THE RELATION BETWEEN ROTATION AND MAGNETIC ACTIVITY ON LOWER MAIN SEQUENCE STARS AS DERIVED FROM CHROMOSPHERIC INDICATORS

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It is now firmly established that lower main sequence (LMS) stars show a qualitative correlation between rotation rate and chromospheric and coronal emission. By analogy with the Sun, the emission is believed to be intimately associated with surface magnetic fields. This association is especially close on the Sun for the Ca II H and K lines, for which the spatial correlation between chromospheric emission and photospheric fields is essentially one-to-one down to scales at least as fine as a few arcseconds and for which the emission flux from an area on the Sun is approximately proportional to the total magnetic flux passing through the same area in the underlying photosphere (Leighton 1959; Skumanich, Smythe, and Frazier 1975; Frazier 1971). The extension of the association to other LMS stars, while based on appeal to analogy, has been strengthened by recent detections of strong magnetic fields covering large fraction of the surface area of chromospherically active stars (see review by Marcy in this symposium).

The association between stellar coronal X-ray emission and rotation is discussed by Vaiana and by Walter elsewhere in this symposium; here we concentrate on the details of the association between rotation and chromospheric emission, and in particular emission in the Ca II H and K lines. We concentrate on the Ca II H and K lines mainly because those emissions are by far the most thoroughly-observed indicator of stellar chromospheric activity. However, as is apparent from the review of Zwaan in this symposium, the emission of other chromospheric or transition zone emission lines is also correlated with magnetic activity, and should also show a dependence on rotation or other stellar parameters qualitatively similar to (even if quantitatively different from) the relations discussed below.

A close relation between rotation rate and magnetic field-induced chromospheric emission for Sun-like stars is to be expected given the widely-accepted picture that magnetic activity in the Sun and other LMS stars is caused by the coupling of rotation and convection to produce a magnetic dynamo. By the same token, we may expect the variation of convective properties from star to star to affect chromospheric

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activity, and inasmuch as these properties vary significantly with spectral type (see for example, Durney and Latour 1978, or Gilman 1980) we may anticipate a strong dependence on spectral type. To isolate this dependence, we shall compare below the chromospheric activity level of stars with similar rotation rates, but different spectral types. Of course other stellar properties, such as surface temperature, mass, radius, etc., vary along the lower main sequence, so we must be cautious in attributing any single physical cause to activity variations with spectral type which may be revealed by the data.

A third stellar parameter, in addition to rotation rate and spectral type, which has long been associated with varying levels of chromospheric activity, is stellar age. However, as has been clearly shown in recent years, age seems to affect stellar activity mainly insofar as it affects a star's rotation rate through the phenomenon of spindown. The RS CVn stars, whose rotation is maintained by tidal coupling in spite of their aging, and whose activity is commensurately high, provide strong support for this conjecture, (see for example, Hall 1981; Ayres and Linsky 1980; or Walter 1981).

A long-standing view has been that stellar chromospheric emission decays smoothly with age as a star spins down (e.g. Schatzmann 1962; Kraft 1967): Both emission level and rotation rate decrease with age approximately as $(\text{age})^{-1/2}$ (Skumanich 1972; see also Skumanich and Eddy 1981). This picture is compatible with the hypothesis of steady spindown through angular momentum shedding by stellar winds, assuming mean surface magnetic field strength is proportional to angular velocity (see Durney 1972; Durney and Stenflo 1972). This scenario has been complicated by the recent discovery of the Vaughan-Preston "gap" in chromospheric emission (Vaughan and Preston 1980). The gap, which was pointed out in data from a survey of lower main sequence stars in the solar neighborhood, is also quite visible in the stars of Wilson's (1978) long-term activity survey, as may be seen in Figure 1 (see also Vaughan 1980). There are at least four possible explanations for the gap: (a) It may be simply a chance distribution and not a statistically significant description of properties of stars in the solar neighborhood. (b) It may be a real characterization of the solar neighborhood, but one produced simply by a paucity of stars of a given age (and hence emission level), rather than by an intrinsic stellar mechanism. (c) The gap may be real and represent a physical change in the character of magnetic activity generation at a given (perhaps spectral type-dependent) age and activity level. As example of this possibility, the gap might be produced by an abrupt decrease of dynamo efficiency at a given rotation rate. Several suggestions to this effect have been made (e.g. Duncan 1981; Middelkoop 1982) and specific physical mechanisms have been suggested by Durney, Mihalas, and Robinson (1981) and Knobloch, Rosner, and Weiss (1981). On the other hand (d), it is conceptually possible that it is not the relation between rotation and activity which changes, but that the rotation rate itself suddenly slows when a critical rotation rate is reached. (For example, at a critical

