I. INTRODUCTION

The Vaughan-Preston survey of Ca II H and K emission is a large homogeneous sample of the chromospheric activity of late-type main-sequence stars (Vaughan and Preston 1980, hereafter VP). This survey is nearly complete for stars in the neighborhood of the Sun and can therefore be used for statistical tests of stellar activity. Although VP expressed the hope that "the age distribution (of late-type dwarfs) and the statistical tests of stellar activity. Although VP expressed the hope that "the age distribution (of late-type dwarfs) and the functional form of the law of chromospheric decay may eventually be inferred from the results," a quantitative analysis of the data has not yet been made.

Qualitative studies of the survey data suggest that a "gap" in chromospheric emission exists for stars in the range 0.45 < B—V < 1.0 (Vaughan and Preston 1980; Durney, Mihalas, and Robinson 1981; Middelkoop 1982). There are relatively large numbers of stars in this color range with either strong or weak chromospheric emission, but very few with moderate emission. Because chromospheric activity decays with increasing stellar age or decreasing rotation rate (Wilson 1963; Kraft 1967; Skumanich 1972), the gap could represent a rapid, qualitative change in the nature of chromospheric emission at a certain stellar age or rotation rate (Vaughan and Preston 1980; Middelkoop 1982; Durney, Mihalas, and Robinson 1981; Knobloch, Rosner, and Weiss 1981; Soderblom 1982).

AN ANALYSIS OF THE VAUGHAN-PRESTON SURVEY OF CHROMOSPHERIC EMISSION

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ABSTRACT

The statistical properties of the Vaughan-Preston survey of chromospheric emission of nearby stars have been investigated using models of the decay of chromospheric activity with increasing age. It has been suggested that the "gap" in the distribution of emission observed in the survey indicates a discontinuous change in chromospheric behavior at a critical value of age (or rotation). However, this interpretation of the data has been made without considering two crucial effects. First, photospheric light maintains a minimum value of the Vaughan-Preston Ca II emission index (S) even in the absence of any chromospheric activity. Second, solar-type stars in the Pleiades do not follow the Skumanich relation for chromospheric decay if the nuclear age of the cluster is used. The emission levels of the Pleiades F-G stars are lower than the extrapolation of the t−1/2 emission variation between the Hyades cluster and the Sun, suggesting that there may be a saturation of chromospheric emission in very young stars. This tendency toward an upper limit of chromospheric emission, combined with the lower limit from photospheric flux, creates concentrations of strong and weak emission stars in the Vaughan-Preston diagram, enhancing the impression of a "gap."

We show that the observed large-scale distribution of chromospheric emission in solar-type stars can be modeled using a smoothly varying decay of chromospheric activity with age. A statistical analysis shows that no discontinuous change in magnetic activity is required to fit the data.

The survey shows small-scale structure which appears to be statistically significant. Although fine discontinuities in chromospheric behavior cannot be ruled out, it seems more plausible to interpret this structure with reasonable fluctuations in the local birthrate of solar-type stars on time scales of a few times 10^8 yr.

Subject headings: Ca II emission — stars: chromospheres — stars: evolution — stars: late-type
the Ca II fluxes of Pleiades stars are lower than estimated by Skumanich, and is also consistent with recent observations of the relationship between chromospheric emission and rotational period (Noyes et al. 1983).

In § II we describe the observational data and its calibration in terms of a relative flux scale. We have used Monte Carlo techniques to simulate the diagram relating chromospheric emission and color; the methods and conclusions are presented in § III. Finally, § IV deals with the “gap” and its significance.

