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Evidence of the connection between internal magnetic fields and chromospheric activity in late-type stars

B. Montesinos *Department of Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP*

M. J. Fernández-Figueroa and E. de Castro *Departamento de Astrofísica, Facultad de Ciencias Físicas, Universidad Complutense de Madrid, Ciudad Universitaria, 28040 Madrid, Spain*

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Summary. In this work we try to establish a connection between the dynamo effect, which operates in the convection zone of late-type stars, and the chromospheric activity observed in these objects. We estimate in a theoretical way, for a sample of main-sequence active stars with spectral types G and K, the magnetic field generated in a region close to the base of the convection zone and the filling factor (fraction of stellar surface covered by strong magnetic fields). The analysis of the behaviour both of the filling factor and the activity indicator R(Ca II+Mg II) against several stellar parameters (*B–V* and the Rossby number) supports the existence of a link between the interior processes and the surface activity.

1 Introduction

The presence of magnetic fields in late-type stars is one of the most important factors to take into account in understanding the origin of chromospheric and coronal activity. The term 'activity' in the Sun, and by analogy, in stars of spectral types F or later, refers to all the phenomena related to structures in the outer atmospheric layers which show both long-term and short-term variability (Catalano 1984).

The present conception of the partially magnetic nature of the chromospheric activity has its starting point in Wilson's studies (see Wilson 1978). He observed systematically the variation of the chromospheric emission in the *H* and *K* lines of Ca II (the most important chromospheric indicators in the optical domain) in a wide sample of late-type stars. It is known that in the Sun we can observe strong Ca II emission associated with plages and the supergranulation network; both zones show strong magnetic fields and therefore it is reasonable to suppose that the Ca II emission detected in late-type stars also originates in magnetic structures. Wilson discovered the presence of activity cycles in a portion of stars included in this sample; such a cycles can be related, in a qualitative way, to the well known 11-yr solar cycle. His approach has been continued and expanded, and there are cycle detections for 26 stars in the report of Vaughan (1983).

On the other hand, is now possible to measure the surface magnetic field strengths in some late-type stars. This is not an easy task, partly because of the intrinsic theoretical difficulties of the methods of interpretation and partly because of the high-quality observations and spectral resolution required. In this way, Robinson (1980) developed a method to obtain values of both the surface magnetic fields and the filling factor, based on the measurement of the changes produced by Zeeman broadening in the profiles of magnetic-field sensitive lines compared with the unaltered profiles of non-sensitive lines. Following this method, Robinson, Worden & Harvey (1980) detected magnetic fields in the stars ξ Boo A (G8V) and 70 Oph A (K0V). Marcy (1984), in the same way, found magnetic fields values in 19 stars, analysing a sample of 29 objects.

The existence of magnetic – in origin – processes in late-type stars is also demonstrated when short-term variability is observed in active stars. For instance, the presence of a distortion, outside of eclipse, in the light curve of some stars of the family RS CVn (Hall 1976, 1981), is explained by means of a model with dark and cool zones covering the surface of the active component (Eaton & Hall 1979) and the variations observed in the light curve of some BY Dra systems are understood following the same model (Hartmann 1981). Note that it is usual to call such dark areas as 'spots', by solar analogy.

The dynamo theory (Parker 1955a, b; Steenbeck & Krause 1969; Leighton 1969; Roberts & Stix 1972; Schüssler 1980; Yoshimura 1975; Gilman 1981; Belvedere 1983) is one of the present alternatives to explain the deep origin of the stellar activity by means of the generation, from induction effects on masses of ionized fluid, and amplification of subphotospheric magnetic fields. These fields later rise to the stellar surface and dissipate in form of MHD waves (see, for instance, Priest 1982), interacting with the surrounding material.

The goal of this work is the construction, and application to a sample of main-sequence active stars, of a model from which we can estimate values of the magnetic field (B_c) in the generation zone, close to the base of the convective zone, along with the other important parameter, the filling factor (A_r), i.e., the fraction of stellar surface covered by strong magnetic fields. This will allow us to make comparisons between theory and observations, in order to test whether the dynamo effect is (or is not) the origin of the detected atmospheric activity.

2 The model

The model applied to estimate these parameters is based on that presented by Durney & Robinson (1982) (DR henceforth) in which the main process limiting the strength of the magnetic field is the buoyancy of the flux tubes. The starting point is the three equations given by Parker (1979) relating several parameters at the bottom of the convection zone: u (rate of rise of the flux tubes) N_R (Reynolds number), V (turbulent velocity), V_A (Alfvén velocity), L (pressure scale height) and R (radius of the flux tubes). [Note that in the expression (2c) in DR, the term (V_A/V), should be $(V_A/V)^2$.] From these equations, in a very straightforward way we can find an explicit expression for V_A:

$$V_A=\{(3/8)(R/L)^2(uV)^{-1}[1.3093-\ln(3uR/VL)]\}^{-1/2}. \tag{1}$$

V has been computed from the equation $V=L/\tau$ following the definition of τ given by Gilman (1980) and the other parameters have been taken from interior models as we will see below. τ is a characteristic parameter of the convective transport, because it indicates the time in which a convective cell carries energy from the low part of the convection zone travelling a distance proportional to the mixing length. We also suppose that $R/L\cong 1$. u is the only parameter that can not be extracted from the interior models. To compute u we start from the assumption that t_a (the amplification time for a flux tube)$=t_r$ (the rising time for a flux tube to leave the amplification region). We consider that the dynamo operates in a zone placed at a distance of one pressure scale height above the base of the convection zone. The equations for both times are:

$$t_a=(\tilde{\alpha}\, d\omega/dr)^{-1/2}, \qquad \text{where } \tilde{\alpha}=c_1L^2\omega/R_g \qquad \text{and } t_r=L/u \tag{2}$$

(see DR for details). The value of c_1 is fixed to obtain, from t_a, agreement with the period P_c of the solar cycle ($P_c \approx 2\pi t_a$, Parker 1955b; Yoshimura 1975). From this we can obtain u, and so, B_c, using $B_c=V_A(4\pi\varrho)^{1/2}$.