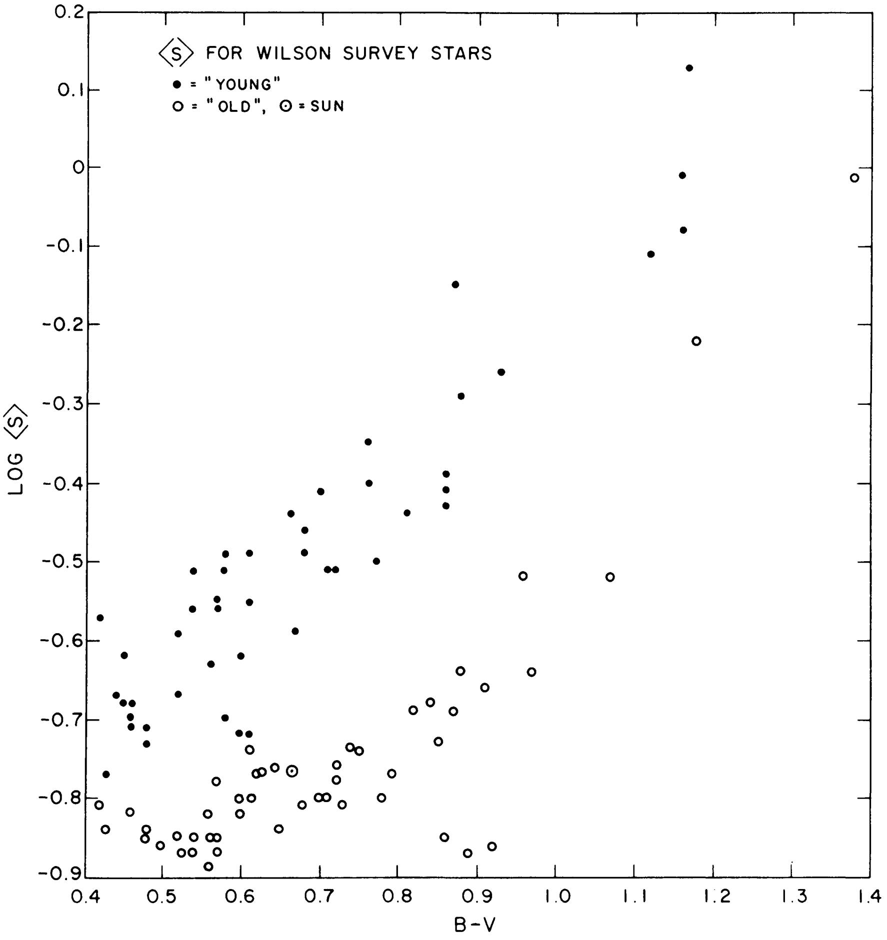

Figure 1. Mean values S of the Mt. Wilson H-K flux index, as determined from the long-term survey data of Wilson (1978). Closed and open circles represent "young" and "old" stars respectively (Vaughan 1980).

rotation rate, previously closed field lines might open up and increase the stellar wind angular momentum loss).

Clearly detailed empirical relations between rotation rate, spectral type, age, and chromospheric emission level would go far toward understanding the nature of the gap. For example, empirical evidence for a drop in activity at a particular rotation rate would argue for explanation (c) above. Evidence of this sort has been presented by Middelkoop (1982), but it is based on measured values of v sin i near the threshold of sensitivity of such measurements, and is scarcely conclusive. Conversely, evidence for continuity of the relation between rotation, activity, and spectral type across the gap would argue against explanation (c).

Even the "zero-order" spin-down scenario mentioned earlier has still to be quantitatively defined and tested by detailed measurements of many stars of different rotation rates, ages, and activity levels. However, because of the increasingly clear importance of such a test, there have been many recent studies aimed at this goal. The largest body of systematic data so far available on chromospheric losses as a function of rotation, age, and spectral type are measurements of emission in the Ca II H and K lines, and we shall now focus our discussion on these lines. Vaughan et al. (1981) found that rotation periods generally increase toward later spectral types, and that for stars of a given spectral type slower rotators had less chromospheric activity. Their quantitative relation between rotation and activity was spectral type-dependent, primarily because the chromospheric emission indicator which they used, the H-K flux index, is a quantity which depends on spectral type as well as on chromospheric activity. Middelkoop (1982), after converting the H-K flux index into absolute surface fluxes F_{HK} (erg/cm^2/sec) within the Mt. Wilson H-K photometer bandpass, found much less dependence on spectral type, with $F_{HK} \propto \log v_{eq}$. Catalano and Marilli (1982) find the surface luminosity L_K (erg/sec) to vary as exp(-P_{rot}/27 days), independently of spectral type. Also, as discussed elsewhere in this symposium, several investigators have derived relations between coronal activity indicators (i.e. X-ray luminosity, surface flux, or ratio of surface flux to bolometric luminosity) and rotation as a function of spectral type (see for example, Walter 1982; Pallavicini et al. 1981).