II. THE CHROMOSPHERIC COLOR-MAGNITUDE DIAGRAM

a) The Vaughan-Preston Survey

The data we have analyzed are primarily those illustrated by VP, and obtained by the techniques described in Vaughan, Preston, and Wilson (1978). Briefly, VP measured the flux through triangular bandpasses of 1.09 Å FWHM centered at the Ca II H and K lines (see Fig. 1). They also measured the fluxes in two 20 Å “continuum” bands centered at 3901 Å and 4001 Å. Two observational quantities are produced: S', the flux in the H and K lines relative to the continuum bands; and C_{RV}, the ratio of the red continuum band to the violet one. In this paper we shall assume that the variability of the chromospheric emission dominates possible changes in the reference continuum; the latter are generally small, of order 1% (Radick et al. 1983).

The C_{RV} ratio is useful as a color index for some stars but not for others. In their Figure 3, VP show C_{RV} versus B − V. For B − V ≤ 1.0, the two quantities are well correlated, but for B − V > 1.0, the correlation is very poor, and turns over so that the red stars (in terms of B − V) appear increasingly blue (in terms of C_{RV}). This behavior of the continuum bands probably arises from variation of the complicated and severe line blanketing present in the coolest stars. Since the chromospheric emission is presented relative to the heavily blanketed continuum bandpasses, the scatter in C_{RV} suggests that S may not be a useful index for red stars. Most of the analysis of this paper will be devoted to the “yellow” stars, 0.5 ≤ B − V ≤ 1.0.

Vaughan and Preston selected their targets from the catalog of stars within 25 pc of the Sun (Woolley et al. 1970). Attention was restricted to northern hemisphere dwarfs later than about F5, and spectroscopic binaries were excluded from that survey. A few close visual binaries were also omitted if they could not be observed separately. One star included in the survey was found by Soderblom (1982a) to be a spectroscopic binary and was omitted from the present discussion.

Most of the data analyzed here come from the original VP survey, as illustrated in their Figure 1; we call this Group I. There are 39 stars in the survey which were not included in VP’s Figure 1 for which (B − V) colors were obtained from Nicolet (1978) (Group II). An additional 59 stars (Group III) have been observed since VP prepared their 1980 paper, and we added 12 stars (Group IV) from Vaughan et al. (1981) that met the criteria given above for inclusion in the survey. These data are available on magnetic tape for interested scientists.

The survey as a whole is 88% complete at present but is 97% complete for stars with 0.5 ≤ B − V ≤ 1.0. The spectral types or magnitudes/parallaxes of the 96 stars for which B − V is unknown indicate that few have B − V < 1.0. Thus the incompleteness of the survey cannot significantly affect the conclusions we reach.

On the average, each star was observed 2.2 times. The 12 stars in Group IV were observed many times as part of a study of rotational modulation of the Ca II lines, but at

Fig. 1.—The central bandpass of the HK photometer is shown superposed on a spectrum of the quiet Sun taken from White and Livingston (1981), with the minimum photospheric contribution to the S index indicated.
least 75% of the stars of greatest interest to this study (0.5 ≤ B−V ≤ 1.0) were observed three or fewer times. Thus, the survey represents a “snapshot” of chromospheric activity for most stars.

b) Calibration of Ca II Fluxes

The S index is instrumentally convenient because it is essentially free from extinction and seeing effects, but it is not a physically meaningful quantity. Because the continuum fluxes vary rapidly with spectral type in late-type stars, it is difficult to compare the chromospheric emission of stars with much different effective temperatures in terms of S.

Middelkoop (1982) has presented a relation which converts S into a physical quantity using a correction factor which depends only on B−V. This calibration provides the ratio R_{HK} = (Ca II H and K flux)/(bolometric flux), i.e., R_{HK} is the fraction of the stellar luminosity which appears as emission in the H and K lines. Note that R_{HK} contains an arbitrary scale factor. In the system used here, the solar Ca II chromospheric emission is equivalent to log R_{HK} = 0.48; subtracting 5.1 from the values of log R_{HK} in this paper would produce emission levels in approximate agreement with the actual ratio of chromospheric to bolometric luminosity (Noyes et al. 1983).