A_r, the relative stellar surface covered by magnetic flux, has the following expression:

$$A_r=c_2(L_s/L)^2(R_g/R_s)^2(t_d/t_a). \tag{3}$$

L_s and L are, respectively, the scale heights in the surface and in the magnetic field generation zone, R_g and R_s are the radius of this zone and the stellar radius, and $t_d=L_s^2/\eta_s$ (the dissipative time for the surface magnetic field) where $\eta_s=L_sV_s/3$ (the magnetic diffusivity) and V_s is the gas velocity at the surface, computed from the ratio V_s/V_{sound} appearing in the interior models. Introducing the expressions for t_d and t_a in equation (3) we obtain:

$$A_r=c_2'(L_s/L)^3(R_g/R_s)^2(u/V_s) \tag{4}$$

where the constant c_2' is fitted so that the computation in the solar case agrees with the value $A_{r\odot} \approx 0.002$.

As we see, the estimation of the several internal parameters in the generation zone involves the use of derivatives of ω, the angular velocity, with respect to r, the radial coordinate. We have adopted a semi-empirical expression for the angular velocity as a function of depth and latitude. As it is well known, observational evidence shows that the Sun does not rotate like a rigid body, but presents differential rotation both at the surface and in the interior. Nevertheless, the dependence $\omega(r, \theta, \phi)$ is not exactly known although we can infer something about its behaviour from surface phenomena like, for example, the 5-min oscillations. There are several theories devoted to showing how the rotation of the fluid of the convection zone occurs. Köhler (1970) and Tassoul (1978) suggest a dependence $\omega=\omega_0r^{2(s-1)}$, being $s\neq1$ if one considers that the turbulent velocities are anisotropic. Köhler proposed $s=1.2$ for the Sun; in such a case $d\omega/dr \sim r^{-0.6}$. On the other hand, Durney (1985), from data obtained by Duvall *et al.* (1984) analysing the frequency of solar oscillations, found a dependence:

$$\omega_\odot(r, \theta)=2.57\times10^{-6}[\omega_0(r)+\omega_2(r)P_2(\cos\theta)] \tag{5}$$

where θ is the colatitude, r is the distance to the centre of the Sun,

$$\omega_0=1+(R_\odot-r)/R_\odot,$$

$$\omega_2=-0.189\{1+(1-r/R_\odot)[1+(l_h/l_v)^2/2]\},$$

and $P_2(\cos\theta)$ is the second-order Legendre polynomial; l_h and l_v are the typical horizontal and vertical dimensions of a convective eddy in zones where $r \cong R_\odot$. This law is reliable for zones close to the solar surface, becoming its validity liable to discussion for deeper layers. Assuming this dependence we obtain $d\omega/dr \sim R_\odot^{-1}$.

It is not easy to decide what criterion should be used because there are many factors (age, evolutionary status, chemical composition, binarity, etc.) influencing the rotation of the material in the convection zone (Demarque 1987). The Köhler and Tassoul's criterion could be applied taking into account that the $\tilde{\alpha}$ term in equations (2) arises from the expression $\tilde{\alpha}=-\langle \mathbf{V}\cdot\nabla\times\mathbf{V}\rangle\tilde{\tau}/3$, valid for isotropic turbulence ($\mathbf{V}$: convective velocity, $\tilde{\tau}$: lifetime of the convective eddy; see appendix 1 in DR).

We have preferred to apply a law similar to that shown in equation (5) to describe the internal rotation of the stars selected, modifying the constant outside the brackets, and taking $l_h=l_v$, so that $\omega(R_*, \pi/2)$ equals to $2\pi/P_{\rm rot}$ for each star. We assume that an extrapolation of this dependence toward inner layers could be reasonable. We have also checked the model by applying the Köhler and Tassoul's model with $s=1.2$; the results do not show remarkable differences when comparing with those shown in Table 3.

To develop the model and apply it to stars of several spectral types it is necessary to know some physical parameters of the stellar interior such as temperatures and densities in the generation zone, the depth of this zone, etc. This has been carried out by interpolating over a grid of interior models (Maeder 1985, private communication) with the following characteristics: masses 0.85, 1, 1.25 and 1.5 $M_\odot$, chemical composition $X=0.699$, $Y=0.282$ and $Z=0.019$ (typically solar), and $\alpha=1.9$ (mixing length/pressure scale height).

The choice of α was made according to the results of Noyes *et al.* (1984). These authors found that the best correlation between the chromospheric indicator $R_{\rm Ca\,II}$ and the Rossby number P/τ (P: rotation period, τ: turnover time of the convective cells) is reached for those values of τ computed with $\alpha=1.9$. The Rossby number is considered as a good parameter to determine whether or not a star presents efficient convection in comparison with others, because P/τ indicates, in a rough sense, how many times, during a rotation, a convective cell carries energy from the bottom of the convection zone across one mixing length.

On the other hand, Lebreton & Maeder (1986), found that the value of $\alpha=1.9$ reproduces most accurately the observed solar parameters (radius, luminosity). These authors have constructed evolutionary tracks and isochrones for stars of 0.85, 1.25 and 1.5 $M_\odot$ and have compared with a diagram magnitude–colour (m_v, $B-V$) of the old open cluster NGC 188, which shows a well-defined red giant branch. Using $\alpha=1.9$ and $Y=0.282$ they find good agreement between the set of tracks and isochrones and the position in the HR diagram of the red giant branch.

