuration (Spruit 1999). Such instabilities are well studied in cylindrical geometry in the context of laboratory fusion research (Goedbloed et al. 2004). In astrophysical conditions, the instability caused by electric currents is studied mainly in cylindrical geometry as well (Tayler 1973a,b, 1980). It turns out that the properties of instability depend on the ratio of the axial and toroidal fields and, even if this ratio is small, the axial field can alter the instability substantially (Knobloch 1992; Bonanno & Urpin 2008a). The effect of an axial field on the Tayler instability of the toroidal field has been studied in detail in cylindrical geometry also with direct numerical simulations Bonanno & Urpin (2008b, 2011). The nonlinear evolution of the Tayler instability was considered by Bonanno et al. (2012) who argued that symmetry-breaking can give rise to a saturated state with non-zero helicity even if the initial state has zero helicity.

The effects of stratification and rotation that are of great importance in stellar radiation zones. It is widely believed that both these effects can provide a stabilizing influence on the Tayler instability (Pitts & Tayler 1985; Spruit 1999). Stability of the spherical magnetic configurations is much less studied because of its mathematical difficulties. With numerical simulations Braithwaite & Nordlund (2006) studied the stability of a random initial field and

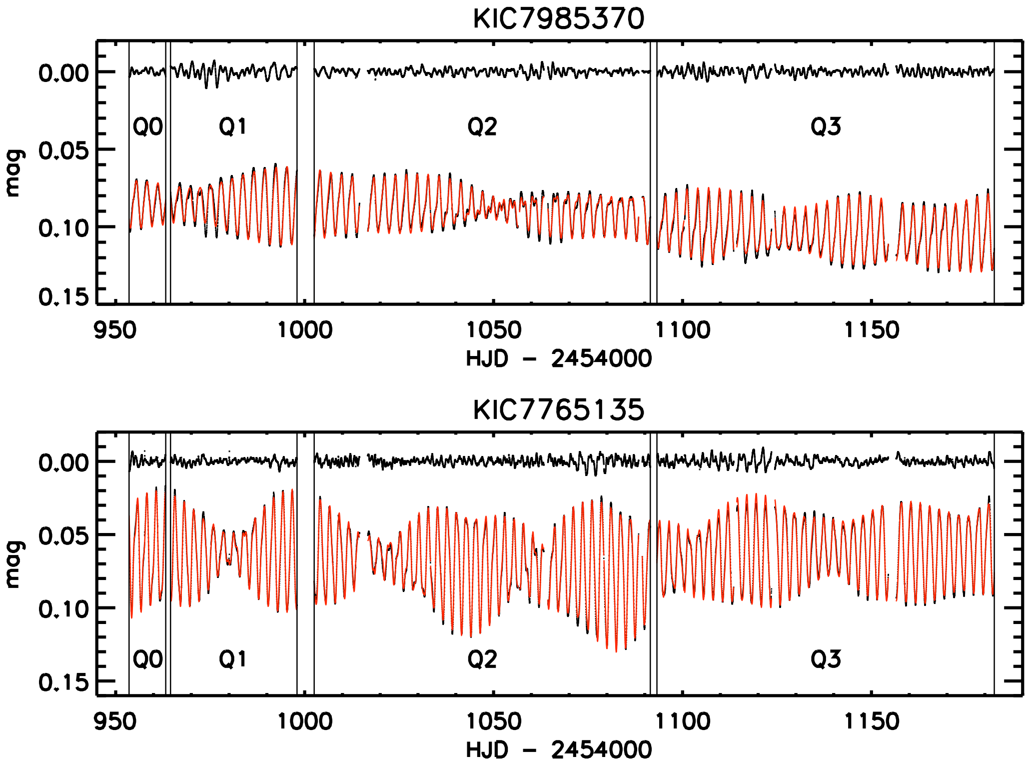

Fig. 2. Upper panel: light curve with best fit for KIC7985370 over-plotted. The residuals, shown at the top, are ±2.14 mmag. Lower panel: light curve with best fit for KIC7765135 over-plotted. The residuals, shown at the top, are ±2.35 mmag. From Fröhlich et al. (2012).