We have attempted to check Middelkoop’s results using other spectrophotometry (Noyes et al. 1983). Our conclusion is that the relative calibration of the S index versus B−V is probably known within 0.1 dex for stars in the range 0.5 ≤ B−V ≤ 1.0. The situation for B−V > 1.2 is much less certain, based on the disagreement of the spectrophotometry.

We have used Middelkoop’s formula to transform S to R_{HK}. The result, a chromospheric color-magnitude diagram, is illustrated in Figure 2 (cf. Soderblom 1982b). We have separated the stars kinematically into disk stars (solid points) and old disk/halo objects (open circles). We judged a star to be an old disk/halo object if |U−2V| > 30 km s^{-1} or (U^2 + V^2)^{1/2} > 65 km s^{-1}. Other kinematic criteria would not change these assignments significantly.

We have not attempted to correct R_{HK} for metallicity effects. The appropriate correction is unknown; however, our analysis will strongly concentrate on the disk stars, for which differences in metal abundances should be minor (cf. Twarog 1980).

As noted above, Middelkoop’s transformation of S to R_{HK} depends only on B−V so that Figure 2 has the same general appearance as VP’s Figure 1 (S vs. B−V). In particular, the “gap” in chromospheric emission can be seen for stars with 0.5 ≤ B−V ≤ 1.0, the “yellow” stars, but no gap is evident for the “red” stars, B−V > 1.0. For both the yellow and red stars, the R_{HK} values are near the solar level, R_{HK} = 0.48.

![Figure 2](https://example.com/fig2.png)

**Fig. 2**—The chromospheric emission-color diagram for stars within 25 pc of the Sun, based on the data of Vaughan and Preston (1980) combined with Middelkoop’s (1982) flux calibration. R_{HK} is the Ca II H and K surface flux, measured relative to the stellar surface flux σ T_{eff}^4.
stars, the old disk/halo stars have generally smaller chromo-
spheric fluxes than the stars of the disk population, in
accord with a decline of chromospheric emission with age.
However, the separation is much less clear for the red stars.
It is possible that the S indices for the red stars are
confused because the continuum bands in these stars are so
heavily blanketed. Because of these problems, more data are
needed to interpret the Ca II emission of the red stars.
The remainder of this paper will concentrate on analysis of
the yellow stars. For some additional remarks on red stars,
see Soderblom (1982c).

The errors in the S measurement should be only a few
percent. Systematic errors in the calibration should be small
for $B-V < 1.0$, but may be substantially larger for cooler
stars. None of our analysis depends strongly on the dependence
of the calibration as a function of $B-V$.

c) Photospheric Correction

One obvious feature of Figure 2 is a concentration of stars
along the lower edge of the distribution, with an absence of
stars in the lower left-hand corner. Wilson (1963) noted this
apparent lower limit to chromospheric emission among F and
G dwarfs. The lower limit declines with increasing $B-V$,
consistent with the idea that photospheric emission is con-
tributing to the S index.

There has been debate in the literature about the proper
correction to make for photospheric light in the Ca II H and
K lines. Blanco et al. (1974) adopted a parabolic fit to the
H and K wings, and took only the line core emission
above this parabolic fit to represent the radiative losses
in the chromosphere. Linsky and Ayres (1978) showed rather
convincingly that this could not be correct. Radiative
equilibrium atmospheres without a chromospheric tempera-
ture rise produce Ca II line profiles in which the central
intensity approaches zero in the line cores. One would expect
a very dark line core from a pure scattering line (i.e., one
in which no photons are being created locally) at the large optical
depths associated with Ca II in the Sun. The photospheric
correction estimated by Linsky and Ayres for the Ca II K line
in the Sun was about 40% of the total flux between the
two K1 points.

Both Blanco et al. (1974) and Linsky and Ayres (1978)
agree that the flux outside of the K1 and H1 points, in the
line wings, should not be attributed to chromospheric radiative
losses (emission arising from regions exterior to the tempera-
ture minimum). This follows from a simple interpretation of
the line profile in terms of the Eddington-Barbier relation,
in which the profile maps out the temperature structure of the
upper photosphere and the lower chromosphere. The 1.09 Å
bandpass of the HK photometer used by VP transmits a
large amount of radiation exterior to the line core, as defined
by the K1 and H1 points in F–G stars, and this radiation
contributes to the S index. In Figure 1 the transmission of the instrument is schematically superposed upon the quiet
Sun Ca II K profile from White and Livingston (1981).