Finally, to find the $A_{\rm r}$ factor (see DR) the surface magnetic field in active regions must be estimated, because we compute the surface scale height $L_{\rm s}$ by using the hypothesis of flux conservation $B_{\rm c}L^2=B_{\rm s}L_{\rm s}^2$. If we consider that the inside magnetic pressure in a flux tube is in approximate equilibrium with the external gas pressure (Parker 1978), we can assume that $(B_{\rm s}^2/8\pi)p_{\rm ex}\approx1$ (equipartition theorem), and so compute $B_{\rm s}$ from $p_{\rm g}$. We have taken the values for the surface pressure from the grids of models by Peytremann (1974) (models with $T_{\rm eff}=5000$ K and $\log g=4.0$, 4.5) and Kurucz (1979) (models with $T_{\rm eff}=5500$, 6000, 6500 and 7000 K, and the same values of $\log g$). All the models have solar metallicity and the pressure has been computed at an optical depth $\tau=0.40$, following the early work by Aller (1963).

3 The sample of stars

We have collected data on 34 active stars whose characteristics are given in Table 1 and whose chromospheric fluxes in the lines H and K of Ca II and h and k of Mg II relative to $F_{\rm bol}$ (in usual notation R_{HK} and R_{hk}) can be seen in Table 2. Obviously, the number of active stars in which chromospheric emission has been observed and measured is larger than those presented here, but some additional conditions have been required of the stars in the sample: they must belong to the main sequence or to be very close to it, so it will be possible to extract, by interpolation, parameters from the available interior models. It would be very interesting to have available trustworthy and detailed interior models for evolved stars, such as subgiants of the same spectral type as some active components of several RS CVn systems, which have been extensively observed (Fernández-Figueroa *et al.* 1986b), but, unfortunately, this is not possible. On the other hand, the selected stars have their rotation period measured by means either the short term modulation of the Ca II emission, or assuming, in case of binarity, and orbital periods lesser than ~10 day, the hypothesis of synchronism. Both methods avoid computing the period (or the angular velocity) through the parameter $v \sin i$.

Table 1. The sample of active stars. Dimensions and properties. Single stars or binary systems not belonging to RS CVn family are marked #.

Star		Sp.Tp.	R	M	B-V	P	Ref.
	Sun	G2 V	1.00	1.00	0.66	25.4	1
HD 1835	9 Cet	G2 V	1.00	1.00	0.66	7.7	1#
HD 3651	54 Psc	K0 V	0.85	0.79	0.85	48.0	1#
HD 10700	τ Cet	G8 V	0.90	0.88	0.72	31.9	1
HD 13974	δ Tri	G0 V	1.10	1.05	0.61	10.0	2#
HD 17925		K0 V	0.85	0.79	0.87	6.6	1
HD 20630	κ Cet	G5 V	0.92	0.92	0.68	9.4	1
HD 22049	ϵ Eri	K2 V	0.80	0.74	0.88	11.3	1
HD 30495	58 Eri	G1 V	1.06	1.02	0.61	7.6	1
HD 39587	χ Ori	G0 V	1.10	1.05	0.59	5.5	2
HD 97334		G0 V	1.10	1.05	0.61	7.6	1#
HD 98231	ξ UMa B	G0 V	1.10	1.05	0.59	4.0	2#
HD 101501	51 UMa	G8 V	0.90	0.88	0.72	17.1	1#
HD 114710	β Com	G0 V	1.10	1.05	0.58	12.4	1
HD 115404		K3 V	0.77	0.72	0.93	18.8	1#
HD 128620	α Cen A	G2 V	1.09	1.10	0.68	25.0	2#
HD 128621	α Cen B	K1 V	0.74	0.90	0.88	25.1	2#
HD 131156	ξ Boo A	G8 V	0.90	0.88	0.76	6.2	1#
HD 141004	λ Ser	G0 V	1.10	1.05	0.60	18.0	1#
HD 149661	12 Oph	K2 V	0.80	0.74	0.81	21.3	1
HD 155885	36 Oph	K1 V	0.83	0.77	0.86	22.9	1#
HD 160346		K3 V	0.77	0.72	0.96	33.5	1
HD 165341	70 Oph A	K0 V	0.85	0.79	0.86	19.7	1#
HD 166620		K2 V	0.80	0.74	0.87	42.0	1
HD 190406	15 Sge	G1 V	1.06	1.02	0.61	13.5	1
HD 206860		G0V	1.10	1.05	0.58	4.7	1

RS CVn systems

Star		Sp.Tp.	R	M	T_{eff}	P	Ref.
HD 77137	TY Pyx 1	G2 IV	1.59	1.22	5400	3.20	3
	TY Pyx 2	G5 IV	1.68	1.20	5340	3.20	3
HD 107760	AS Dra 1	G3 V	0.99	0.97	5830	5.41	4
	AS Dra 2	K0 V	0.85	0.79	5250	5.41	4
HD 146361	σ^2 CrB 1	G0 V	1.10	1.05	6030	1.14	4
	σ^2 CrB 2	G0 V	1.10	1.05	6030	1.14	4
HD 166181	1	G5 V	0.92	0.92	5400	1.81	4

Notes

The radii and masses of the stars not belonging to RS CVn systems have been assigned according to the spectral type and the colour index except in the case of α Cen (A and B) whose radii, masses and temperatures are taken from Smith, Edvarson & Frisk (1986). $B-V$ of the components of this binary are taken from Popper (1980). References for $B-V$ and periods are: 1, Noyes *et al.* (1984); 2, Vilhu (1984).

For the components of RS CVn systems, the references are: 3, Andersen et al. (1981); 4, Fernández-Figueroa *et al.* (1986b).

The radii and masses of the stars AS Dra (1 and 2), σ CrB (1 and 2) and HD 166181 (1) have been assigned according to the spectral type because they belong to non-eclipsing systems.

Radii and masses are given in solar units and P (rotation period) in days.

Table 2. $F(\mathrm{Ca\,II})/F_{\mathrm{bol}}$ and/or $F(\mathrm{Mg\,II})/F_{\mathrm{bol}}$ for the stars of the sample.

