1986A&A...167..297M

Astron. Astrophys. 167, 297–303 (1986)

ASTRONOMY
AND
ASTROPHYSICS

Chromospheric emission luminosity versus rotation in late main sequence stars

E. Marilli [1], **S. Catalano** [2], **and C. Trigilio** [2]

[1] Astrophysical Observatory, Viale A. Doria, Citta Universitaria, I-95125 Catania, Italy
[2] Institute of Astronomy, University of Catania, Viale A. Doria, I-95125 Catania, Italy

Received February 14, accepted June 13, 1986

Summary. From an extended sample of single main sequence stars later than F7, for which well determined rotation periods and Ca II H+K or Mg II h+k emission luminosities are available, we have reexamined the chromospheric emission rotation period correlation. The linear relation between the logarithm of the emission luminosity and the rotation period found by Catalano and Marilli (1983), $\log L(\mathrm{HK}) = -aP+b$, is confirmed, but both the coefficients in the relation are found to be colour-dependent.

The slope, a, decreases from early to late spectral types and remains almost constant for spectral types later than G8, which implies a weak response of the chromospheric emission to the rotation rate in this spectral interval. The b term that represents the H−K limiting luminosity for a very rapidly rotating star (very active star), decreases steadily with increasing B–V. The influence of photospheric parameters and the ability of the chromosphere to respond to the magnetic activity in very late type stars is discussed.

Key words: stars: atmospheres – chromospheres – rotation – activity

1. Introduction

The emission intensity of the Ca II line-core in the Sun appears to be an indicator of the level of magnetic activity since it is related to the magnetic field intensity (Howard, 1958; Skumanich et al., 1975).

Recent determinations of the rotation period in late main sequence stars from the modulation of the Ca II H and K chromospheric emission lines (Noyes et al., 1984) have enabled the connection between rotation and surface magnetic field generation to be investigated in the framework of the dynamo mechanism. Quantitative relations between stellar rotation and chromospheric emission in the Ca II K and H resonance lines have been searched for, using as chromospheric activity parameter either the flux normalized to the bolometric one (Noyes et al., 1984; Baliunas et al., 1983) or the excess flux (Schrijver, 1983) on the H and K line. Catalano and Marilli (1983) analyzing a limited set of stars of known K line emission and rotation period, between F8 and K5, showed that the emission luminosity $L(\mathrm{K})$ decays exponentially with the rotation period. From a similar analysis on C IV and X-ray luminosities of main sequence stars Marilli and Catalano (1984) found that the emissions in the transition region and coronae follow similar exponential relations. These relations, within the errors of the emission luminosity values, seemed to be independent of or weakly dependent on the spectral types. The aim of this study is to investigate, on the basis of a more complete sample of data, the dependence of the exponential relationship $L(\mathrm{HK}) - P(\mathrm{rot})$ upon the spectral type, and to discuss quantitatively this dependence in terms of the stellar parameters. The analysis is based on the integrated luminosity of the Ca II H and K and Mg II h and k emission cores and rotation periods directly determined from chromospheric modulation or photometric variations.

2. Observational data

2.1. Ca II *and* Mg II *chromospheric emissions*

The Ca II H and K line emission core luminosities analysed in this paper have been deduced from spectrographic and spectrophotometric flux measurements obtained by several authors (Linsky et al., 1979; Giampapa et al., 1981; Blanco et al., 1974, 1982, 1985; Catalano, 1979; Vaughan et al., 1981; Soderblom, 1982; Baliunas et al., 1983; Duncan et al., 1984; Noyes et al., 1984). Since the original data are given in different units, i.e. flux or flux normalized to the bolometric one, conversion to luminosities has been made using appropriate average relations as a function of (B–V) for the radii and bolometric luminosities, taken from Allen (1973) and from Pettersen (1980).

In all cases the used fluxes refer to the net chromospheric radiative losses determined by measuring the excess flux above the K line photospheric flux (Blanco et al., 1974; Linsky and Ayres, 1978). The correction produce applied to the spectrophotometric data from the Mt. Wilson Ca II H and K photometer is somewhat different (Noyes et al., 1984). Basically it includes all the flux between the H1 and K1 features. The two methods give equivalent results for very late type stars, while the flux on Mt. Wilson observations appears to be overestimated for earlier type stars (F7–G5) of low emission.

In order to increase our set of data we have also collected data on the h and k resonance emission lines of Mg II, obtained with the IUE spectrometer. Fluxes have been taken from high and low