From these data one can estimate that approximately 50% of
the light contributing to the $S$ index of a star like the Sun
originates exterior to the K1 and H1 line cores.

In order to make quantitative estimates of the amount of
this minimum photospheric correction for main sequence stars
as a function of $B-V$, we have taken high-dispersion Ca II K
spectra of selected stars and multiplied the spectral distribu-
tions by the transmission function provided by Vaughan,
PRESTON, and Wilson (1978) in order to estimate the minimum
fraction of the $S$ index that is photospheric. Spectra of α Com,
59 Vir, and 61 Cyg B were taken from Linsky et al. (1979); an
unpublished spectrum of α Eri taken at high dispersion with
the Kron camera on the 1.5 m Mount Hopkins telescope by
one of us (L. H.) was included; and the quiet Sun spectrum
of White and Livingston (1981) was used to estimate the
photospheric correction at $B-V = 0.66$. For the specific stars,
the observations of Wilson (1978), as calibrated to the
VAUGHAN-PRESTON scale (Vaughan, Preston, and Wilson 1978),
or observations from Vaughan et al. (1981) or Baliunas et al.
(1983) were used to estimate the $S$ index. In the case of 61
Cyg B, which exhibits a large variability of $S$ with time, the
average $S$ for the year of spectroscopic observation was used:
because of the (potentially) large (and unknown) rotational
modulation, $S$ is probably uncertain by $\sim 10\%$, from variability
alone. In any event, the correction is not likely to be
more accurate than $\sim 10\%$ for any star because of ambiguity
in determining the exact locations of the K1 points. The
correction is assumed to be the same for all stars at a given
value of $B-V$. The correction has been transformed by
Middledoop's (1982c) flux calibration for direct application in
the form of Figure 1.

The results of this process are given in Table 1. The slope
of the correction is roughly parallel to the observed bottom
of the Vaughan-Preston diagram for stars in the range
$0.45 \leq B-V \leq 1.0$. Table I also lists a maximum photospheric
correction that was computed by interpolating the H and K
wings into the line core in the manner of Blanco et al.
(1974) for late-type stars, while adopting the Linsky and
Ayres (1978) correction for solar-type stars. These maximum
corrections reproduce the absolute level of the lower boundary
of the distribution shown in Figure 2 quite well. However,
following the discussion by Linsky and Ayres (1978), there
seems to be little justification for adopting such a large
photospheric contribution, suggesting that some chromo-
ospheric emission is present even in the oldest stars in the survey.

III. SIMULATIONS OF THE SOLAR NEIGHBORHOOD SURVEY

Previous investigations have shown that Ca II chromospheric
emission decays with increasing age (Wilson 1963; Skumanich
1972). Thus one expects that stars first appear near the top
of Figure 2, and move downward as they grow older.
VP confirmed this trend by showing that space motions increased with decreasing emission. The deficiency of stars with moderate emission led some authors to consider the possibility
that chromospheric emission decreases rapidly with time at

| $B-V$ | $\log R_{\text{phot}}$ | $\log R_{\text{phot}}(\text{max})$
<table>
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<td>0.66</td>
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<tr>
<td>0.82</td>
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<td>0.25</td>
</tr>
<tr>
<td>1.38</td>
<td>-0.59</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

* On a scale where $\log R_{\text{phot}}(\text{max}) = +0.48$. 

