ANGULAR MOMENTUM LOSS AND CHROMOSPHERIC ACTIVITY IN LATE-TYPE DWARFS

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A chromospheric color-magnitude diagram has been constructed from the Vaughan-Preston survey of Ca II emission among solar neighborhood stars. The relative flux in the H and K lines declines with mass on the lower main-sequence as a consequence of the decline of the ZAMS rotational velocity with mass. The features of this C-M diagram are discussed, and some evidence for a gap in the distribution of Ca II emission with age is examined.

We know qualitatively that chromospheric emission (CE) is a manifestation of stellar magnetic fields, and that it diminishes with age for cool main-sequence stars. Skumanich (1972) fit a $t^{-1/2}$ law (t=age) to the available data for solar-type stars (near G2V), but the survey of Vaughan and Preston (1980, hereafter VP) shows an apparent gap in the distribution of Ca II emission vs. (B-V). This gap would imply a discontinuity in the relation between CE and age for stars bluer than (B-V)=1.0.

VP showed S, the equivalent width of the Ca II emission cores, as a function of (B-V). S is sensitive to the stellar temperature because the continuum in the ultraviolet weakens for the cool stars; this accounts for the steep slope of VP's log S vs. (B-V) diagram. Middelkoop (1982) has recently derived a correction for this effect so that the true emission flux (except for an arbitrary scale factor) can be obtained. His method gives values that agree with an independent derivation for solar-type stars (Soderblom 1983b). For the range over which Middelkoop's formulae apply (0.45≤(B-V)≤1.50), I have computed R_{HK}=(Ca II flux)/σT_e^4, i.e., the fraction of the star's luminosity that appears as emission in the H and K lines.

Figure 1 shows this chromospheric color-magnitude diagram. After correcting for the changing continuum, the CE shows a trend opposite to that seen in VP's plot of log S vs. (B-V). In other words, the cooler stars produce relatively less CE (as a fraction of their luminosity) than the hotter stars. This trend can be attributed to the decline of the zero-age-main-sequence (ZAMS) rotational velocity with mass, which in turn is a consequence of the greater time spent in the pre-main-sequence

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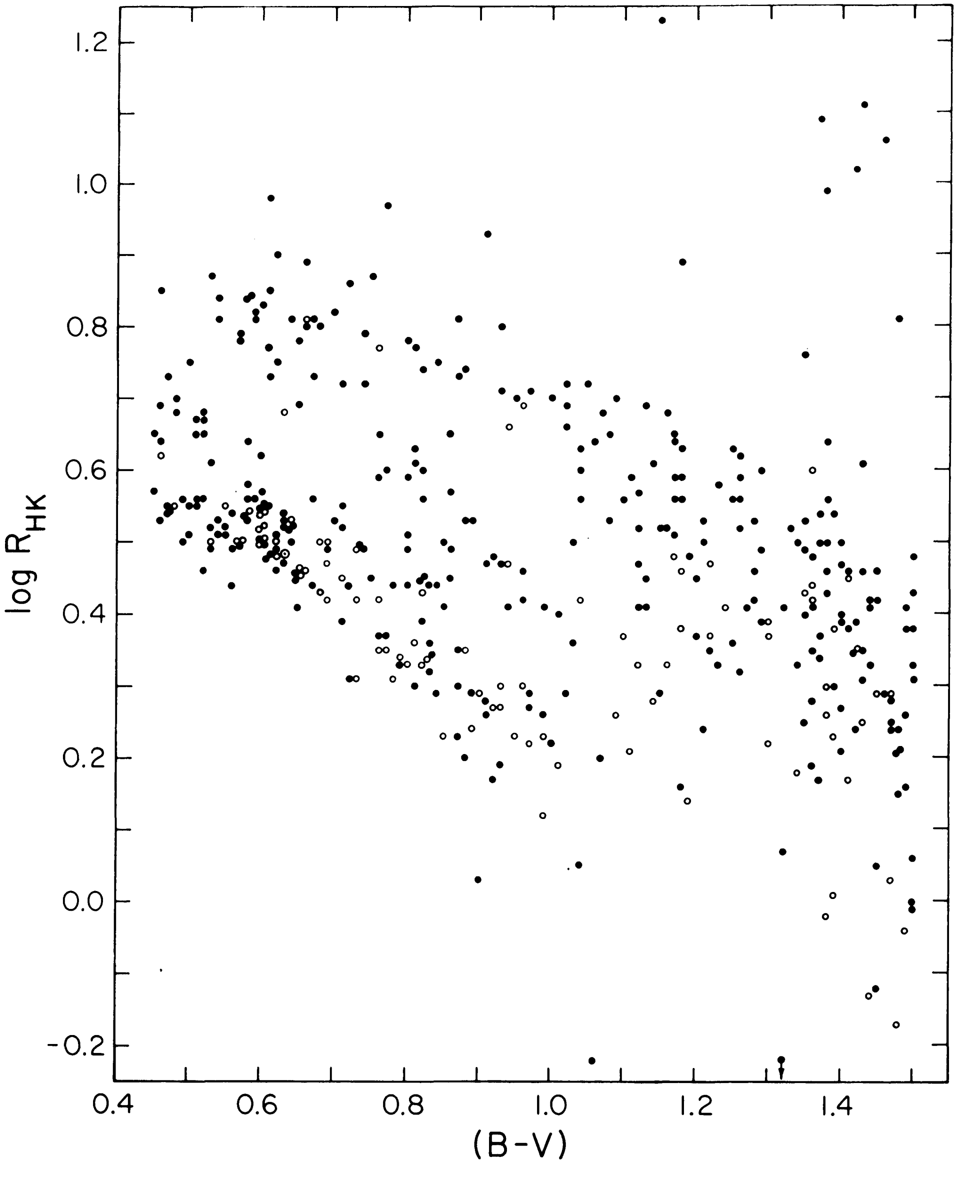