---

Send offprint requests to: E. Marilli

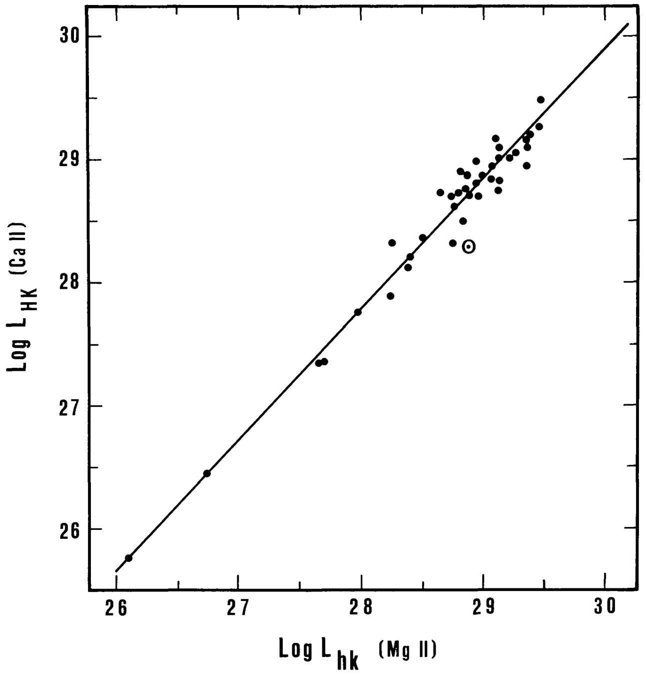

Fig. 1. Observed H + K emission luminosities plotted vs. h + k ones. The solid line represents the best fit to the data points

Table 1. H – K emission luminosities and rotation periods

N	NAME	Sp.type	B-V	logL(HK)	ND	P(rot)	ref.
1	SUN	G2V	0.66	28.642	4	25.40	1
2	HD 1835	G2V	0.66	29.096	3	7..70	1
3	HD 3651	K0V	0.85	28.001	3	48.00	1
4	HD 4628	K4V	0.88	28.244	2	38.00	1
5	HD 6920	F8V	0.60	28.899	2	13.10	1
6	HD 16160A	K4V	0.97	28.095	3	45.00	1
7	HD 16673	F6V	0.52	29.077	3	5.70	1
8	HD 17925	K0V	0.87	28.859	3	6.60	1
9	HD 20630	G5V	0.68	29.077-	2	9.40	1
10	HD 22049	K2V	0.89	28.728	8	11.30	1
11	HD 25998	F7V	0.54	29.239	1	2.60	1
12	HD 26913	G3V	0.70	29.055	2	7.20	1
13	HD 29697	K3Ve	1.11	28.791	1	4.00	2
14	HD 30495	G1V	0.61	29.158	2	7.60	1
15	HD 39587	G0V	0.59	29.194	7	5.20	1
16	HD 45088	K2Ve	0.94	28.867	2	7.36	3
17	HD 89744	F6V	0.53	28.630	1	12.30	1
18	HD 95735	M2V	1.51	26.463	2	48.00	1
19	HD 97334	G0V	0.61	29.157	4	7.60	1
20	HD100180A	F7V	0.57	28.764	1	14.00	1
21	HD101501	G8V	0.72	28.928	3	17.10	1
22	HD114710	G1V	0.58	28.812	6	12.40	1
23	HD115404	K3V	0.95	28.695	3	18.80	1
24	HD118100	K5Ve	1.18	28.657	3	3.96	4
25	HD131156A	G8V	0.76	29.073	7	6.20	1
26	HD131156B	K4V	1.17	28.379	2	11.50	1
27	HD141004	G0V	0.60	28.699	2	18.00	1
28	HD149661	K0V	0.81	28.736	4	21.30	1
29	HD152391	G8V	0.76	28.955	2	11.10	1
30	HD154417	F8V	0.58	29.202	3	7.60	1
31	HD155885	K1V	0.86	28.679	1	22.90	1
32	HD155886	K1V	0.86	28.713	2	20.30	1

resolution spectra as reported by Blanco et al. (1982, 1985), Catalano and Marilli (1984, 1985), Linsky et al. (1982), Hartmann et al. (1981), Walter et al. (1984), Rutten (1985). To extract the net chromospheric emissions we have adopted the same criteria used for Ca II lines. However, due to the decrease of the continuum at the Mg II h and k line wavelengths the correction adopted for the photospheric contribution was found to be significant only for the earliest spectral types (F7–G0).

For some stars we have collected emission luminosities both in the Ca II and Mg II lines, then to make the entire sample of our data homogeneous we have made a comparative analysis of the radiative losses in the HK–Ca II and hk–Mg II lines. In Fig. 1 the Mg II luminosities L(hk) are reported versus the Ca II luminosities L(HK) in a log-log scale. A linear relation between the two quantities is apparent. A least square fit to the data given by

$$\log L(\mathrm{HK}) = 1.053 \log L(\mathrm{hk}) - 1.700 \tag{1}$$

is represented in Fig. 1 as a continuous line.

The standard error in the logarithmic HK luminosities deduced from Mg II emissions is about 0.1, a value comparable with the average intrinsic accuracy of the data, even accounting for long and short term variations in the emissions. The relation gives the same dependence of Mg II emission on Ca II as that found by Hartmann et al. (1984) using emission luminosity normalized to the bolometric one, R(HK); however our relation shows a much smaller scatter and extends over more than three orders of magnitude.