The above discussion points up a certain arbitrariness in describing the dependence of emission on spectral type, for the dependence will vary significantly as one expresses emission in terms of absolute luminosity L_{HK}, surface flux F_{HK}, or ratio R_{HK} of luminosity to the star's bolometric luminosity. In the discussion below, we will use the last of these, which may be equivalently described as the flux ratio $R_{HK} = F_{HK}/\sigma T_{eff}^4$. We note in passing that because virtually all of a LMS star's luminosity is carried upward through the convection zone as a mechanical energy flux, the ratio R_{HK} may be thought of as approximately porportional to that fraction of the mechanical energy flux in the convection zone which is converted into magnetic field-related chromospheric heating.*

We shall not attempt here to derive a relation between H-K emission,

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*This statement is strictly true of course only when R_{HK} is corrected for the non-magnetic contribution to the emission, and even then the proportionality will depend on spectral type, insofar as the ratio of chromospheric H-K losses to all chromospheric losses (including Lyman lines, Mg II h and k, the Ca II infrared triplet, etc.) varies with spectral type.

rotation, activity, and age sufficiently definitive to lead to conclusions about physical mechanisms. Our rather more modest goal is two-fold: (a) to address the question of the physical meaning of the Vaughan-Preston gap by studying how the empirical rotation-activity-spectral type relation varies across the gap, and (b) to derive an empirical relation between activity, spectral type, and rotation sufficient to allow estimation of rotation periods from the measured activity level of a star of a given spectral type.

The most extensive homogeneous set of data on chromospheric activity for LMS stars is the Ca II H and K flux measurements of Wilson (1978). For many of these same stars, Vaughan and colleagues (Vaughan et al. 1981, Baliunas et al. 1983) have determined rotation periods from the rotational modulation of Ca II flux. The Ca II flux data of Wilson have another very important attractive feature: Because the observations of these stars extend from 1966 up to the present (when combined with the more recent data obtained by Vaughan and his collaborators), it is possible to make allowance for the variations in Ca II flux level associated with long-term activity variations, as well as short-term rotational modulation. Figure 1 shows the mean value S of the Ca II H-K flux index $< S >$, as taken from Wilson's (1978) data, updated to the present. The flux index S is proportional to the equivalent width of the emission in 1A bands centered on H and K, and referenced to the mean quasi-continuum at 3922 and 4001A (Vaughan et al. 1978). The mean value $< S >$ is a value approximately halfway between the minimum and maximum levels of S attained for each star between 1966 and the present. Because of the greater reliability of $< S >$ as an indicator of overall chromospheric emission level for a particular star, we shall confine the remainder of this discussion to the relation between the data in Figure 1 and the rotation period and spectral type determined for these stars.

Before proceeding further, we convert the observational parameter S into the chromospheric flux ratio $R'_{HK} = F'_{HK}/\sigma T^4_{eff}$, where F'_{HK} is the chromospheric flux per unit area in the H and K lines (the prime denotes subtraction of the photospheric contribution, as we describe below). This requires a two-step process:

1) The flux index S is the ratio of the total flux in instrumental bandpasses centered on the H and K line cores, to that in the nearby "continuum." The "continuum" flux however decreases steeply toward later spectral types; this effect is principally responsible for the general increase of $< S >$ toward later spectral types in Figure 1. Middelkoop (1982) has determined an empirical conversion function C_{cf} (B-V), such that the $C_{cf}S$ yields the ratio of total flux F_{HK} within one Angstrom bandpasses centered on H and K to the stellar bolometric flux σT^4_{eff}. We denote this ratio R_{HK}. The function C_{cf} was determined from Mt. Wilson observations of stars in the solar neighborhood by comparison of the fluxes in the two "continuum" channels of the H-K photometer to the bolometric flux inferred from the measured color of

each star and its visual magnitude.

2) The flux F_{HK} is made up of radiation from both the chromosphere and the photosphere. The photospheric contribution is due primarily to the fact that the instrumental profile of the Mt. Wilson H-K photometer is triangular with a halfwidth of 1.09Å (Figure 2) and is sensitive well beyond the K_1 and H_1 minima of intensity in the line profiles. Hartmann (personal communication) in analyzing the Vernazza et al. (1981) model C for the quiet Sun, notes that there is close agreement between the amount of radiative losses in the K line from the chromosphere and the totality of emission inside the K_1 minima. Thus the regions outside the K_1 and H_1 minima, shown shaded in Figure 2, are essentially photospheric in origin, whereas the unshaded regions inside the K_1 and H_1 minima are mainly completely chromospheric in origin.