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However, no attempt has been made to assess the statistical significance of the gap. In part, this is due to difficulties involved in separating the many different effects which combine to produce the observed distribution of points in the diagram. For example, it is clear that the impression of the gap is enhanced by the cluster of points near the bottom of the diagram for $B - V \leq 1.0$. Yet in the previous section we showed that the photospheric contribution is of importance for weak emission stars, creating a "floor" for the HK flux. In other words, the chromospheric emission may vary smoothly in its rate of decay and still produce a concentration of points in terms of the "flux" measurement of the HK photometer.

One can perform nonparametric statistical tests to show that stars above and below the gap are drawn from different parent populations. However, this is not physically significant when, for example, the photospheric correction can produce a different "population" that does not represent a change in the intrinsic variation of chromospheric emission. Such tests cannot distinguish between different physical mechanisms which might produce the observed distribution of points. Instead, it is necessary to develop a model for interpreting the Vaughan-Preston survey.

Interpretation of Figure 2, the chromospheric emission (CE)-color diagram, requires an analysis of several contributing factors, including (1) the photospheric correction; (2) emission isochrones; (3) the stellar birthrate as a function of spectral type (i.e., mass) and age in the solar neighborhood; and (4) the age-scale height relationship for dwarf stars in the solar neighborhood.

In addition, there may be sample selection effects due to incompleteness for faint stars, but we hope to minimize these effects by concentrating on stars with $B - V \leq 1.0$. In any event, we are not concerned with the distribution of these properties with spectral type. The analysis may then yield the variation of chromospheric emission with stellar age. The finite number of stars in the sample must be considered in determining the statistical significance of conclusions drawn regarding the time variation of stellar chromospheric activity.

We have not considered the effects of the time variability of chromospheric emission due to rotational modulation and to cyclic or long-term variation (Wilson 1978; Vaughan et al. 1981). These effects may be important in analyzing a survey in which most stars have been observed only twice. A further complication for old stars is the effect of metal abundance on the chromospheric emission and the photospheric blanketing, which together determine the S index.

Since we do not know the four properties listed above very accurately, we cannot interpret the solar neighborhood survey in a detailed manner. But even with these uncertainties, we can draw some important conclusions from the Vaughan-Preston diagram, and we can begin to explore the sensitivity of the results to various parameters; our results indicate what new observations are needed to make further progress.

Our procedure is to make various simple assumptions about the properties (1)-(4) and then generate synthetic (Monte Carlo) CE-color diagrams using a random number generator for the appropriate number of stars in a given bin. The survey contains 210 stars in the range $0.5 \leq B - V \leq 1.0$. We normalized the number of stars in $B - V$ bins of width 0.1 mag to the number observed in the survey. An independently generated random number assigns an age to each star based on the probability distribution resulting from the assumed birthrate function (3) combined with the loss function (4). The age then specifies the intrinsic chromospheric flux from relation (2), and combination with the photospheric flux (1) yields the vertical position of the star in the modeled CE-color diagram.

We initially assumed that the photospheric contribution is given by the lower values in Table 1. Emission isochrones were estimated by assuming that the time-dependent chromospheric emission $R_e(t)$ from stars in this restricted range of $B - V$ can be written as $R_e(t) = g(B - V)h(t)$. We assume henceforth that $g(B - V)$ is constant, i.e., the emission (after subtraction of the photospheric contribution) from stars of a given age is independent of $B - V$ (in the limited range $0.5 \leq B - V \leq 1.0$). This assumption is based on the following two observations:

1. The positions of stars in the Hyades cluster in the CE-color diagram are known from Wilson's (1970) results (Vaughan and Preston 1980). After subtraction of the minimum photospheric component adopted here, the Hyades relation is roughly horizontal.

2. Comparison of widely separated physical pairs with different spectral types is also presented in Figure 3. Although not conclusive, such data suggest comparable chromospheric emission in the range $0.5 \leq B - V \leq 1.0$ for presumably coeval stars.

For our purposes, the long-term behavior of the star formation rate cannot easily be distinguished from the effects of variation in the stellar scale heights as a function of age. We assume smoothly varying functions for both effects, ignoring for the moment the possibility of bursts of star formation.