2.2. *Rotation periods*

In order to increase the accuracy of our analysis we have used only rotation periods measured directly from chromospheric emission modulation (Vaughan et al., 1981; Duncan et al., 1984; Noyes et al., 1984) or from photometric modulation attributed to large dark

Table 1 (continued)

N	NAME	Sp.type	B-V	logL(HK)	ND	P(rot)	ref.
33	HD156026	K5V	1.16	28.206	3	18.00	1
34	HD160346	K3V	0.96	28.333	3	33.50	1
35	HD165341A	K0V	0.78	28.848	3	19.70	1
36	HD166620	K2V	0.87	28.194	2	42.00	1
37	HD175742	K2V	0.91	28.941	1	2.88	5
38	HD190007	K4V	1.12	28.162	3	29.30	1
39	HD190406	G1V	0.61	28.789	2	13.50	1
40	HD201091	K5V	1.18	27.913	9	37.90	1
41	HD201092	K7V	1.38	27.373	7	48.00	1
42	HD206860	G0V	0.58	29.211	7	4.70	1
43	HD212754	F5V	0.52	28.704	1	13.00	6
44	HD219834A	G8V	0.79	28.347	1	42.00	1
45	HD219834B	K2V	0.91	28.239	1	42.00	1
46	GL 182	dM0.5e	1.37	28.334	1	1.86	7
47	GL 685	M0V	1.48	27.390	3	19.20	2
48	GL 285	M4.5 eV	1.59	27.761	3	2.78	4
49	GL 803	M1.6 eV	1.51	27.641	1	4.85	3
50	VB29		0.56	29.204	1	3.00	8
51	VB31		0.57	29.236	1	5.40	8
52	VB48		0.52	29.279	1	2.50	8
53	VB50		0.60	29.254	1	5.10	8
54	VB52		0.59	29.221	1	3.95	8
55	VB58		0.68	29.115	1	6.20	8
56	VB63		0.63	29.194	1	7.80	9
57	VB64		0.66	29.146	1	8.70	9
58	VB69		0.75	28.982	1	11.50	9
59	VB73		0.61	29.197	1	7.40	9
60	VB79		0.83	28.841	1	11.40	9
61	VB97		0.63	29.114	1	8.50	9
62	BD+36 232	dM0	1.42	28.110	1	3.17	3
63	EV Lac	dM4.5	1.58	27.803	1	4.38	3

References :

1) Noyes et al. (1984)
2) Rutten (1985)
3) Pettersen (1982)
4) Bopp and Fekel (1977)
5) Bopp et al. (1981)
6) Vaughan et al. (1981)
7) Vogt, Soderblom and Penrod (1983)
8) Duncan et al. (1984)
9) Lockwood et al. (1984)

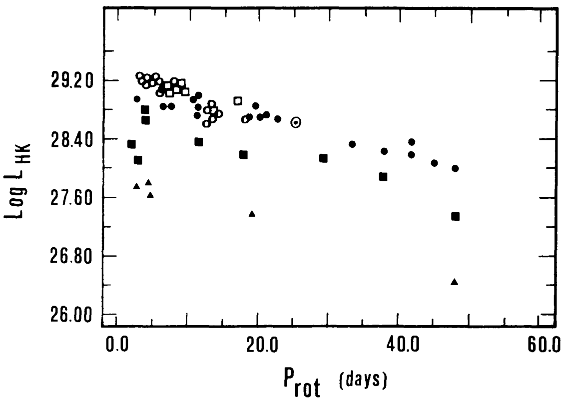

Fig. 2. Logarithm of the H + K emission luminosity of the stars in Table 1 plotted vs. observed rotation periods. Different symbols refer to different spectral type intervals: (○) F7–G0; (□) G0–G5; (●) G8–K4; (■) K4–M0; (▲) M0–M5; (⊙) Sun

spots on the stellar surfaces (Bopp and Fekel, 1977; Bopp et al., 1981; Pettersen, 1982; Vogt et al., 1983; Lockwood et al., 1984; Vogt et al., 1984). We have not considered in our sample close spectroscopic binaries because the strong tidal interactions may influence the chromospheric emissions. Components of wide binaries have been considered as single stars.

Table 1 shows the data on the HK-emission chromospheric luminosity and rotation periods we used in our analysis. L(HK)'s are average values obtained from different available determinations of the emission, including Mg II converted to Ca II from relation (1). ND is the number of these independent determinations. References for P(rot) are also given.

2.3. *Correlations*

In the framework of the dynamo theory the most obvious relation between the magnetic field and the stellar rotation is a power law or an exponential dependence (Parker, 1979). However, as shown by Marilli and Catalano (1984), the exponential relation seems to be the most reliable to represent the magnetic activity of late type stars, so we will use this kind of correlation in our analysis.

In Fig. 2 the plot of $\log L(\mathrm{HK})$ versus P(rot) shows an appreciable scatter mainly due to a colour dependence contrary to the previous result based on a smaller sample of data (Catalano and Marilli, 1983). Binning the data in B–V intervals, we obtain well-defined relations (Fig. 3) of the form

$$\log L(\mathrm{HK}) = -a(B\text{–}V)P + b(B\text{–}V)\,. \tag{2}$$

The degree of correlation is high for all (B–V) intervals, as reported in Table 2.

The behaviour of a and b as a function of B–V is displayed in Fig. 4. The b values show a very smooth trend that can be easily fitted by a third degree polynomial. The $|a|$ values show a steep decreasing trend for $B\text{–}V < 0.75$, while they appear to follow a nearly constant trend for $B\text{–}V > 0.75$. A five degree polynomial curve (solid line in Fig. 4) gives a satisfactory fitting to all the observed a values. However a constant value $a = -0.0195$ represented by the dashed line in Fig. 4 for $B\text{–}V > 0.75$ appears very reasonable. As a matter of fact the higher point around $B\text{–}V = 1.53$ is essentially determined from only one M2 star, HD 95735 (solid line fit in Fig. 3). The fitting excluding HD 95735 (dashed line in Fig. 3) gives $a = -0.023$, in better agreement with a constant trend for a.