Star	log R_{HK}	log R_{hk}	Ref.
Sun (q)	-4.937	-4.70	1,3
9 Cet	-4.415	-4.31	1,2
54 Psc	-4.960	-	1
τ Cet	-4.955	-	1
δ Tri	-	-4.00	4
HD 17925	-4.278	-4.30	1,2
κ Cet	-4.454	-4.26	1,2
ϵ Eri	-4.441	-4.30	1,2
58 Eri	-4.522	-4.26	1,2
χ Ori	-4.476	-4.24	1,2
HD 97334	-4.450	-4.33	1,2
ξ UMa B	-	-4.13	4
51 UMa	-4.548	-4.37	1,2
β Com	-4.756	-4.81	1,2
HD 115404	-4.467	-4.33	1,2
α Cen A	-	-4.74	5
α Cen B	-	-4.60	5
ξ Boo A	-4.375	-4.29	1,2
λ Ser	-4.971	-4.95	1,2
12 Oph	-4.541	-4.48	1,2
36 Oph	-4.571	-	1
HD 160346	-4.787	-4.61	1,2
70 Oph A	-4.557	-4.39	1,2
HD 166620	-4.910	-4.98	1,2
15 Sge	-4.818	-4.68	1,2
HD 206860	-4.424	-4.27	1,2
TY Pyx 1	-4.165	-4.20	6,7
TY Pyx 2	-4.165	-4.20	6,7
AS Dra 1	-4.684	-4.16	8,4
AS Dra 2	-4.592	-4.16	8,4
σ^2 CrB 1	-3.933	-3.60	8,4
σ^2 CrB 2	-3.821	-3.60	8,4
HD 166181 1	-3.749	-4.21	8,9

Notes

References: 1, Noyes *et al.* (1984); 2, Hartmann *et al.* (1984); 3, Vilhu (1984); 4, Basri, Laurent & Walter (1984); 5, Ayres, Marstad & Linsky (1981); 6, Bopp (1983); 7, Fernandez-Figueroa *et al.* (1986a); 8, Fernandez-Figueroa *et al.* (1986b), 9, Vilhu & Rucinski (1983).

There is a lack of F stars in the sample. Several of them (44 And, 50 Per, α Com and χ Her) were included at the beginning of our works, but the values of the internal magnetic fields and filling factors found with the model were very small in comparison with those obtained for G and K stars, taking into account that, for main-sequence objects, the activity indicators for F stars follows the same trends as those marked by stars with later spectral types, i.e., there are not

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breaks in the relationships between the activity indicators and the stellar parameters (rotation period, temperature). This suggests that, perhaps the dynamo mechanism does not work in this type of stars. We have included three stars – TY Pyx (1 and 2) and α Cen A – whose spectral type is G but whose radii and masses are typically those of a F star. We will see their behaviour and will discuss it in Section 4.

The effective temperature has been assigned to each star from the value of $B-V$, applying the calibration of Hauck (1985), with the exceptions of α Cen A and B [temperatures 5820 K (A) and 5280 K (B) from Smith, Edvarson & Frisk (1986)] and the RS CVn systems (see Notes to Table 1).

4 Results and discussion

In Table 3 we show the results obtained for the magnetic field B_c and the filling factor A_r. Note that our computations have been carried out with $R/L=1$ instead of $R/L=0.5$ (DR). We have chosen this value to match our solar B_c with that given in DR. We find B_c values slightly larger than those here presented by using $R/L=0.5$.

In Fig. 1(a) we show a plot of the convective magnetic field (in Gauss) against the rotation period for the stellar sample. We have labelled the colour index $B-V$ beside each point. It can be seen there is a stratification for the several spectral types. If we consider a fixed colour index, the magnetic field increases when the rotation period decreases, and, for a fixed period, the magnetic field is larger for stars with deeper convection zones, i.e., later spectral types. These facts demonstrate an important conclusion: *the efficiency of the generation of magnetic fields increases with the stellar rotation rate and depth of the convection zone*, already pointed out in DR.

We have marked with arrows the three stars quoted in Section 3. Two of them are the components of the system TY Pyx. Both stars are slightly evolved and possess radii 1.59 and 1.68 $R_\odot$ and masses 1.22 and 1.20 $M_\odot$, so that, the use of interior models corresponding to main-sequence stars assigns to these stars parameters, such as depth of the convection zone, temperatures and densities at the generation zone, etc., that are typical of an F star. A similar effect is

Table 3. Results.

	B_c	A_r		B_c	A_r
Sun	515	0.002	ξ Boo A	2115	0.093
9 Cet	1110	0.021	λ Ser	560	0.003
54 Psc	790	0.004	12 Oph	1635	0.028
τ Cet	740	0.004	36 Oph	1360	0.017
δ Tri	790	0.010	HD 160346	1225	0.010
HD 17925	2960	0.184	70 Oph A	1390	0.020
κ Cet	1430	0.030	HD 166620	1035	0.007
ϵ Eri	2450	0.091	15 Sge	815	0.008
58 Eri	1180	0.026	HD 206860	1395	0.049
χ Ori	1225	0.035			
HD 97334	945	0.017	TY Pyx 1	305	0.005
ξ UMa B	1515	0.066	TY Pyx 2	500	0.017
51 UMa	1095	0.013	AS Dra 1	1850	0.076
β Com	745	0.007	AS Dra 2	3495	0.295
HD 115404	1795	0.034	σ^2 CrB 1	3880	0.958
α Cen A	205	<0.001	σ^2 CrB 2	3880	0.958
α Cen B	415	0.001	HD 166181	4905	0.961

Units of B_c are Gauss.