Figure 1. A chromospheric color-magnitude diagram. R_{HK} is the fraction of the stellar luminosity appearing in the emission reversals of the Ca II H and K lines, i.e., the equivalent width S of Vaughan and Preston (1980) transformed with Middelkoop's (1982) formulae. The solid points are disk population stars, while the open circles are old disk and halo objects (either $|W+10|>30$ km s^{-1} or $(U^2+V^2)^{1/2}>65$ km s^{-1}.

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contraction stage, where most of the initial angular momentum is lost. The youngest, most rapidly rotating stars at (B-V)=0.60 have $v \sin i$'s = 10-12 km s^{-1} (Soderblom 1982). This drops to about 6 km s^{-1} at (B-V) = 0.80 (Soderblom 1981) and goes below 4 km s^{-1} for the M dwarfs (Soderblom *et al.* 1982). The rotation periods found by Baliunas *et al.* (1983) and the tight correlation between R_{HK} and period (R.W. Noyes, this conference) confirm this steady decline of rotation with mass on the lower main-sequence. The weakest chromospheric emitters among the M dwarfs must be rotating very slowly indeed.

In Figure 1, VP's sample has been divided into two kinematic groups: the young disk stars (filled circles) and the old disk/halo population objects (open circles). For (B-V)<1.0, the concentration of halo stars near the lower edge of the distribution underscores VP's conclusion that kinematically old stars have weak CE. Among the chromospherically active stars at the upper edge of the distribution are objects kinematically associated with the Pleiades and Hyades clusters, in addition to the Ursa Major group stars that VP found. Members of old groups such as Eggen's (1969) Wolf 630 and 61 Cygni groups lie along the lower edge with the halo objects. If one postulates that CE$\propto t^{-1/2}$ (Skumanich 1972) and if a constant stellar birthrate is assumed, the vertical distribution of points is reasonable given: 1) the size of the sample, 2) the attrition of old stars in the solar neighborhood due to their large space velocities, and 3) the photospheric contribution to R_{HK} which condenses the distribution for the oldest stars. The vertical spread in R_{HK} implies a ratio of ages of oldest to youngest stars of about 100.