In Fig. 5 the periods calculated from the fittings on a's and b's, whose coefficients and standard deviations are given in Table 3, are plotted versus the corresponding observed rotation periods. The scatter around the bisector (solid line in Fig. 5) is quite acceptable with the exception of stars with $B\text{–}V > 1.45$. Among these HD 95735 ($P(\mathrm{rot}) = 48$ days) shows the largest deviation, giving a computed period $P(\mathrm{rot}) = 75.5$ days. Some other stars of this group are found to show too short or negative computed periods, i.e. their emission luminosities are too high for their rotation period. Since these stars are mainly flare stars, emission enhancements due to flaring or the uncertainty in the calibration can explain the disagreement of the computed periods. It is of importance to note that the computed rotation period of the Sun is in very good agreement with the observed one.

3. Discussion

From the present analysis the correlation between $\log L(\mathrm{HK})$ and the rotation period of single late type stars is found to be clearly dependent on the spectral type. Both the coefficients a and b appear to be dependent on the spectral type. We will discuss separately their behaviour.

3.1. *The slope* $|a|$

The slope, $|a|$, appears to decrease steadily from $B\text{–}V = 0.52$ (the earliest spectral type in our sample) to $B\text{–}V = 0.75$ where it becomes almost constant. This means that the influence of the rotation on the Ca II emission is decreasing toward later spectral types.

It is attractive to relate the inverse of the a coefficient with the turnover time, assuming that the magnetic activity, represented by the Ca II chromospheric emission, can be characterized by the Rossby number, R = (rotation time/turnover time) (Gilman, 1980). Apart from a numerical factor $f = 2.5$, the $(1/a)$ values follow very closely the behaviour of the turnover time τ_G (Fig. 6) as computed by Gilman (1980) on pressure scale height above the bottom of the convection zone and for a ratio of the mixing length to the pressure scale height $\alpha = 2$. Even the constant value of $1/a$ for $B\text{–}V > 0.75$ agrees with $\tau_G\,(\alpha = 2)$ up to $B\text{–}V = 0.9$ where Gilman's calculations unfortunately stop.

Noyes et al. (1984) showed that the ratio $L(\mathrm{HK})/L(\mathrm{bol})$ is well correlated with the Rossby number $R = P(\mathrm{rot})/\tau$, where τ was computed with an iterative procedure assuming that it can be represented by the same polynomial dependence from B–V followed by the Gilman values for $\alpha = 2$. This correlation is well represented either by a third degree polynomial in a $\log L(\mathrm{HK})/L(\mathrm{bol}) - \log P(\mathrm{rot})/\tau$ relation or by the exponential relation

$$L(\mathrm{HK})/L(\mathrm{bol}) = 6\;10^{-5}\,e^{-0.9P/\tau}\,.$$

Using decimal logarithms we have

$$\log L(\mathrm{HK})/L(\mathrm{bol}) = -P/(2.56\;\tau) - 4.22\,,$$

in full agreement with our results.

Anyway we would like to stress that the turnover time from our data, $\tau = (1/a)/2.5$, agrees perfectly well with the Gilman one without any a priori assumption on its trend as a function of B–V.

3.2. *The limiting luminosity b*

The coefficient b represents the limiting luminosity $L(\mathrm{HK})_0$ expected for a star rotating at very high speed. This seems to be an