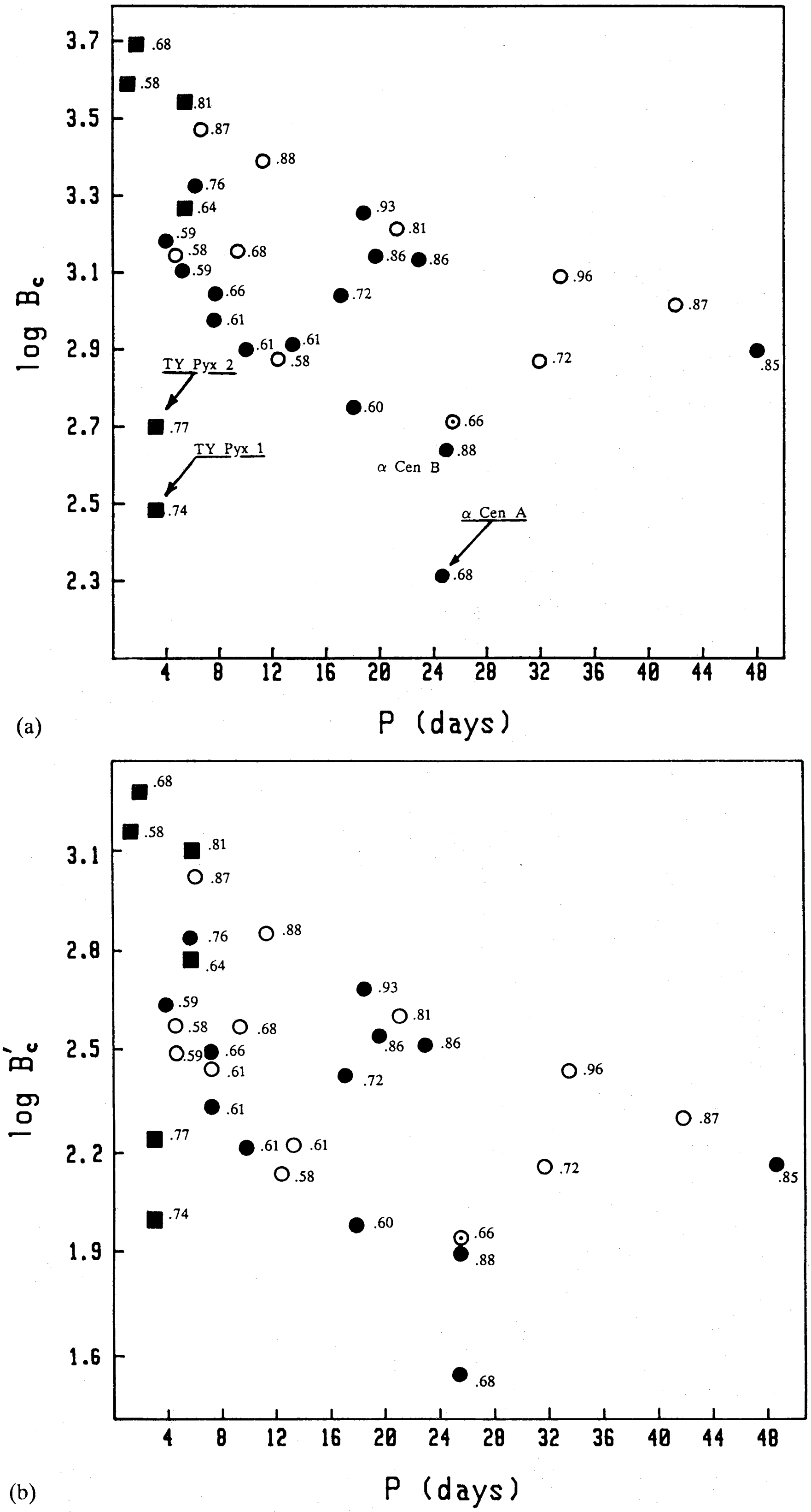

Figure 1. (a) The magnetic field B_c in the low part of the convection zone (in Gauss) against the rotation period (in days) computed by means of equation (1). Each star has been labelled with the colour index $B-V$. Symbols (here and in the following figures) are (■) RS CVn systems; (●) components of binary systems not belonging to RS CVn family; (○) single stars. Note the position of α Cen B in comparison with other stars of similar colour index. In (b) we show a similar graph in which the magnetic fields have been computed assuming that $u \sim V_A$ (see text).

found for α Cen A, whose radius is $1.09\,R_\odot$ and mass $1.10\,M_\odot$, but appears catalogued as G2V. The low B_c values obtained for these stars, and, in general, for F stars, arise from the low densities existing at the low part of their convection zones ($\sim 10^{-6}\,\mathrm{g\,cm^{-3}}$) compared with that found in K stars ($\sim 10^{-1}\,\mathrm{g\,cm^{-3}}$) (Maeder 1985, private communication). Furthermore, this extremely low density is the largest one reached in the convection zone of these stars, and therefore, the generation of magnetic fields by means of ionized fluid currents cannot be effective. This result is confirmed by Wolff, Boesgaard & Simon (1986) who found, by analysing a sample of F stars, that the activity levels in this type of star are independent of the Rossby number, and so there may exist heating mechanisms other than that associated with the dynamo effect to explain the presence of activity in these stars, which possess shallow convection zones. We will comment briefly at the end of the section the position of α Cen B.

In Fig. 1(b) we have plotted a similar graph, but in this case the convection-zone magnetic field has been computed by considering that the rise velocity of the flux tube coincides with V_A, the Alfvén velocity. The definition of t_r is now L/V_A, and the magnetic field can be computed by means of:

$$B'_c = \{4\pi\varrho\alpha\, d\omega/dr\}^{-1/2}L. \tag{6}$$

This expression has been extracted by equalling t_a from equations (2) and the new t_r, and using the known relationship between B'_c and V_A. The assumption $u \sim V_A$ is reasonable if the radius of the tube, R, is comparable to the scale height, L (Parker 1979). The qualitative behaviour of the magnetic field is the same as that observed in Fig. 1(a); nevertheless the B'_c-values are smaller than those presented in Table 3.