argued that this field relaxes on a stable mixed magnetic configuration with both poloidal and toroidal components. Stability of magnetic configurations with a predominantly toroidal field draws a particular attention. Numerical modeling by Braithwaite (2006) confirmed that the toroidal field with $B_\varphi \propto s$ or $\propto s^2$ (s is the cylindrical radius) is unstable to the $m = 1$ mode (Tayler 1973a). Recently, the effect of stratification and thermal conductivity on the Tayler instability of the toroidal field has been considered in Bonanno & Urpin (2012). The authors studied a linear stability and used a local approximation in latitude and global in the radial direction. They calculated the growth rate of instability and argued that the combined influence of gravity and thermal conductivity can never suppress the instability entirely. Stratification suppresses the instability at the pole more efficiently than at the equator. The growth rate of instability can be essentially reduced by a stable stratification. A decrease of the growth rate caused by stratification is inversely proportional to the Brunt-Väisälä frequency. Therefore, if gravity is strong, the instability developes very slowly. A simple fitting expression has been presented for the growth rate of instability in a stratified radiation zone in Bonanno & Urpin (2012) who argued that modes with a large number of nodes in the radial direction are significantly more suppressed than the fundamental eigenmode, although the effect of gravity is much weaker in this case.

Some general stability properties can be derived in the short wavelength approximation in radial and latitudinal direction. In this case, the perturbed fluid velocity in the radial direction can be written as $v_{1r} \propto \exp(-ik_r r)$, where k_r is the radial wavevector. If $k_r r \gg 1$, with the accuracy in terms of the lowest order in $(k_r r)^{-1}$, the following set of equation is obtained (Bonanno & Urpin 2012)

$$-(\sigma + \kappa k^2)\frac{T_1}{T} = \frac{\omega_{BV}^2}{\beta g} v_{1r}, \tag{2}$$

$$k_r^2(\sigma^2 + \omega_A^2)v_{1r} = k_\perp^2 \beta g \sigma \frac{T_1}{T}, \tag{3}$$

where $k^2 = k_r^2 + k_\perp^2$, T_1 is the local temperature perturbation, κ is the thermal diffusivity, β the thermal diffusion coefficient, ω_{BV} the Brunt-Väisälä frequency and σ the growth-rate.

The corresponding dispersion relation reads

$$\sigma^3 + \kappa k^2 \sigma^2 + \left(\omega_A^2 + \frac{k_\perp^2}{k^2}\omega_{BV}^2\right)\sigma + \kappa k^2 \omega_A^2 = 0 \tag{4}$$

The conditions that at least one of the roots has a positive real part (unstable mode) is determined by the Routh criterion. Since the quantities κ and ω_A^2 are positively defined, the only non-trivial condition of instability is $\omega_{BV}^2 < 0$ which is not satisfied in the radiation zone by definition. Therefore, modes a with short radial wavelength are always stable to the current-driven instability.

For these reasons the possibility of having a dynamo action working in radiation zone, although not completely excluded, is very unlikely on the basis of the present theoretical understanding (Zahn 2007).

4. Photospheric magnetic fields and pulsations in fast rotating solar-type stars

The structure of the photospheric magnetic field can be very different in fast rotating, young solar-type stars. It is expected that the Ω-effect play an important role in this case, producing characteristic "wreaths" on large scales (Nelson et al. 2011).

In Fröhlich et al. (2012) a detailed study of the two Sun-like *Kepler* targets KIC 7985370 ($V = 9.98 \pm 0.08$, $T_{\rm eff}$=5815±95 K, Sp.Type G1.5 V, $\log g = 4.24 \pm 0.12$ and $v \sin i = 18.2 \pm 1.3$ km s^{-1}) and KIC 7765135 ($V = 11.82 \pm 0.08$, $T_{\rm eff}$=5835±95 K, Sp.Type G1.5 V, $\log g = 4.34 \pm 0.12$ and $v \sin i = 21.4 \pm 1.3$ km s^{-1}) based on 229 observing days during the Q0-Q3 quarters has been presented

The spot distribution has been determined by means of a Bayesian photometric imaging as described in Frasca et al. (2011) using an analytical star-spot model Dorren (1987) generalized to a quadratic limb-darkening law. In particular the latitudinal dependence of the angular velocity has been parametrized by a series expansion using Legendre polynomials including also a $\sin^4\beta$ term, being β the latitude angle and the spots are assumed to be long living.