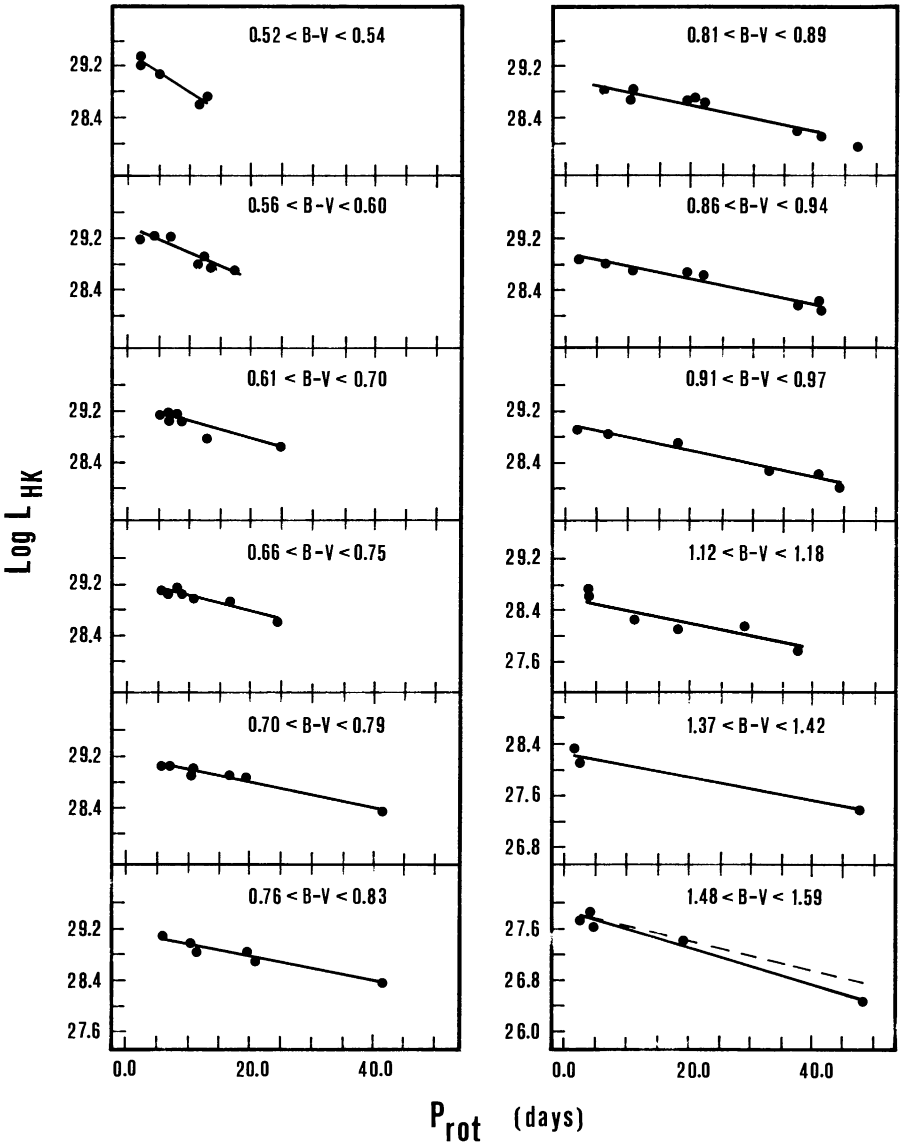

Fig. 3. $\log L(\mathrm{HK})$ vs. rotation periods binning the stars in the indicated *B–V* intervals. The solid lines represent the fittings to the data points. The dashed line in the group of very late type stars is the best-fit line obtained including the point representative of HD 95735

Table 2. Computed coefficients of the relation $\log L(\mathrm{HK}) = -a\,P(\mathrm{rot}) + b$. The $\langle(B-V)\rangle$ average value, the ND number of stars and the *R* correlation coefficient for each interval of (*B–V*) are given

INT.(B-V)	<(B-V)>	b(sigma)	a(sigma)	|R|	ND
0.52-0.54	0.525	29.407(.0408)	-0.0583(.0048)	.99	5
0.52-0.60	0.575	29.401(.0463)	-0.0451(.0049)	.92	16
0.52-0.63	0.58	29.433(.0438)	-0.0458(.0047)	.91	22
0.56-0.60	0.585	29.414(.0394)	-0.0417(.0041)	.96	11
0.61-0.70	0.65	29.350(.0459)	-0.0296(.0042)	.91	12
0.66-0.70	0.67	29.294(.0379)	-0.0253(.0030)	.97	6
0.66-0.75	0.685	29.286(.0363)	-0.0241(.0028)	.96	8
0.70-0.79	0.75	29.213(.0240)	-0.0200(.0012)	.99	7
0.76-0.79	0.765	29.202(.0308)	-0.0201(.0013)	.99	4
0.76-0.83	0.78	29.154(.0482)	-0.0190(.0022)	.97	6
0.81-0.89	0.865	29.047(.0598)	-0.0195(.0024)	.96	8
0.86-0.94	0.885	29.006(.0360)	-0.1860(.0014)	.98	9
0.91-0.97	0.95	29.017(.0196)	-0.0196(.0010)	.99	6
1.12-1.18	1.165	28.655(.0784)	-0.0195(.0033)	.96	5
1.37-1.42	1.385	28.271(.1055)	-0.0188(.0038)	.98	3
1.48-1.59	1.53	27.866(.0474)	-0.0287(.0020)	.99	5

important parameter since it represents the maximum power that is radiated by the chromosphere of a star at its maximum of activity (completely covered by active regions?).

In Fig. 7 the plot of $\log L(\mathrm{HK})_0$ versus $\log L(\mathrm{bol})$ shows indeed that the limiting luminosity decreases a bit faster than the bolometric one, while the Noyes et al. (1984) results give simply a constant $L(\mathrm{HK})_0/L(\mathrm{bol})$ ratio. In our representation a linear fit gives the relation

$$\log L(\mathrm{HK})_0 = 0.881\ \log L(\mathrm{bol}) - 0.227\,.$$

The exponential fits of Mg II emission versus rotation by Hartmann et al. (1984) show the same trend for the limiting luminosity $L(\mathrm{hk})_0$.

In principle there is no reason why the limiting luminosity $L(\mathrm{HK})_0$ is correlated with the bolometric luminosity or it represents a constant fraction, as in the Noyes et al. (1984) analysis, unless there is a link between the line formation process and the effective temperature of the star.

