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ROTATION IN LOWER MAIN-SEQUENCE STARS

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ABSTRACT. From Vaughan & Preston's survey of chromospheric emission on nearby stars and using the procedures described by Noyes et al. (1984) we calculated the rotational periods for F and later stars. The known periods of BY Dra stars allowed us to calibrate their relation for redder stars. Samples of stars with different kinematical ages are well separated, showing that older stars are rotating slower than younger ones in a way that depends on spectral type. If age is the main parameter governing the braking of rotation in single stars, then BY Dra stars must be very young.

Key words: Rotation; chromospheric activity; lower main-sequence stars.

The discovery of relatively fast rotators among lower main-sequence stars, through the BY Dra syndrome, arose the question about the evolution of rotation in late dwarf stars in general. But determining rotation by Vsini is of little help, since in addition to its intrinsic indetermination it is also limited to faster rotators. Period determination by photometric modulation is of little use too, since it is restricted only to the most active stars (BY Dra stars).

A help to the problem came with the work of Noyes et al. (1984) who showed that there is a good correlation between the average chromospheric emission in the H and K lines and the rotation.

We use Vaughan and Preston's survey (1980) of chromospheric emission on nearby stars and the procedures described by Noyes et al. (1984) to calculate rotational periods for a sample of stars of spectral type F and later. Their relations hold only for mean chromospheric emission, averaged over more than a decade (~one activity cicle), so some scatter may be expected when we apply them to values obtained by only a few observations. But since a large number of stars have been measured, we can interpret the results statistically.

Although not being a good parameter for red stars, we use below the (B-V) index because it is the only one available for most stars of the Vaughan-Preston's sample. The basic data are observed flux indices S for the CaII H and K lines, as measured with the Mt. Wilson H-K spectro-photometer (Vaughan et al., 1978). Following Middelkoop (1982) we can convert S into the quantity R_{HK}, that measures the flux within the bandpass independently of spectral type using the relation

$$R_{HK} = 1,340 \times 10^{-4} C_{cf} S$$

where C_{cf} is a color-dependent conversion factor.

We prefer to use the calibration of Rutten (1984) for C_{cf}, because it was obtained for a wider range of B-V :

$$\log C_{cf} = 0.25 (B-V)^3 - 1.33 (B-V)^2 + 0.43 (B-V) + 0.24$$

for main-sequence stars $0.3 \leqslant B-V \leqslant 1.6$.

Some stars of the sample have B-V greater than 1.6. We tentatively use the same relation for these stars but the results will not be affected by these cases.

The bandpass of the HK photometer includes the chromospheric emission and some flux from the stellar photosphere. The problem has been discussed by Hartman et al. (1983) an by Noyes et al. (1984) and to estimate the photospheric flux we use their relation :

$$\log R_{phot} = -4.898 + 1.918\ (B-V)^2 - 2.893\ (B-V)^3$$

for $0.44 < B-V < 0.82$

This relation is in approximate agreement with that obtained by Linsky et al. (1979 which holds also for stars of later spectral type. This correlation becomes negligible for very cool atmospheres. It should be noted that the photospheric correction of Linsky et al. is larger than that of Noyes et al. for (B-V) < .5. We use the relation given above for all the stars in the sample.

Following Noyes et al. the true chromospheric emission ratio is :

$$R'_{HK} = R_{HK} - R_{phot}$$

Assuming that the chromospheric emission depends on dynamo generation and using stars with observed rotation periods (P), they obtained a good correlation between R'_{HK} and P/τ_c, where τ_c is the convective turnover time. Actually, since τ_c is not well known, they calibrate also a relation between τ_c and (B-V) by an iterative procedure together with the $R'_{HK} \times P/\tau_c$ relation. The $\tau_c \times$ (B-V) relation was calibrated for .5 < (B-V) < 1.2, and the $R'_{HK} \times P/\tau_c$ relation for $-5.2 < \log R'_{HK} < -4.1$.