In both cases the inclination value i is ill-defined by the spot model applied to the *Kepler* photometry. Only with seven spots and allowing for enough spot evolution it was possible to arrive at acceptable inclination values and spot intensities If the inclination is fixed to the spectroscopically derived value of $i = 75°$ the residuals are rather high, ±2.46 mmag, exceeding the residuals of the best solution (±2.14 mmag).

In the case of KIC 7765135 the best solution allows for nine spots, but despite two additional spots, the residuals, ±2.35 mmag, are greater than those of the seven-spot model of KIC 7985370 (±2.14 mmag). This is not due to the fainter magnitude of KIC 7765135 compared to KIC 7985370, because the photometric uncertainties are typically 0.047 mmag for the former and 0.022 mmag for the latter. The reason may be that three of the nine spots are definitely short-lived with a life span as low as two months which is less than twice the lapping time of 38 days between the fastest and the slowest spot.

Although both stars share the same spectral type and age, there are differences concerning the spots. The spots of KIC 7985370 seem to be darker and longer living than those of KIC 7765135. Moreover, unlike KIC 7985370, in the case of KIC 7765135 mid-latitude spots (30–50°) are missing. One can argue that this fact is a consequence of the topological magnetic field "wreaths" on large scales often pro-

Table 1. Two 7-spot solutions for KIC 7985370 and a 9-spot solution for KIC 7765135. Listed are *expectation* values and 1-σ confidence limits. Periods P are given in days, the spot intensity κ is in units of the intensity of the unspotted surface. The differential rotation dΩ (rad d^{-1}) is the equator-to-pole value of the shear. Residuals are in mmag. In the first 7-spot solutions for KIC 7985370 (second column) the inclination is fixed to $i = 75°$. In the second 7-spot solutions for KIC 7985370 (third column) the inclination is not fixed.

parameter			KIC 7985370		KIC 7985370		KIC 7765135	
inclination		i	75°.0	*fixed*	41°.4	$^{+0.5}_{-0.5}$	75°.6	*fixed*
1st	latitude	β_1	34°.0	$^{+0.1}_{-0.1}$	29°.4	$^{+0.4}_{-0.4}$	20°.6	$^{+0.1}_{-0.1}$
2nd	latitude	β_2	−10°.0	$^{+0.6}_{-0.9}$	−6°.9	$^{+0.9}_{-0.9}$	76°.3	$^{+0.2}_{-0.2}$
3rd	latitude	β_3	32°.2	$^{+0.2}_{-0.2}$	29°.9	$^{+0.3}_{-0.3}$	1°.7	$^{+0.2}_{-0.2}$
4th	latitude	β_4	86°.8	$^{+0.1}_{-0.1}$	87°.5	$^{+0.1}_{-0.1}$	21°.8	$^{+0.3}_{-0.3}$
5th	latitude	β_5	53°.8	$^{+0.1}_{-0.1}$	53°.6	$^{+0.1}_{-0.1}$	0°.1	$^{+0.3}_{-0.2}$
6th	latitude	β_6	35°.8	$^{+0.2}_{-0.2}$	35°.8	$^{+0.3}_{-0.2}$	12°.0	$^{+0.1}_{-0.1}$
7th	latitude	β_7	29°.6	$^{+0.3}_{-0.2}$	19°.9	$^{+0.9}_{-0.9}$	16°.0	$^{+0.3}_{-0.3}$
8th	latitude	β_7	29°.6	$^{+0.3}_{-0.2}$	19°.9	$^{+0.9}_{-0.9}$	−75°.0	$^{+0.2}_{-0.2}$
9th	latitude	β_7	29°.6	$^{+0.3}_{-0.2}$	19°.9	$^{+0.9}_{-0.9}$	60°.0	$^{+0.4}_{-0.4}$
1st	period	P_1	2.8581	$^{+0.0001}_{-0.0001}$	2.8563	$^{+0.0001}_{-0.0001}$	2.4223	$^{+0.0001}_{-0.0001}$
2nd	period	P_2	2.8350	$^{+0.0003}_{-0.0003}$	2.8428	$^{+0.0007}_{-0.0006}$	2.5651	$^{+0.0001}_{-0.0001}$
3rd	period	P_3	2.8541	$^{+0.0004}_{-0.0004}$	2.8572	$^{+0.0004}_{-0.0005}$	2.4020	$^{+0.0001}_{-0.0001}$
4th	period	P_4	3.0895	$^{+0.0001}_{-0.0001}$	3.0898	$^{+0.0001}_{-0.0001}$	2.4237	$^{+0.0004}_{-0.0004}$
5th	period	P_5	2.9382	$^{+0.0002}_{-0.0002}$	2.9421	$^{+0.0002}_{-0.0002}$	2.4019	$^{+0.0001}_{-0.0001}$
6th	period	P_6	2.8629	$^{+0.0003}_{-0.0004}$	2.8700	$^{+0.0004}_{-0.0003}$	2.4092	$^{+0.0001}_{-0.0001}$
7th	period	P_7	2.8490	$^{+0.0003}_{-0.0002}$	2.8460	$^{+0.0002}_{-0.0002}$	2.4151	$^{+0.0004}_{-0.0005}$
8th	period	P_7	–		–		2.5645	$^{+0.0001}_{-0.0001}$
9th	period	P_7	–		–		2.5313	$^{+0.0010}_{-0.0010}$
spot intensity		κ	0.437	$^{+0.005}_{-0.004}$	0.396	$^{+0.006}_{-0.006}$	0.671	$^{+0.003}_{-0.003}$
equ. period		P_{eq}	2.8347	$^{+0.0003}_{-0.0003}$	2.8427	$^{+0.0007}_{-0.0006}$	2.4018	$^{+0.0001}_{-0.0001}$
diff. rotation		dΩ	0.1839	$^{+0.0002}_{-0.0002}$	0.1774	$^{+0.0004}_{-0.0005}$	0.1760	$^{+0.0003}_{-0.0003}$
residuals			±2.46		±2.14		±2.35	