In the hypothesis of optically thick lines that are formed at a defined temperature T_e, we must expect for stars fully covered by

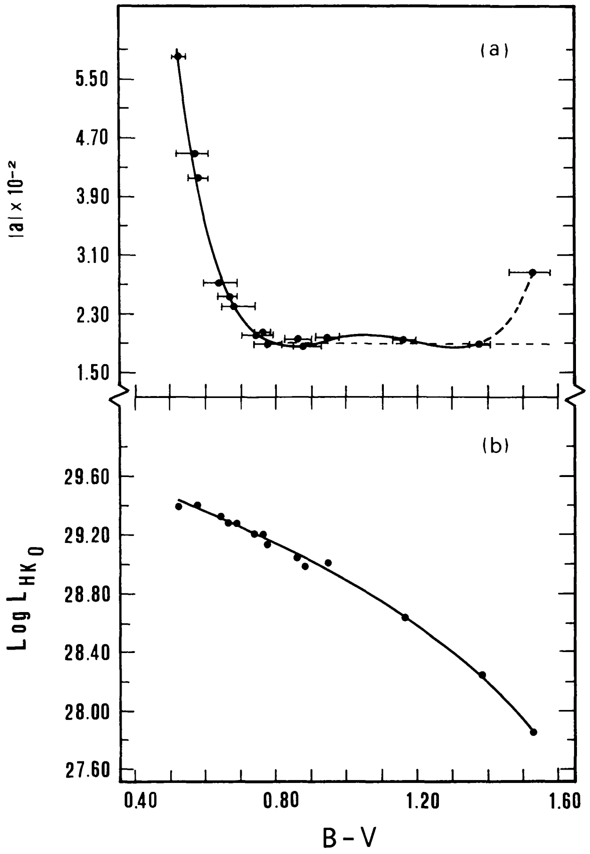

Fig. 4. The upper panel and the lower panel represent respectively the trend of the *a* and *b* coefficients in relation The solid lines are the polynomial fits to the data points deduced from the B–V intervals shown in Fig. 3. In the upper panel the bars of error for the single points give the width of the adopted B–V ranges. The slight dashed line represents the average *a* value for $B\text{–}V > 0.75$ when the point at $B\text{–}V = 1.53$ is not considered

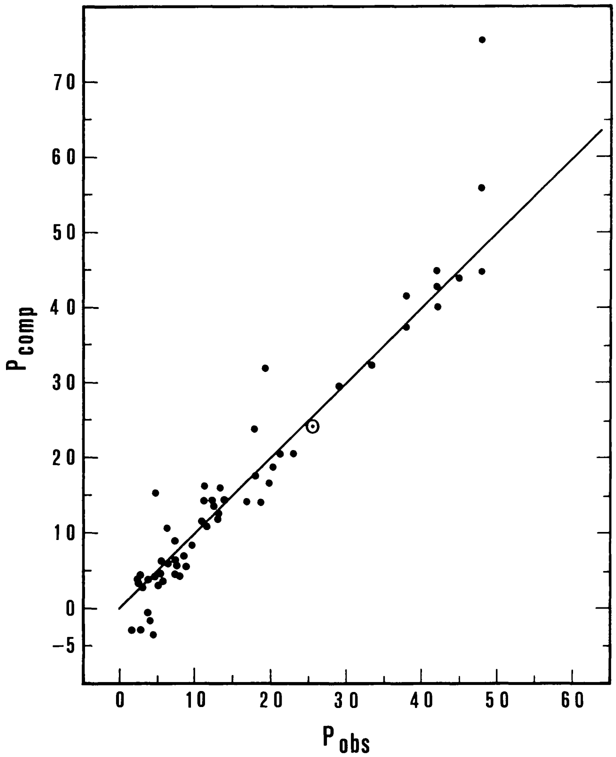

Fig. 5. Plot of the observed rotation periods vs. the computed ones. Almost all the points are satisfactorily distributed along the solid line representing the bisector

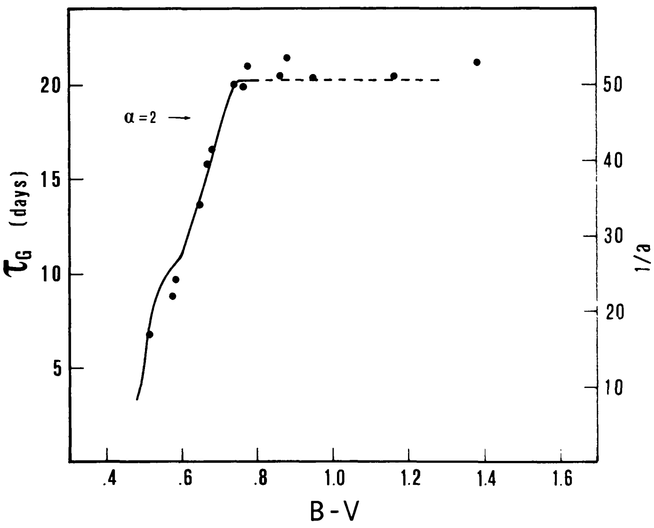

Fig. 6. The solid line represents the turnover time τ_G plotted vs. B–V as calculated by Gilman (1980) at $\alpha = 2$. The dashed line an extrapolation of τ_G to $B\text{–}V > 0.8$. The scaled points relative to the inverse of the observed *a* values are in very good agreement with the trend of the turnover time