To extend these relations to shorter rotational periods and higher chromospheric activity, we use BY Dra stars with known periods and with H and K emission measured by Vaughan and Preston (1980), neglecting that we are using instantaneous values of S, not mean values. At the other extreme, that is, for very weak emission, the only useful star is HD 95735 (Noyes et al., 1984) : but we suppose that the given period is actually half the true period. This is based on the idea that sometimes we may be observing two chromospheric plages on opposite hemispheres, analogous to the case when two spots are observed on a BY Dra star. The observed period of HD 95735 would not fit any calibration. Repeating the procedure of Noyes et al. we obtain similar relations, with similar scattering, showing that the use of instantaneous values of S is acceptable. The $\tau_c \times$ (B-V) relation we obtained may be represented by the empirical functions :

$$\log \tau_c = -3.20 + 12.48(B-V) - 10.94\ (B-V)^2 + 3.00\ (B-V)^3$$

for $.45 \leqslant (B-V) < .90$

and

$$\log \tau_c = 1.24 + .14(B-V)$$

for $(B-V) \geqslant .9$

As previously we use this relation for all sample stars. The relation $\log R'_{HK} \times \log P/\tau_c$ has a shape similar to a curve of growth and may be represented by the empirical function :

$$\log P/\tau_c = .54X - 2.79 + .26\ tg^{-1}\ (18X - 79.4)$$

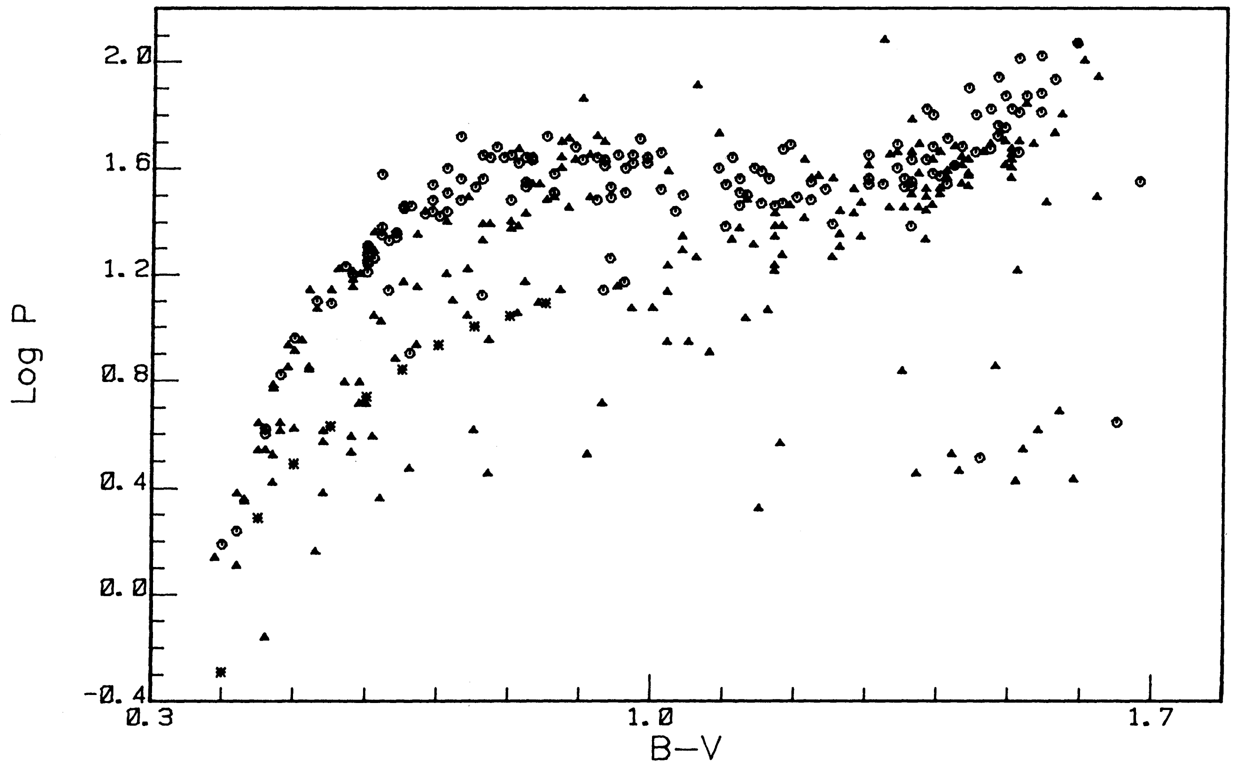
where $X = -\log R'_{HK}$

The main difference to the curve of Noyes et al. (1984) is the addition of an ascending branch for the most active stars ($\log R'_{HK} > -4.3$)

Although the scattering in the new ascending branch is similar to that of the previous calibration, it was obtained by only 8 stars, as we can see in Table 1. There is a good agreement between the observed period and the one obtained by the CaII emission, except

TABLE 1. Additional calibration stars

Name	B-V	S	-log R'_{HK}	P_{obs}	P_{calc}
HD175742	0.91	0.908	4.219	2.9	3.31
Gl 233	0.93	0.722	4.350	7.36	5.15
V1005 Ori	1.38	7.168	4.042	4.39	2.85
EF CVn	1.42	7.214	4.130	3.17	3.32
DT Vir	1.43	9.192	4.043	2.85	2.91
GT Peg	1.51	15.890	3.954	2.55	2.63
HD95735	1.51	0.490	5.465	(96)	102
AD Leo	1.54	9.809	4.220	2.6?	4.07
EV Lac	1.57	9.705	4.282	4.37	4.77
YZ CMi	1.59	22.408	3.956	2.77	2.70



Rotation periods (in days) predicted from HK lines flux indices S. Kinematically old stars are represented by circles, young kinematically old stars by triangles. The mean Hyades rotation, obtained from Duncan et al. (1984) is plotted by "*".