As VP cautioned, the authenticity of a gap in this diagram is problematical. Stars above and below the "gap" may indeed differ in some fundamental way, but there may be systematic effects responsible for this hiatus as well. For example, there is not so much a gap as a concentration of stars near the upper edge of the distribution. If the CE saturates at large magnetic field strengths, such an effect would arise. Also, the stars in the survey were mostly observed once or twice. Significant variability is seen, particularly for the strong emitters, as well as cyclic modulation over periods of years (Wilson 1978). If the mean CE averaged over, say, 20 years were plotted, would the gap disappear? The sample size also affects our perception of the gap. Figure 1 contains about 40 more stars than VP's diagram did because (B-V)'s were now available. By coincidence, about 6 of these new points tend to fill in the gap near (B-V)=0.80. VP's planned extension of the survey to southern declinations is a necessary augmentation of the sample. One last effect on this diagram is the lower average metal abundance of old stars. The conditions of formation of the Ca II H and K lines are too complex to easily predict the result of this effect.

There is some circumstantial evidence relevant to this "gap". The tight correlation between R_{HK} and rotation period (Noyes, this conference) implies that any discontinuity in the relation between CE and age should be matched by a corresponding discontinuity in the rotation-age data, but no such lacuna is seen (Soderblom 1983b). Similarly, the relation between lithium depletion and age is smooth for solar-type stars (Soderblom 1983b).

Whether or not a gap truly exists in the distribution for (B-V)<1.0, the distribution for cooler stars seems significantly different. Except for a few BY Draconis and flare stars in the upper right corner, there is no apparent gap and the vertical spread is less. The halo stars still exhibit lower R_{HK}'s overall. The Pleiades, Ursa Major and Hyades group stars lie along an extension of their loci among the hotter stars. The Wolf 630 and 61 Cygni group stars cooler than (B-V)=1.0 are displaced upward by 0.3 in log R_{HK} relative to the hotter stars in those groups. This shear in the distribution at (B-V)=1.0 is also seen in members of visual binaries whose components span that color.

This jog in the isochrones at (B-V)=1.0 could be rationalized if in fact a gap runs across the entire diagram. For (B-V)>1.0, the old stars would not have evolved across the gap because their ZAMS rotational velocities are so low that angular momentum loss requires most of the stellar lifetime. (The main-sequence lifetime approaches the age of the Galaxy for (B-V)>1.0). Before accepting this explanation, however, the data for these cool stars should be carefully examined. First, (B-V) is a poor photometric index for M stars, but (V-R)'s are not available for most of the sample. A plot of log S vs. (R-I) (Soderblom 1983a) is ambiguous because (R-I) is inappropriate for F and G stars. For (B-V)> 1.0, VP's continuum bands do not behave as expected (see their Fig. 3), suggesting that the S's may be muddled. Observations of the flux in the continuum bands of these stars should clarify the situation.

REFERENCES

Baliunas, S.L., Vaughan, A.H., Middelkoop, F., Hartmann, L.W., Mihalis, D., Noyes, R.W., Preston, G.W., Frazer, J., and Lanning, H.: 1983, Astrophys. J., in press.

Eggen, O.C.: 1969, Pub. Astron. Soc. Pacific 81, 553.

Middelkoop, F.: 1982, Astron. Astrophys. 107, 31.

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

Soderblom, D.R.: 1981, in M. Giampapa and L. Golub (eds.), *Second Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, Cambridge, Mass., Smithsonian Astrophys. Obs., Special Report 393, p. 197.

Soderblom, D.R.: 1982, Astrophys. J. 262, 275.

Soderblom, D.R.: 1983a, in P. Byrne and M. Rodonò, *Activity in Red Dwarf Stars* (IAU Coll. 71) D. Reidel, Dordrecht.

Soderblom, D.R.: 1983b, Astrophys. J., in press.

Soderblom, D.R., Vogt, S.S., and Penrod, G.D.: 1982, Bull. Am. Astron. Soc. 13, 873.

Vaughan, A.H. and Preston, G.W.: 1980, Pub. Astron. Soc. Pacific 92, 385.

Wilson, O.C.: 1978, Astrophys. J. 226, 379.