The stellar birthrate function is poorly known. VP concluded that the stellar birthrate has been nearly constant and may have increased in recent times by no more than a factor of 2. Twarog (1980), on the other hand, concluded that the birthrate (of F dwarfs) may have been higher in the past than at present. He found that the ratio of the mean star formation rate to the present rate is less than 2.5, with the most probable value being in the range 1.0–1.5, for stars formed in the last $1.2 \times 10^{10}$ yr.

We assume a constant star formation rate over the last $1.2 \times 10^{10}$ yr. The upper age cutoff is relatively unimportant, because the scale height distribution of the disk increases rapidly with increasing age (Twarog 1980), and the local space density of stars formed at the earliest times is very small. We have used a scale height distribution derived by Twarog (1980), as listed in Table 2.

We have also neglected the fact that stars with $B - V < 0.6$ probably cannot have ages approaching $10^{10}$ yr. The inclusion or deletion of stars in the range $0.5 \leq B - V \leq 0.6$ makes little difference to our conclusions, considering the uncertainties involved in the detailed form of the emission decay law as a function of spectral type.

a) Skumanich ($t^{-1/2}$) Decay

Having made the above assumptions, we can simulate the CE-color diagram, given a law of chromospheric emission
Fig. 3.—The chromospheric emission-color diagram for the Vaughan-Preston survey, with the positions of widely separated but physically associated pairs of stars linked by straight lines.

decay $R_e(t)$. An obvious initial choice is $R_e \propto t^{-1/2}$, i.e., to adopt the Skumanich (1972) relation. The relation is normalized by requiring the flux to match the Sun at the Sun's age, as shown in Figure 4.

The truncated survey is shown in Figure 5a, and a typical realization using the Skumanich law is shown in Figure 5b. Normalization to the Sun reproduces the bottom boundary of the CE-color diagram well. However, there are young objects in the simulation with emission stronger than that observed (typically, there are about five stars with emission levels that are too large; note that four stars lie completely above the upper boundary of Figure 5b and hence are not shown). This conclusion is unaffected by the choice of scale height correction.

### TABLE 2

<table>
<thead>
<tr>
<th>$t$ ($10^{10}$ yr)</th>
<th>$h$</th>
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<tr>
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</table>

The absence of strong-emission stars in the survey data led us to reexamine the open cluster results. Vaughan (1983) observed some of the solar-type stars in the Pleiades during 1979–1980 with the HK photometer. Although the program is not complete, and the individual stars exhibit large scatter in their emission, the data indicate that the solar-type Pleiades stars have Ca II emission levels that are only slightly above comparable stars in the Hyades. These results are indicated schematically in Figure 4. The Pleiades mean flux level is uncertain, due to the small number of stars observed, and also because rotational modulation may affect the mean flux level determined from a small number of observations for each star. Nevertheless, it is apparent from Figure 4 that the Pleiades, Hyades, and solar data cannot be represented by a $t^{-1/2}$ chromospheric decay law. That is, the Skumanich dependence of Ca II chromospheric emission on stellar age appears to be incorrect for young stars.

Although the reasons for the disagreement with Skumanich (1972) are not entirely clear, one can identify several possible contributing factors. First, Skumanich's emission data for the Pleiades were derived from the photographic spectra of Kraft and Greenstein (1969). These observations were made with relatively low-dispersion ($\sim 90$ Å mm$^{-1}$ and $\sim 200$ Å mm$^{-1}$), so that the results may be less accurate than the photoelectric studies. Second, the low dispersions used precluded the detection of chromospheric emission in F–G stars. As a result,
the comparison of Pleiades and Hyades emission performed by Skumanich (1972) was limited to K dwarfs, and then extrapolated to earlier spectral types (Skumanich and Eddy 1981). This extrapolation may not be appropriate for our simulations, which are restricted to $B - V < 1.0$. Furthermore, there is reason to think that the chromospheric emission of K dwarfs in the Pleiades may be anomalous. A large fraction of the K dwarfs have very large rotational velocities, $\sim 50 - 150 \text{ km s}^{-1}$ (van Leeuwen and Alphenaar 1982; Stauffer