The upper curve of Figure 2, illustrating the spectrum of a solar plage, may be considered as comparable to that of an active chromosphere G2 star (i.e., in the upper branch of Figure 1). We note that in the plage the part of the K line profile outside the K_1 minimum is enhanced much less than that inside the K_1 minimum, which implies that the photospheric response to magnetic fields is much less than that in the chromosphere. Thus, to a first approximation the fraction of the emission detected outside the K_1 minima (shaded in Figure 2) does not respond to the magnetic flux through the underlying photosphere. We therefore correct the observed flux emission F_{HK} by subtracting off the photospheric component F°_{HK}. We write the true chromospheric flux as

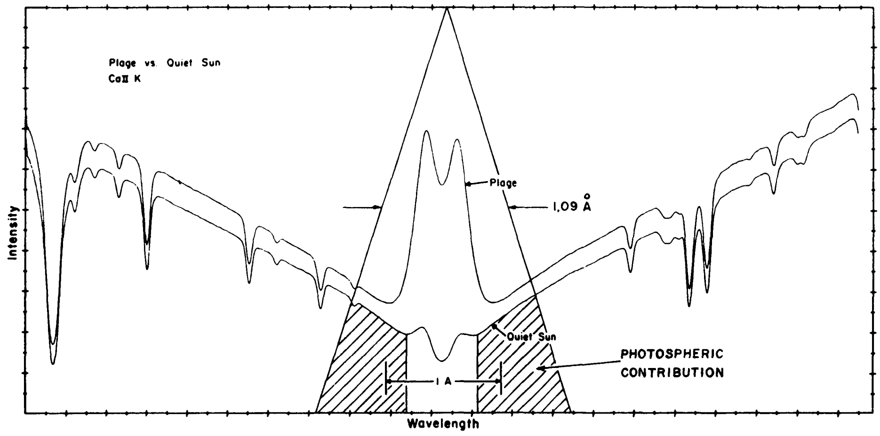

Figure 2. The triangular H-K photometer profile (Vaughan et al. 1978) is superimposed on profiles of the solar Ca II K line for the quiet Sun and for a solar plage, as observed by White and Livingston (1981). The emission outside the K_1 minima which is recorded by the instrument (schematized by the shaded area) is attributed to photospheric radiation.

$$F'_{HK} = F_{HK} - F_{HK}^{\odot},$$

and the chromospheric flux ratio as

$$R'_{HK} = F'_{HK}/\sigma T_{eff}^{4}.$$

For the quiet Sun, the photospheric correction is about 0.5 (i.e., $R_{HK}^{\odot} \sim 0.5\ R_{HK}$).

Hartmann et al. (1983) have determined the ratio $R_{HK}^{\odot}/R_{HK}$ from high-resolution line profiles of four representative stars with weak chromospheric activity and from the observed values of R_{HK} for these stars have derived an empirical relation* for $R_{HK}^{\odot}$ (B-V). Values of the residual chromospheric flux, obtained for the stars in Figure 1 by using this correction, are plotted in Figure 3.

Zwaan (this symposium) has discussed the sharp lower boundary seen in F_{HK} (or, equivalently in the value of $\langle S \rangle$ plotted in Figure 1), and suggests that it could be produced by residual H-K emission in stars whose magnetic activity is so low as to contribute negligibly to the total observed H-K flux. However, the emission $F_{HK}^{\odot}$ we have subtracted is less than that corresponding to the lower boundary of points in Figure 1. In other words, even the most inactive stars still have some residual chromospheric emission. In terms of the search for a relation between rotation and magnetic activity, the question is whether this residual chromospheric emission is associated with surface fields or with purely acoustic heating. An important test is to determine the rotation rate of the most inactive stars in Figure 1 (a difficult task since these stars show little rotational modulation). If these stars are indeed rotating very slowly, one may infer a low level of surface magnetism and hence that the residual chromospheric emission is nonmagnetic. On the other hand, rotation rates not grossly slower than somewhat more active stars such as the Sun would suggest surface magnetic fields on even the least active stars, which would create the observed chromospheric emission by magnetic-associated heating. (In this case, the sharp lower boundary of Figure 1 could be produced by a decreased rate of spindown for very old stars.) In the absence of definitive data on the above point, we shall proceed in this discussion simply to subtract off the photospheric part $R_{HK}^{\odot}$, and investigate how $\langle R_{HK} \rangle = \langle R_{HK} \rangle - R_{HK}^{\odot}$ varies with spectral type and rotation period, recognizing the uncertainties implied by the above discussion.

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*The stars used were HD 114378, B-V = .45; HD 115383, B-V = .58; the Sun, B-V = .66; and HD 23249, B-V = .92. The resulting fit is log $R_{HK}^{\odot} = -4.90 + 1.92\ (B-V)^{2} - 2.89(B-V)^{3}$, valid for $0.45 < B-V < 1$; for $B-V > 1$ the correction is negligible for any of the stars considered here.