DISCUSSION

WALTER: Can the apparent saturation at the top of the gap be, in part, attributed to peculiarities in the Pleiades relative to the Hyades? If, as I understood you to say, the v_{rot} for the Pleiades is lower than expected from the Skumanich relation, and Ca II fluxes scale as v, and not as $t^{-1/2}$, then the inferred saturation may be due only to the low $\langle v_{rot} \rangle$ for the Pleiades. How important is the scatter from cluster to cluster about the Skumanich relation? There is some evidence for differing initial velocities in pre-main-sequence (PMS) stars: M. Smith finds that the G PMS stars in the Orion Ic association rotate very slowly, whereas the G PMS stars in Taurus, which are of similar ages (and presumably similar masses), rotate far more rapidly.

SODERBLOM: My observations of main-sequence $1 M_{\odot}$ stars from the age of the Ursa Major group and older show no greater dispersion about the $t^{-1/2}$ law than can be ascribed to a random distribution of rotation axes, observational error, and a modest intrinsic dispersion about the mean. In other words, nothing peculiar is seen. If you consider high mass stars which do not lose angular momentum on the main sequence, such stars in the Pleiades were seen by Abt to rotate faster than comparable field stars. Abt attributed this property to a relative lack of binaries in the Pleiades. This suggests that the Pleiades stars have greater than average angular momenta, which is opposite to what is needed to agree with your explanation.

MARCY: There is support for your contention that the Ca II H and K emission saturates in the young stars. The X-ray, ultraviolet, and magnetic field observations of the more active stars suggest the necessity of rather high photospheric fluxtube densities to explain the high values of the activity diagnostics. Such high densities of diverging fluxtubes would result, perhaps, in considerable field-line overlap in the lower chromosphere, and hence in saturation of the H and K emission.

SODERBLOM: I forgot to mention that solar observations support this saturation hypothesis. Skumanich, Smythe, and Frazier (1975, *Astrophys. J.* **200**, p. 747) looked at Ca II emission strength as a function of the local magnetic field strength. For weak fields the relation was linear, but for strong fields saturation occured. Their data seemed to fit something like Ca II emission $\sim B^{1/2}$, where B is the magnetic field.

FOING: How sensitive is the lithium depletion to the depth of the convective zone? Does it give a quantitative measurement of the distance between the Li burning shell and the subconvective layer, whatever the overshooting process could be?

SODERBLOM: The lithium depletion is *very* sensitive to the convective zone depth. Both myself and Duncan have examined the Li abundances of solar-type stars to derive Li abundance vs. age relations. In stars as young as the Hyades, the Li is already depleted in the K dwarfs. The transition from late F to K is fairly smooth, providing some information on the depth of the convective zones in these stars. I personally do not know how to interpret the data, however. There is evidence that the convective zone depth is sensitive to [Fe/H]. Recently the Spites observed a few G subdwarfs that are definitely Population II. Despite their age, these stars have strong Li lines, which is completely contrary to the simplest models of Li depletion. Their observations can be explained if the convective zones of low metal-abundance stars are thinner due to the lower opacity in the outer layers.

The Li data provides one of the few observational constraints on the convective properties of late-type dwarfs. Careful theoretical interpretation of the data is needed.

VAUGHAN: (1) In your statistical models have you tried yet to take the saturation in the Ca emission into account (for example $S \sim exp(-P_{rot}/P_0)$)? (2) Considering the space motions of the stars involved, could Pleiades "escapees" have wandered into the solar neighbourhood yet? In the case of the Ursa Major group the velocity dispersion is exceedingly small.

SODERBLOM: (1) No, I have not tried any other set than the $t^{-1/2}$ law. There are two reasons: First, the simulations were done in the last couple of weeks, so we tried the most obvious case first. Second, we tried to minimize the number of assumptions needed to simulate the chromospheric color-magnitude diagram to avoid any systematic effects. For example, we deliberately avoided any attempt at accounting for short and long time scale variability for that reason. (2) I am not sure. That question occured to me, but I have not addressed it. The Pleiades, Ursa Major, and Hyades group members all have space motions essentially identical to the cluster velocity, considering the uncertainties. Eggen has applied liberal criteria to determine group membership — he only requires that the stars corotate in the Galaxy. My criteria are stricter: all three space velocities should agree to 3 or 4 km s^{-1}. The spectroscopic properties of these group members make their membership very plausible. You pointed out some group members (Ursa Major and 61 Cygni groups) in your original paper.