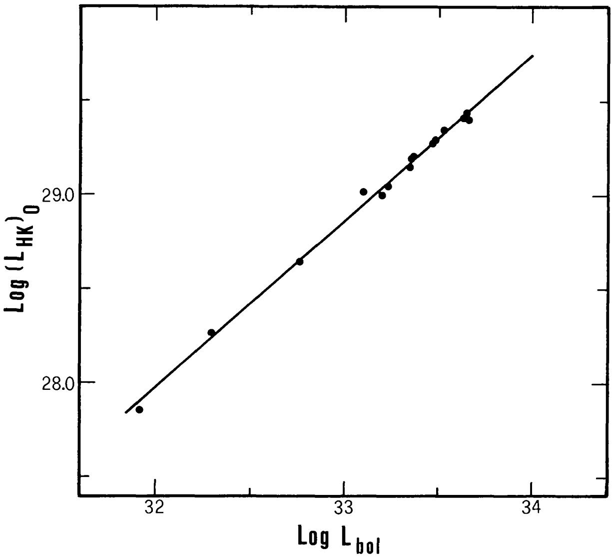

Fig. 7. The limiting luminosity *b* for narrow B–V intervals given in Table 2 plotted versus the corresponding bolometric luminosity. The solid line represents the linear best-fit

active regions a constant average flux $F(\mathrm{HK}) = L(\mathrm{HK})/4\pi R^2 = \mathrm{const}$. This is not the case with our results because the average fluxes deduced from $L(\mathrm{HK})_0$ decrease with $B-V$. This trend can be explained if the Ca II lines are effectively thin as Athay (1976) showed, at least in the Sun and solar type stars. In such a case the total emission power and the flux are directly related to the emitting volume, so that the decrease in the limiting $L(\mathrm{HK})_0$ luminosity in late type stars might result from a decrease in the emitting volume. The temperature gradient in the chromosphere of main sequence stars appears to increase toward lower effective temperatures (Kelch et al., 1978) and is much steeper for active stars. This leads to a decrease of the geometrical thickness of the chromospheric layer where the Ca II lines form, and therefore of the emitting volume, which can more likely account for the decrease of the limiting flux than for a decrease of the area covered by plages.

4. Conclusion

The above analysis has clearly shown that the chromospheric emission-rotation relation of late main sequence stars depends on the spectral type, i.e. on the stellar convection depth, with a behaviour in very good agreement with the turnover time τ_G given by Gilman (1980), therefore suggesting that the Rossby number is the most suitable parameter to characterize the dynamo model for magnetic activity. The low values of the a slope in Table 2, for stars later than G8, indicate a weak dependence of the Ca II emission on rotation. However in such a case larger turnover times corresponding to deeper convective zones could be responsible for the high $L(\mathrm{HK})/L(\mathrm{bol})$ ratios observed in late spectral types.

The emission luminosity we have used as activity parameter is obviously a combination of the local strength of the emission (intensity) and of the area covered by plages. If late type stars are more active as suggested by Belvedere et al. (1980) the filling factor may be large even at slow rotation, so any increase in the activity (faster rotation) would lead to an increase in the intensity of the emission rather than in the filling factor.

On the other hand the decrease of the limiting flux $F(\mathrm{HK})_0$ with the effective temperature seems to be suggestive of a controlling effect of the photospheric temperature in the structure of the chromospheric temperature in the structure of the chromosphere mainly through an increase of the temperature gradient (Kelch et al., 1978). An increase in magnetic activity giving a higher non-thermal energy deposition would lead, ad observed in the Sun, to an increase of the temperature gradient without an equivalent increase of the chromospheric emission, because the temperature gradient becomes steeper and the Ca II emission component forms in a thinner and thinner layer. The non-thermal energy excess will be channelled into other radiators, like the Hα and H$^-$ ion continuum, which become more efficient in color stars (Giampapa, 1980). Obviously relations between emission and rotation should be tested more carefully using energy losses in all chromospheric radiators and solving the energy balance equation.

So the observed behaviour of the a slope in Fig. 5, in addition to the behaviour of the magnetic field generation as a function of the rotation period, may reflect the ability of the stellar chromospheres to radiate in the Ca II as a result of non-thermal energy deposition. In this sense the Ca II and Mg II emission may be regarded as poor diagnostic tools for magnetic activity in main sequence stars later than G8.

We should like to conclude our discussion by remarking that, as an improvement on the previous analysis of Noyes et al. (1984), we have shown that the turnover time can be deduced without any a priori restriction on its dependence on $B-V$, and for main sequence stars up to $B-V = 1.53$. Moreover we have found that the limiting luminosity $L(\mathrm{HK})_0$ is not simply scaled to the bolometric luminosity as found by Noyes et al. (1984).

Finally we would like to emphasize, as already shown by Catalano and Marilli (1983), that the "emission luminosity" (in the Ca II H and K or other emission lines and continua) better represents the energy loss connected with the magnetic activity in the chromosphere-corona of Sun and stars (see also Catalano, 1984; Mangeney and Praderie, 1983) and that the exponential dependence of the emission luminosity on the rotation period appears to be the most physically meaningful one in the framework of the dynamo model for magnetic activity.

Acknowledgements. This work was supported by Catania Astrophysical Observatory, the Ministero della Pubblica Istruzione through the University of Catania and the C.N.R.-Gruppo Nazionale di Astronomia under contract No. 84.00188.02. We acknowledge the use of the computer facilities of the Catania ASTRONET Pole and thank Mr. P. Massimino for the graphic software. We are grateful to Dr. O. Vilhu for useful comments on this work.