for AD Leo, whose observed period is uncertain, and V1005 Ori. The period used for that star is a new one based on a new re-analysis of all available photometric data and may be considered very well determined. The new branch should be used with caution, but, even if the real dependence were very different, that would not affect the other conclusions of this paper.

Now we can compute the periods for the Preston-Vaughan sample. We plot log P x (B-V) in Figure 1 only for stars within one of two non-adjacent cylinders in space velocity.

1) For kinematically young stars (triangles in Figure 1) :

$$[(U+10)^2 + (V+10)^2]^{1/2} < 35 km/s$$

and

$$| W+10 | < 20 km/s$$

2) For kinematically old stars (circles in Figure 1) :

$$[(U+10)^2 + (V+10)^2]^{1/2} > 50 km/s$$

or

$$| W+10 | > 25 km/s$$

We used 152 "old" and 203 "young" stars. We do not use the stars in the volume between the two cylinders (88 stars) in order to better discriminate the age effect. We also plotted in Figure 1 the mean Hyades stars denoted by "*" as obtained by Duncan et al. (1984).

There are 30 stars in the sample that also have average $\bar{S}$ values. From these star we can estimate that the mean error in log P obtained by instantaneous S is about 0.09.

From Figure 1 we can conclude that the young stars brake effectively in a way tha depends on spectral type. For stars of solar age or older the braking is less effective, and there is a residual rotation that depends on spectral type. The Preston-Vaughan gap may be noted in the figure and the addition of the stars of "intermediate" age does not appreciably change the gap.

Once calibrated with stars of known age, as those of the Hyades, the diagram can b used to estimate the age of a star by its rotation period (or calcium emission). A (single) star like BY Dra, for example, must be very young, probably with an age close to that of the Pleiades.

We would also like to call attention to the dip in the upper bound of the log P x (B-V) relation around (B-V) = 1.2, from where the limiting period increases again more rapi ly with (B-V). We have no explanation for these effects.

A theoretical model of the evolution of rotation of late main-sequence stars shoul explain the main features of Figure 1.

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