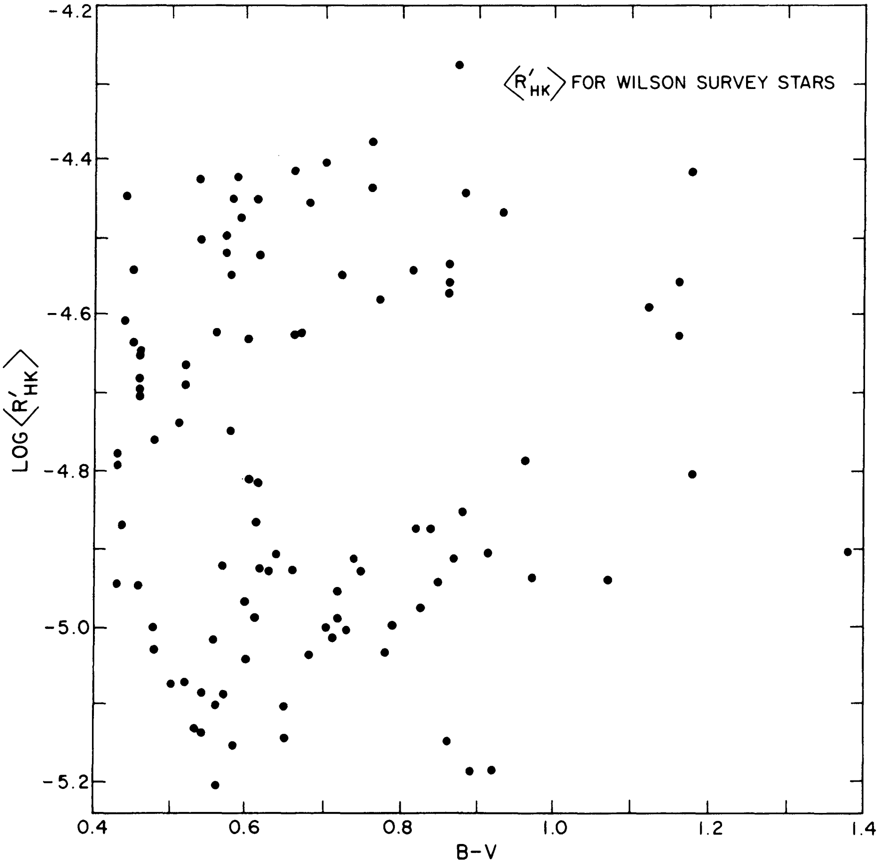

Figure 3. The mean chromospheric H-K flux ratio $< R'_{HK} >$, as obtained from the mean Wilson (1978) survey data plotted in Figure 1.

Figure 4 displays the $< R'_{HK} >$ values of Figure 3, for those stars with measured rotation periods, plotted versus rotation period. There is a general tendency for a decrease in $< R'_{HK} >$ with increasing rotation period, but with considerable scatter. However, examination of the (B-V) colors associated with each point shows that the scatter is clearly color-dependent: for a given period later-type stars show a larger value of $< R'_{HK} >$ than do earlier-type stars.

We note that the general trend of chromospheric emission with rotation period for stars of a given color goes approximately as 1/P, and for the purposes of this discussion we have therefore divided the data by the function $f(P) = 7.94 \times 10^{-5}/P$ (dashed line in Figure 4). The ratio of the observed data to f(P) is plotted in Figure 5a. It may be seen that