duced in the numerical simulations (Nelson et al. 2011).

Both stars exhibit low-latitude spots as well as high-latitude ones at the time of observation making them suitable for studying their latitudinal shear. The most robust result is the high degree of surface differential rotation found for both stars: dΩ = 0.18 rad d^{-1} about three times the solar value. The details of both solutions are described in Table 1 and in Fig. 2.

5. Stellar activity and solar-like pulsations

Solar-like pulsations are directly influenced by the presence of a global magnetic field because a strong field diminishes the turbulent velocities in a convectively unstable layer, thus suppressing the driving of the acoustic modes. On the other hand, a direct effect on the oscillation frequencies is instead much smaller, of the order of the ratio between the Alfvén speed

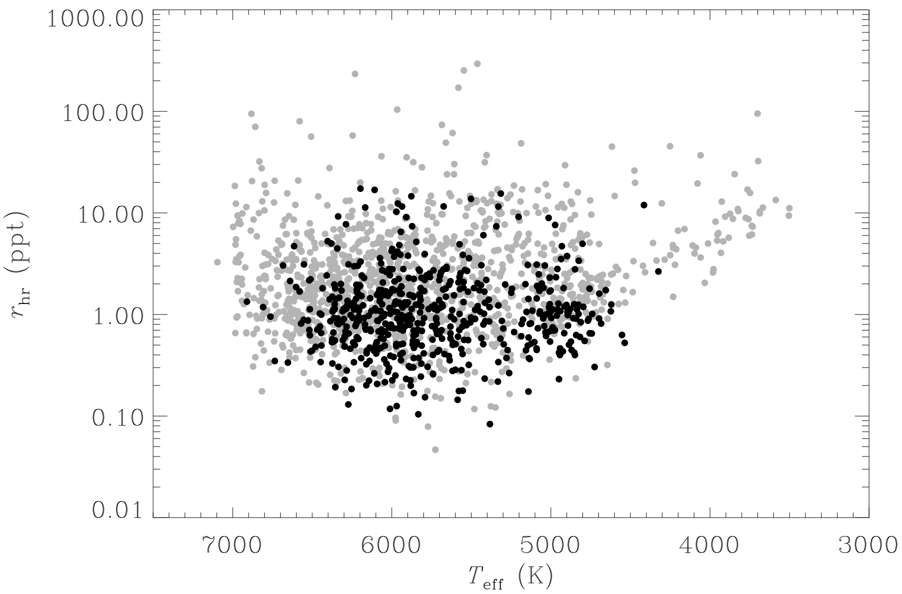

Fig. 3. Range, $r_{\rm hr}$ as a function of $T_{\rm eff}$. Stars with detected solar-like oscillations are plotted in black; stars with no detections are plotted in gray (Chaplin et al. 2011).