References

Allen, C.W.: 1973, Astrophysical Quantities, The Athlone Press, London

Athay, R.G.: 1976, The Solar Chromosphere and Corona: Quiet Sun, Reidel, Dordrecht

Baliunas, S.L., Vaughan, A.H., Hartmann, L., Middlekoop, F., Mihalas, D., Noyes, R.W., Preston, G.W., Frazer, J., Lanning, H.H.: 1983, *Astrophys. J.* **275**, 752

Blanco, C., Catalano, S., Marilli, E., Rodonò, M.: 1974, *Astron. Astrophys.* **33**, 257

Blanco, C., Bruca, L., Catalano, S., Marilli, E.: 1982, *Astron. Astrophys.***115**, 280

Blanco, C., Catalano, S., Marilli, E., Rodonò, M.: 1985 (private communication)

Bopp, B.W., Noah, P.V., Klimke, A., Africano, J.: 1981, *Astrophys. J.* **249**, 210

Bopp, B.W., Fekel, F.: 1977, *Astron. J.* **82**, 490

Catalano, S.: 1979, *Astron. Astrophys.* **80**, 317

Catalano, S.: 1984, in *Space Research Prospects in Stellar Activity and Variability*, eds. A. Mangeney, F. Praderie, Observatoire de Paris-Meudon, p. 243

Catalano, S., Marilli, E.: 1983, *Astron. Astrophys.* **121**, 190

Catalano, S., Marilli, E.: 1984, Mem. Soc. Astron. Ital. **55**, 417

Catalano, S., Marilli, E.: 1985 (private communication)

Duncan, D.K., Baliunas, S.L., Noyes, R.W., Vaughan, A.H., Frazer, J., Lanning, H.H.: 1984, *Publ. Astron. Soc. Pacific* **96**, 707

Durney, B.R., Latour, J.: 1978, *Geophys. Astrophys. Fluid Dyn.* **9**, 241

Kelch, W.L.: 1978, *Astrophys. J.* **222**, 931

Giampapa, M.S.: 1980, in *Cool Stars, Stellar Systems and the Sun*, ed. A.K. Dupree, S.A.O. Spec. Rept. No. 389, p. 109

Giampapa, M.S., Worden, S.P., Schneeberger, T.J., Cram, L.E.: 1981, *Astrophys. J.* **246**, 502

Gilman, P.: 1980, in *Stellar Turbulence*, eds. D.F. Gray, J.L. Linsky, *IAU Coll.* **51**, Springer, 1980

Hartmann, L., Baliunas, S.L., Duncan, D.K., Noyes, R.W.: 1984, *Astrophys. J.* **279**, 778

Howard, R.: 1958, *Astrophys. J.* **130**, 193

Linsky, J.L., Ayres, T.R.: 1978, *Astrophys. J.* **220**, 619

Linsky, J.L., Worden, S.P., McClintock, W., Robertson, R.M.: 1979, *Astrophys. J. Suppl.* **41**, 47

Linsky, J.L., Bornmann, P.L., Carpenter, K.G., Wing, R.F., Giampapa, M.S., Worden, S.P., Hege, E.K.: 1982, *Astrophys. J.* **260**, 670

Lockwood, G.W., Thompson, D.T., Radick, R.R., Osborn, W.H., Baggett, W.E., Duncan, D.K., Hartmann, L.W.: 1984, *Publ. Astron. Soc. Pacific* **96**, 714

Mangeney, A., Praderie, F.: 1983, in *Active Phenomena in the Outer Atmospheres of the Sun and Stars*, eds. J. Pecker, Y. Uchida, CNRS-Paris, p. 96

Marilli, E., Catalano, S.: 1984, *Astron. Astrophys.* **133**, 57

Noyes, R.W., Hartmann, L.W., Baliunas, S.L., Duncan, D.K., Vaughan, A.H.: 1984, *Astrophys. J.* **279**, 763

Parker, E.N.: 1979, Cosmical Magnetic Fields: Their Origin and their Activity, Oxford, Clarendon Press

Pettersen, B.R.: 1980, *Astron. Astrophys.* **82**, 53

Pettersen, B.R.: 1982, in *Activity in Red-Dwarf Stars*, eds. P.B. Byrne, M. Rodonò, Reidel, Dordrecht, p. 17

Rutten, R.G.M.: 1985 (private communication)

Schrijver, C.J.: 1983, *Astron. Astrophys.* **127**, 289

Skumanich, A.: 1972, *Astrophys. J.* **171**, 565

Skumanich, A., Smythe, C., Frazier, F.N.: 1975, *Astrophys. J.* **200**, 747

Soderblom, D.R.: 1982, *Astrophys. J.* **263**, 239

van Leeuwen, F.: 1983, Ph. D. thesis, Leiden

Vaughan, A.H., Baliunas, S.L., Middlekoop, F., Hartmann, L., Mihalas, D., Noyes, R.W., Preston, G.W.: 1981, *Astrophys. J.* **250**, 276

Vogt, S.S., Soderblom, D.R., Penrod, G.D.: 1983, *Astrophys. J.* **269**, 250

Walter, F.M., Linsky, J.L., Simon, T., Golub, L., Vaiana, G.S.: 1984, *Astrophys. J.* **281**, 815