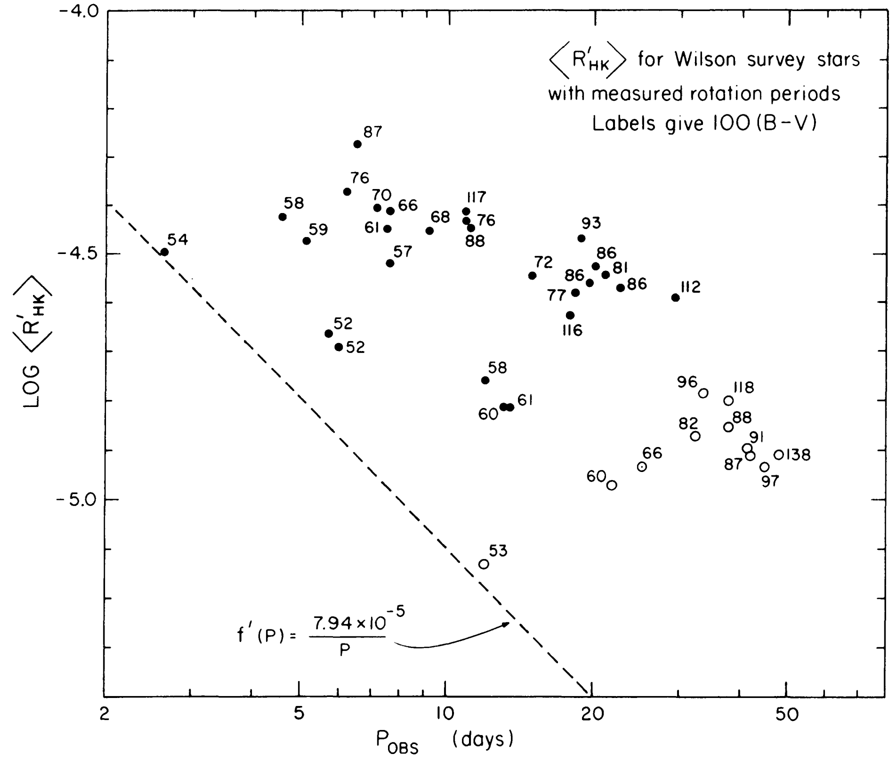

Figure 4. Variation of the mean chromospheric H-K flux ratio $<R'_{HK}>$ with observed rotation P_{obs}, for stars whose rotation period has been measured by rotational modulation of Ca II K (Vaughan et al. 1981; Baliunas et al. 1983; Noyes, in preparation). Closed and open circles represent "young" and "old" stars respectively.

the residual shows a rise of nearly one order of magnitude from earlier to later spectral types.

We have represented the residual in Figure 5a by a function g(B-V), as shown by the solid line. Dividing the data points by g(B-V), we get the plot shown in Figure 5b, illustrating the decreased scatter in the data after the spectral type dependence is factored out.

The factorization $<R'_{HK}>$= f(P) g (B-V), where f(P) ~ 1/P, has not been chosen by least squares or other optimization technique, and indeed there is not strong a priori reason for picking a power law or a different relation for fitting. The purpose of this factoring is simply to point out that chromospheric activity level in LMS stars appears to first order to be a separable function of rotation rate and spectral type (through the variation of convection zone properties, mass,