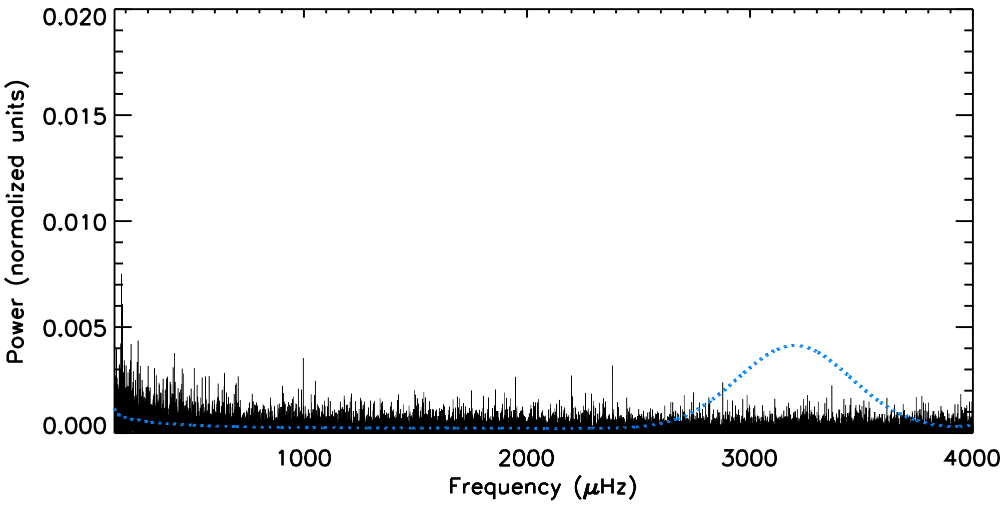

Fig. 4. Power spectrum for KIC7985370 in arbitrary units. The dashed line shows the expected position of the excess of power due to p-modes pulsations for this star.

and the local sound speed. As a consequence in solar-type stars the magnetic field affects not only the properties of the p-mode propagation, but also the turbulence of the convection by reducing its magnitude with increasing stellar activity, thereby reducing the amplitudes of the oscillations. The amplitudes (i.e., the square root of the total powers) of solar p modes are observed to decrease with increasing levels of solar activity (Chaplin et al. 2000). The decrease observed from solar minimum to solar maximum is about 12.5 % for modes of low spherical degree l which are the modes that are detectable in observations of solar-type stars.

In Chaplin et al. (2011) the unprecedented large ensemble of oscillating solar-type stars observed by the NASA *Kepler Mission* has been used to search for evidence of this effect in about 2000 solar-like stars down to *Kepler* apparent magnitude $Kp \simeq 12.5$. The maximum absolute deviations of a smoothed lightcurve from its mean, called $r_{\rm hr}$, can be used as a proxy for stellar surface activity, following Basri (2010). It turned out that the number of stars with detected oscillations fall significantly with increasing levels of activity, as shown in Fig. 3.

6. Conclusions

Probably the most important ingredient of dynamo action in solar-type stars is the actual value of the turbulent magnetic diffusivity η. Only if this transport coefficient is significantly smaller than the value obtained in mixing-length theory, the advection-dominated dynamo can explain several features of the solar and stellar activity cycles.

On the other hand the detection of p-mode pulsations in very active stars represent an observational and theoretical challenge which has the potential to open new avenues in the field of solar-stellar connections. An important question is to understand if the suppression of the p-modes due to the magnetic field occurs gradually, as a function of the magnetic field strength, or if instead there is a threshold beyond which the stochastic nature of the oscillations is completely suppressed. In the first case one might speculate that increasing the magnetic field the life-time of the mode gets shorter, while in the second case the properties of the convective turbulent motions becomes essentially different after a certain field strength. In fact, an analysis of the power spectrum of KIC 7985370 clearly shows no power in the expected frequency range as it is showed in Fig. 4, a fact that can be explained as a direct effect of the magnetic field on the convective eddies.

One can then argue that by measuring the life-time of the modes in very active stars it would be possible to estimate the value of the turbulent diffusivity at least in these stars because the correlation length of the turbulent eddies is determined essentially by the topology and the strength of the magnetic field.

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