Fig. 4.—Representation of the forms for the Ca II emission decay with age used in the simulations of the chromospheric emission-color diagram. The minimum photospheric contribution at $B - V = 0.66$ has been added. The position of the Sun is indicated, along with mean values for the Hyades and Pleiades clusters. The arrow shows the effect on the position of the Pleiades if the G stars have ages comparable to the contraction times indicated for the M dwarfs in that cluster. The positions of T Tauri stars have been indicated schematically using data from Giampapa et al. (1982) and assuming ages $\sim 10^6 - 10^7 \text{ yr}$ for these objects.

Fig. 5.—(a) The CE-color diagram for the Vaughan-Preston survey, limited to the range $0.5 < B - V < 1.0$. (b) A simulation of the survey using the Skumanich emission decay relation and a uniform birthrate. Note that four stars in the simulation lie above the upper boundary of the figure and so are not plotted. (c) Same as Fig. 5b, but with the assumption that no stars have been formed in the solar neighborhood in the last $2 \times 10^8 \text{ yr}$.
This rapid rotation may tend to make the average Ca II emission of K dwarfs larger than for the G stars. We also note that some members of the Ursa Major group are included in the Vaughan-Preston survey. These stars have chromospheric emission levels only slightly higher than the Hyades mean relation, which is also in conflict with Skumanich's (1972) estimate.

The positions of T Tauri stars are also schematically indicated in Figure 4 from the observations of Giampapa et al. (1982). It is interesting that the T Tauri data do not suggest a clear upper limit to chromospheric emission, but rather indicate increasing emission with decreasing stellar age. However, T Tauri stars are so far from the main sequence that any interpolation between the results of Giampapa et al. and the Hyades is questionable.

Stauffer's (1982) photometry indicates that the Pleiades stars lie on the main sequence down to \( V \sim 17 (M \sim 0.3 \, M_\odot) \). Using the evolutionary calculations of Grossman, Hays, and Graboske (1974), this result indicates a contraction age of \( \sim 3 \times 10^8 \) yr. The discrepancy between the upper main-sequence turnoff age and this contraction age suggests non-coeval star formation in the Pleiades (cf. Herbig 1962). We note that the \( t^{-1/2} \) emission decay can be retained if the G stars in the Pleiades actually have an age \( \sim 2-3 \times 10^8 \) yr. In this case, the simulation requires an absence of stars with ages \( \lesssim 2 \times 10^8 \) yr in order to avoid a significant excess of strong-emission stars.

Figure 5c shows a simulation based on the \( t^{-1/2} \) law, assuming no star formation in the last \( 2 \times 10^8 \) yr. The upper and low boundaries of the chromospheric emission are matched reasonably well by this distribution, and some holes appear in the simulated distribution of points which bear some resemblance to the observations.

It should be emphasized that the calibration of stellar evolutionary tracks for low-mass stars is difficult. The tracks are very dependent upon model atmosphere calculations involving complex opacity sources. The calculations of VandenBerg et al. (1983) show that the displacement in effective temperature between the isochrones for ages of \( 1 \times 10^8 \) yr and \( 5 \times 10^8 \) yr only \( \sim 60 \) K for masses on the order of \( 0.3 \, M_\odot \). It is not clear that the theoretical models are sophisticated enough to calculate isochrones this accurately, even in a differential sense. For this reason we feel that adoption of a much larger age for the Pleiades than the upper main-sequence turnoff age is not well justified at present.