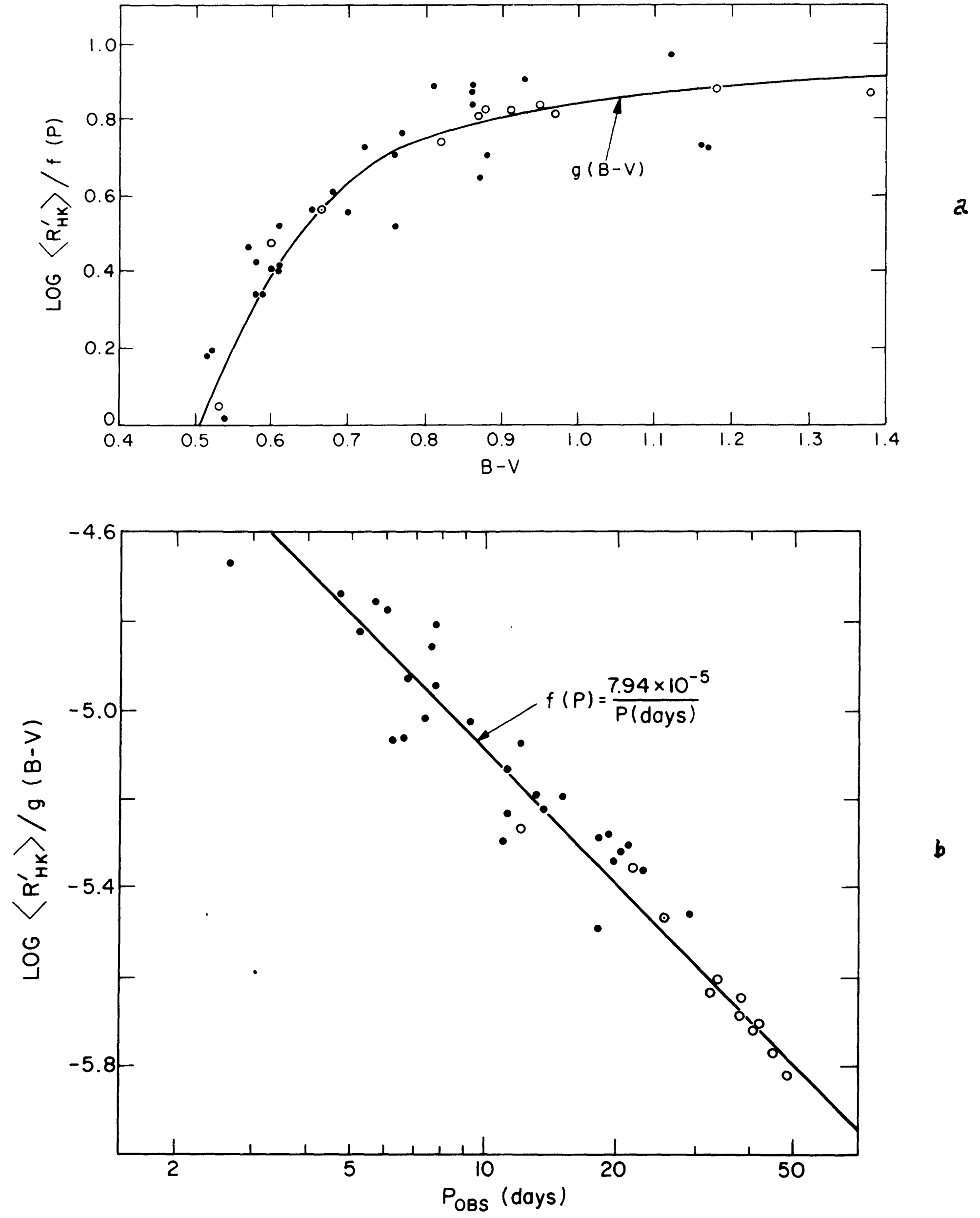

Figure 5. (a) Data of Figure 4, divided by the function f(P) = $7.94 \times 10^{-5}/P$, and replotted versus (B-V). The function g(B-V) is a polynomial fit through the plotted points. (b) Data of Figure 4, divided by the function g(B-V). Closed and open circles represent "young" and "old" stars respectively.

effective temperature, etc.) While an increase of activity with advancing spectral type has been noted before for stars of the same rotation rate (e.g. Walter 1981), the relatively clean separability of the functional dependence is somewhat surprising.

The significance of the shape of the function g(B-V) is not clear. Many potentially significant parameters increase with advancing spectral type, including for example the depth of the convection zone, the convective turn over time, (e.g. Durney and Latour 1978), differential rotation (Belvedere et al. 1980) or the fractional surface area of a star covered by magnetic field (Durney and Robinson 1982). For example, the curve g(B-V) has essentially the same dependence on B-V as does the convective turnover time τ_c (for mixing length to scale height ratio of 1.0), calculated by Gilman (1980). This would imply that chromospheric activity ratio R'_{HK} is approximately proportional to the inverse Rossby number

$$R^{-1} = \tau_c/P_{rot}.$$

The possible importance of the Rossby number in determining overall magnetic activity level is discussed by Schussler in this symposium. However, as Schussler points out, many other physical effects related to the above list of parameters which vary along the main sequence, could lead to a growth of magnetic activity with advancing spectral type (see also Rosner and Vaiana 1980; Durney and Robinson 1981). It is to be hoped that, as the quantity and quality of the data base describing the dependence of chromospheric (and coronal) activity on rotation rate and on spectral type improves, it will be possible to distinguish definitively between different physical mechanisms by the shape of the empirical dependences found.

In Figure 1, 4, and 5, open and closed circles represent stars labeled "old" and "young" respectively by Vaughan (1980), i.e., stars below and above the "gap."* There does not appear to be a significant difference in the dependence of chromospheric emission on rotation rate or color between the two classes of star. This may be taken as suggestive that the cause of the gap is not simply a change in the characteristics of convection or the dynamo at a critical value of the rotation rate (e.g. Durney et al. 1981, Knobloch et al. 1981).

The fact that chromospheric emission ratios R'_{HK} can be empirically represented functionally as f(P) g(B-V) with only moderate scatter permits us to predict rotation rates of stars whose H-K flux index and color are known. This predictive capability has already been used by Vaughan (this symposium) to investigate the rotation period dependence of activity cycles for stars whose period has not yet been measured by

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*The stars 61 Cyg A and B, labeled by Vaughan as "young," are here reclassified as "old" based on their clear activity cycles and their low absolute emission level; see also Skumanich and Eddy (1981).

rotational modulation observations.

In another application of this method of rotation period estimation, we have used observed H-K fluxes of Hyades main sequence stars (Duncan, personal communication)) to predict rotation periods for Hyades stars (Figure 6). The variation of H-K flux with (B-V) suggests that for this presumably coeval group of stars (age ~ 600 million years), rotation rates vary smoothly with mass, decreasing by a factor of about 6 from Log $M/M_\odot$ = .09 (B-V = .45) to Log $M/M_\odot$ = -.10 (B-V = .9). This prediction, which needs to be tested by rotational modulation observations of Hyades stars, is of potential importance for two reasons. First, the smoothness of the relation of H-K flux to mass (Figure 6a) suggests that late-type stars either are born on the main sequence with rotation varying smoothly with mass, or that any