From these results we can check the consistency of the method. Some arguments, similar to those presented by Robinson & Durney (1982), based on the values of the dynamo number, could be used. Nevertheless, the definition $N_D = f_{\mathrm{cycle}} R^2_{cz}/4\eta$ includes the frequency of the activity cycle, $f_{\mathrm{cycle}} = 2\pi/P_{\mathrm{cycle}}$, and η, the turbulent diffusivity, so that a discussion concerning all the stars is not possible. The existence of cycles has been detected in seven stars of our sample, but the confidence level of the detection is high only in three cases: the Sun, 54 Psc and HD 166620; the remaining stars which show tracks of cycles are HD 115404, ξ Boo A, 12 Oph and 70 Oph A (Vaughan 1983). We can use, as an alternative way, the relative effect of the magnetic field energy on the convective motions. We think that this is a more intuitive argument in understanding whether a B_c-value is (or is not) reasonable. The ratio of the density of magnetic energy stored in the field, to the density of kinetic energy (ME/KE) is $(B^2_c/4\pi)/(\varrho V^2/2)$. If the intensity of B_c is very strong then the magnetic effects will dominate the dynamics of the fluid motions in the convection zone, which constitutes a problem for the consistency of the method because one of our starting points is the use of interior parameters computed without assumptions related with the magnetic field. The ratio ME/KE computed with the results shown in Table 3 is always less than 1; the typical order of magnitude is $\sim 10^{-1}$–10^{-2}, with the exception of the fast RS CVn rotators. In these cases ME/KE$\sim$1 (for HD 166181 we have ME/KE$\cong$1.4, being the only star in which ME/KE>1). The ratios computed by using the B'_c-values extracted from equation (6) are always less than 10^{-1}.

We show in Fig. 2(a) the relationship between the chromospheric fluxes in the Ca II and Mg II lines – the most important chromospheric cooling mechanisms (Vernazza, Avrett & Loeser 1981 – normalized to the bolometric fluxes and the colour index $B-V$. Beside each point there is a number, from 1 to 6, depending on the period interval in which each star is placed. It can be seen that the spread in the relation is apparent because the slower rotators are in the lower part of the diagram and the fluxes increase when the periods decrease (see, for example, the behaviour of the stars around $B-V=0.6$). If we plot the same chromospheric indicator against the Rossby number P/τ [τ computed using $\alpha=1.9$ and following the Gilman (1980) work] we reproduce (Fig. 2b) the

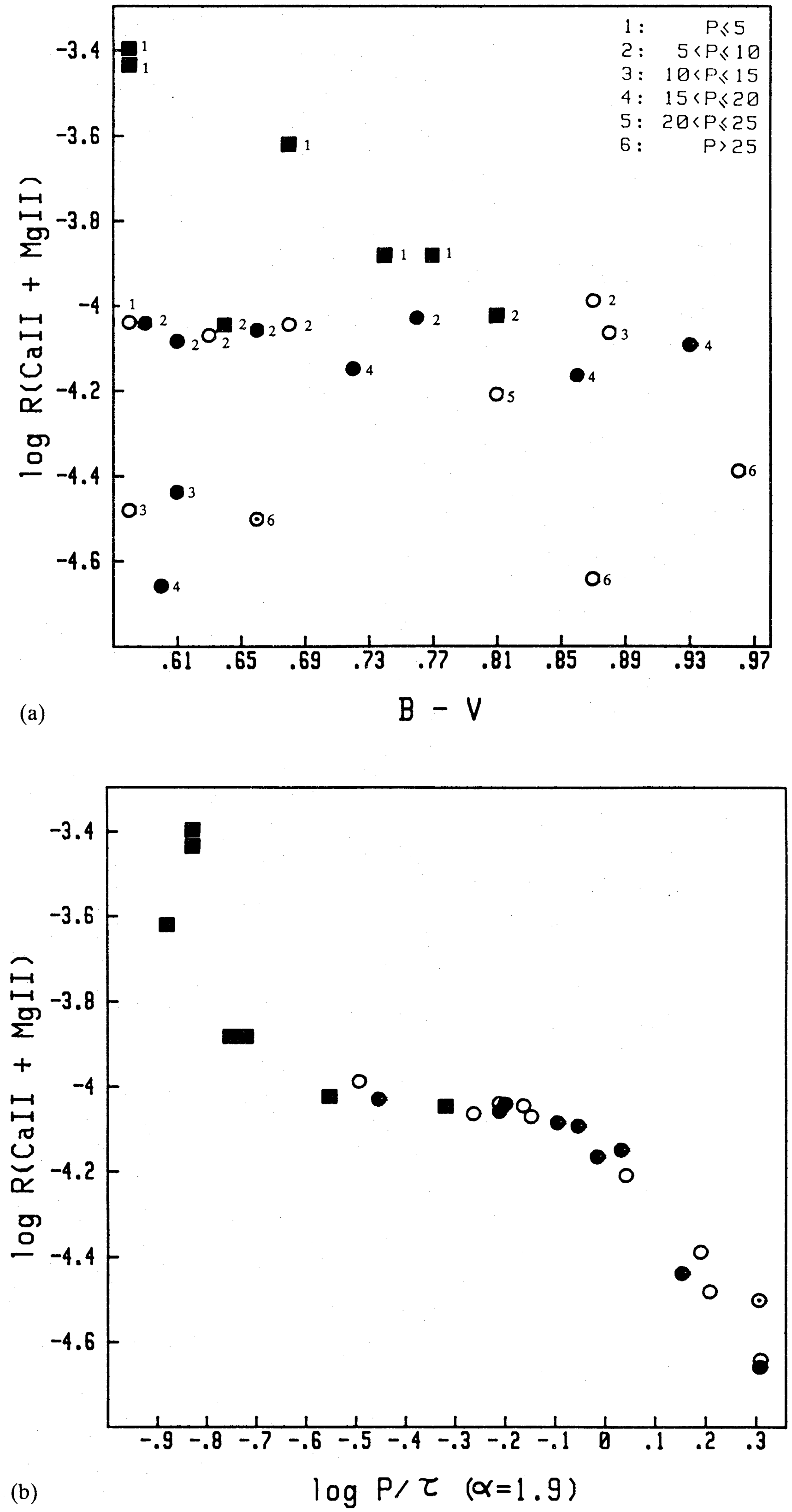

Figure 2. The R(Ca II+Mg II) index [F(Ca II+Mg II)/$F_{\rm bol}$] against the colour index $B-V$ (a), and the same parameter against the Rossby number P/τ computed with $\alpha=1.9$ (b). In (a) the stars are labelled with a number according to their rotation period (see the upper-right corner). The scatter in the graphics (a) disappears if we combine the parameters P and τ to describe the behaviour of the activity versus an indicator of the efficiency of the convective transport.

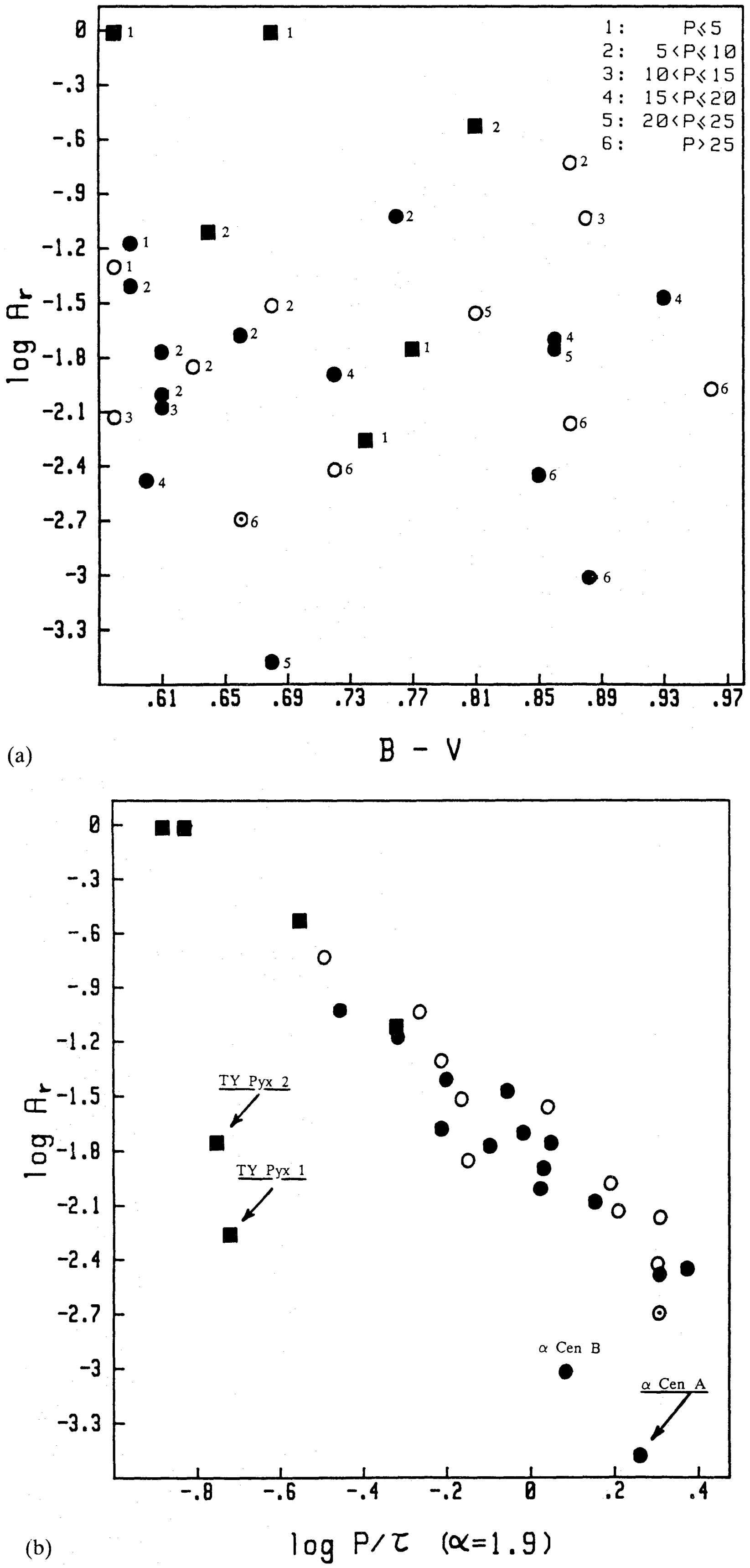

Figure 3. The fraction of stellar surface covered by strong magnetic fields, A_r, against the colour index $B-V$ (a) and the Rossby number (b). The labels in (a) have the same meaning as in Fig. 2(a). We can see a similar behaviour both of the chromospheric activity levels in Fig. 2 and the A_r parameter, suggesting the existence of a link between the two kinds of phenomena.

close relationship found by Noyes *et al.* (1984) for R_{HK}. The RS CVn systems follow, in general, the same trend than that marked by the remaining active systems. This fact can be expected from the similar behaviour of the R_{hk} indicator against the Rossby number studied by Fernández-Figueroa, Sedano & Castro (1986a). These authors found that the dependence $\log R_{hk}$–$\log(P/\tau)$ is the same for active normal stars, RS CVn and W UMa binaries. Nevertheless, the turnover times τ for fast rotators should be taken with caution.

A_r is the most suitable parameter to connect the theory to the observations. In Fig. 3(a) and (b) we show the relationships $\log A_r$ versus $B-V$ and $\log A_r$ versus $\log P/\tau$. From Fig. 3(a) it can be seen that the scatter in the points is similar to that appearing in Fig. 2(a). In general, the stars are stratified, with the lower values of A_r corresponding to stars with larger rotation periods. In Fig. 3(b) we see that A_r follows the same trend against P/τ than the chromospheric indicator R(Ca II+Mg II) suggesting that the chromospheric emission is proportional to the fraction of stellar surface covered by magnetic fields computed with this model. In Fig. 4 we can confirm this fact. We have plotted the surface fluxes in the Ca II and Mg II lines versus the A_r factors and we find a positive correlation among them, showing that the connection between dynamo effect and chromospheric activity, via the rising magnetic fields, is real.