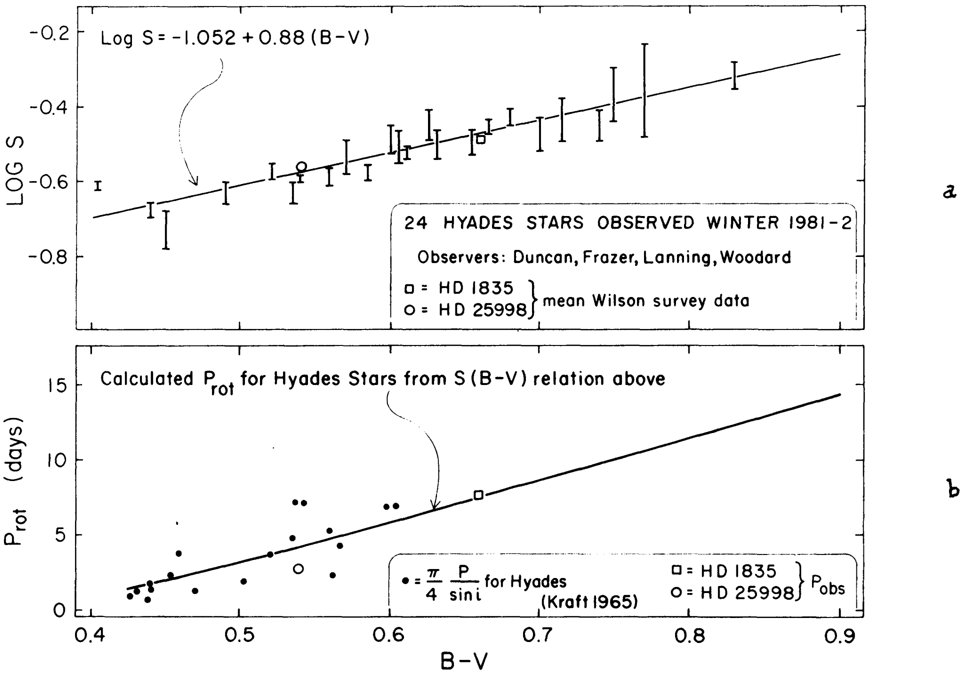

Figure 6. (a) H-K flux index values for 24 Hyades stars (data kindly supplied by D. Duncan), plus the co-moving solar neighborhood stars HD 1835, HD 25998. Solid line is a hand-drawn linear fit to the data. (b) Solid line is the calculated rotation for stars with flux index defined by Log S = -1.052 + .88 (B-V), if the stars obey the relation R_{HK} = f(P) g (B-V) (Figure 5). Also shown are observed rotation periods for HD 1835 and HD 25998, plus periods from Kraft's (1965) values of v sin i of Hyades stars.

idiosyncrasies of rotation rate of individual stars at birth are smoothed out in the process of their spindown as they age to 600 million years. Second, the detailed shape of the curve of rotation versus spectral type (Figure 6b), when compared with similar curves which should be derivable for other clusters of different ages, will allow one to determine the explicit mass-dependence of spindown as a function of age in lower main sequence stars.

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DISCUSSION

CRAM: I was surprised to see such a tight correlation between period and $B-V$ for the Hyades. Do you have any comment on how those stars get the fact that they are presumably born with different angular momentum?

NOYES: Presumably their angular momenta are not at all that different from what they were when the stars arrived at the main sequence. David Soderblom made the suggestion to me that the rate at which the stars spun down to arrive at that particular rotation period is simply related to the amount of time it took them to reach the main sequence.

WEISS: Could you clarify whether there is any clear evidence for a gap if the rotation rate is plotted against spectral type?

VAUGHAN: In a plot of P_{rot} against $B-V$ for the main sequence stars showing cycles or possible cycles, the dichotomy between active and inactive stars is very striking, in the sense that two sequences appear, one resembling the plot of P_{rot} vs. $B-V$ for the Hyades, the other a sequence containing the sun. Obviously the plot should be made for the full sample of solar neighborhood stars.

MOUSCHOVIAS: Quite justifiably, yesterday and to-day there has been a considerable amount of discussion on what the physical parameters are on which stellar and solar activity depends. Naive as the answer may seem, to somebody who "comes from interstellar space" the answer is evident. There are very few dimensionless parameters (ratios of such quantities as the gravitational, magnetic, thermal, and rotational kinetic energies) available at the protostar formation epoch. These parameters (and, more precisely, their distribution within a protostar) determine the subsequent evolution of a star, including its surface activity. It would therefore be useful and appropriate to plot some index of stellar activity against the energy ratios (magnetic/gravitational) and (rotational/gravitational); it is not necessary to plot activity against the ratio (thermal/gravitational), because stars are supported by thermal pressure gradients. Certainly the distribution of these parameters within a star is significant, but is itself determined from the protostar stage.

Quantities such as effective temperature, surface period of rotation, etc., against which activity is plotted, are important but not fundamental, in that they are derivable from the parameters mentioned above. We may miss the underlying fundamental physics if we focus only on the latter quantities as possible indicators of stellar activity.