We have in Fig. 3(b) again marked with arrows the stars TY Pyx, 1 and 2, and α Cen A. According to the small magnetic field estimated at the lower part of the subphotospheric convection zone, the A_r values are smaller than would be expected if we suppose that the origin of the activity is the same for F stars as for G and K stars. We can test the hypothesis of Wolff, Boesgaard & Simon (1986) mentioned above concerning the necessity of introducing the pre-

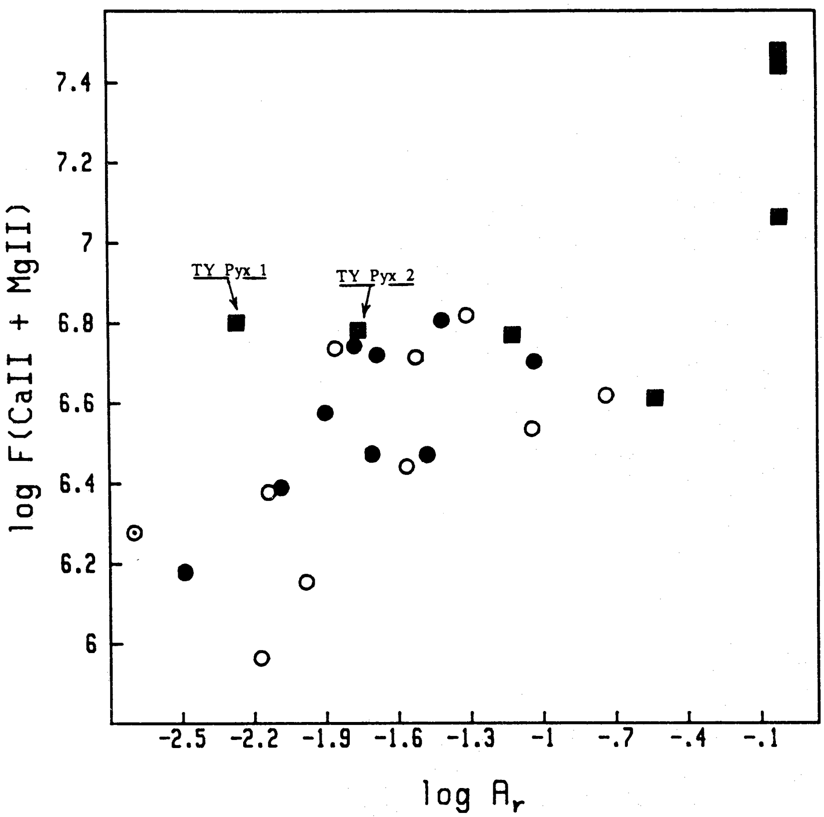

Figure 4. The surface chromospheric fluxes in the Ca II H and K lines and in the Mg II h and k lines, against the fractional area covered by fields. The positive correlation confirms, in a theoretical way, the existence of a close relationship between the stellar activity and the generation of magnetic fields in the subphotospheric convection zone. The two components of TY Pyx appear left shifted because of their smaller A_r.

sence of an acoustic flux to explain the activity levels observed in F stars. Following Stein (1981), for an acoustic wave: Wave flux/Total stellar flux$\sim g^{-1}T_{\rm eff}^{11}$, so, Wave flux (WF henceforth)$\sim g^{-1}T_{\rm eff}^{15}$. We can compare the acoustic flux at the surface of main-sequence stars with different spectral types. Using data on temperatures and gravities from Allen (1973) we find: WF(F5V)/WF(G0V)$\cong$4.5, WF(F5V)/WF(G5V)$\cong$17 and WF(F5V)/WF(K0V)$\cong$100, i.e. the acoustic flux is ~4–100 times larger for F stars than for G0–K0 stars. On the other hand, if we pay attention to Fig. 3(b), we see that the $A_{\rm r}$ values for the two components of TY Pyx are ~30–100 times lower than those predicted by the general trend *if the dynamo model also works* for these stars, while for α Cen A the $A_{\rm r}$ value is ~10–15 times lower than expected. From this fact we can suggest that, if the chromospheric activity originates from interaction of waves and magnetic fields with the surrounding material, the same behaviour observed for the chromospheric indicators in F, G and K stars, can be explained by means of a 'competition' between the dissipation of acoustic waves, more important for the earlier spectral types (F0–F8), and the dissipation of magnetic fields, dominant for cooler stars (G0 or later).

Finally, it is remarkable the position of α Cen B in Figs 1(a, b) and 3(b). Both the magnetic field and the filling factor are smaller than expected, due to the dimensions of this star (R=0.74 $R_\odot$, M=0.90 $M_\odot$) unusual for a main-sequence object with spectral type K1V. A complete discussion about the evolutionary status and dimensions of the components of the binary α Cen can be found in the work by Smith *et al.* (1986).

5 Final remarks

As it is pointed out in DR, this method is a first approximation in the process of explaining the close relationship between the observational phenomena and the interior-generated processes, of which we only have a little direct evidence. Many of the hypotheses should be taken with caution and the results must be interpreted according to these suppositions.

The most remarkable fact found is the existence of proportionality between an observational parameter, the chromospheric flux, and the theoretical parameter $A_{\rm r}$, which relates the internal generation of magnetic fields with the presence of these fields at the stellar surface. This confirms, in a theoretical way, the assumption by which the intense chromospheric emission, detected in many late-type stars, is associated with magnetic structures, in analogy with solar observations.

It is interesting to point out the behaviour of the model for stars with shallow convection zones, and the low $B_{\rm c}$ and $A_{\rm r}$ values found for them, in agreement with the suggestion of Wolff *et al.* (1986) quoted above.

Finally, we stress the importance of many theoretical and observational efforts to improve the quality of the models. So, it would be very useful to construct accurate and detailed interior models for stars off the main sequence, to include other active stars, such as some evolved RS CVn systems, in the analysis. Simultaneously, a deeper insight is required into the rotation and oscillation of the Sun and stars to find reliable relations between the angular velocity and the radial coordinate.

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