b) Exponential Chromospheric Decay

If the main-sequence turnoff age of the Pleiades is used, the data in Figure 4 suggest that the form \( R_{\text{Hk}} \propto \exp (-at) \) might be a better representation of the data; this would have the effect of limiting the maximum chromospheric emission possible as \( t \to 0 \). A typical simulation using an exponential decay law is shown in Figure 6a. This functional form for the decay of chromospheric emission roughly reproduces the upper boundary of the Vaughan-Preston diagram, although there are a few points in the survey which lie above this simulation. The Pleiades observations indicate that short-term variability, which is probably due to rotational modulation, is \( \sim 10\%-20\% \) of the average emission (Vaughan 1983), and such variability may explain occasional high-emission points.

c) Modified Chromospheric Emission Decay

Although the exponential decay law matches the upper boundary relatively well, it produces emission that is too faint...
to match the observed weak emission limit. This problem cannot be solved by decreasing the numbers of old stars in the solar neighborhood by means of increased scale height corrections, since the simulations would not reproduce the increased concentration of points near the low-emission boundary. One remedy is to suppose that the photospheric flux has been underestimated. For example, we might adopt the maximum photospheric flux levels indicated in Figure 4. Although this photospheric level seems to be too large, based on the arguments of Linsky and Ayres (1978) (cf. § II), the extra emission might be interpreted as a “nonmagnetic” chromospheric component, i.e., chromospheric emission which does not depend upon age. After readjusting the exponential decay law in order to fit the Pleiades, Hyades, and the Sun (Fig. 4), we have computed distributions typified by the example shown in Fig. 6b. Although this method yields reasonable representations of the upper and lower limits of the chromospheric emission, the density of points in the simulation near the lower boundary is much more sharply peaked than in the data. This result suggests that chromospheric emission continues to decay in stars older than the Sun.

Another alternative emission law can be constructed by supposing that the pure exponential decrease of intrinsic chromospheric emission is incorrect. For example, suppose the exponential decay law is correct for ages \( \leq 3 \times 10^9 \) yr, followed by a \( t^{-0.5} \) decay for \( t > 3 \times 10^9 \) yr. When combined with the minimum photospheric correction, the resulting emission law has the form shown in Figure 4. A simulation using this representation of the emission decay is shown in Figure 7. The upper and lower boundaries are represented moderately well, and the distribution of points near the lower emission limit matches the survey data better than the pure exponential decay of emission.

The distribution of points in the CE-color diagram depends upon both the time variation of chromospheric emission and the birthrate of late-type stars in the solar neighborhood. Ideally, one could determine the decay of chromospheric activity from clusters of known age and then apply these results to determine the local star formation rate. Unfortunately, there are no data for old clusters at present on the HK photometer system, so our simulations can only suggest a realistic combination of birth rate and emission decay.

Even with this limitation, we may still address an important question: does the observed distribution of points in the Vaughan-Preston diagram require a “sharp” or discontinuous change in either stellar chromospheric activity at a given age or in the birthrate of late-type stars? Or is it possible to explain the observed “gap” as a statistically insignificant fluctuation of a smooth functional decline of chromospheric emission with age and a slowly varying star formation rate?

For simplicity we shall assume a uniform star formation rate. Differing laws for the decay of chromospheric emission in terms of smoothly varying functions can be tested against the data in an attempt to find a representation which is statistically consistent with the observations. If a particular model can produce “holes” in the simulated distribution that are similar to those seen in the real diagram, we clearly cannot attribute the “gap” to a discontinuity in the chromospheric emission-age relation.

One fit to the data is given by the model shown in Figure 7. The visual impression is that the simulation commonly exhibits holes of sizes comparable to the gap. In order to make this statement more precise, we have binned stars in several ways. First, we adopted a scheme in which each bin in the \( \log R_{\text{HK}} \) versus \( B-V \) diagram runs between 0.5 \( \leq B-V \leq 1.0 \), and the upper and lower boundaries are given by lines of the form \( \log R_{\text{HK}} = \text{constant} - 0.44 \times (B-V) \). Each bin is roughly parallel to the visual impression of the gap, with a height of 0.05 in \( \log R_{\text{HK}} \).

The bins are shown in Figure 8, with the numbering scheme running from the bottom to the top of the survey. The number of stars in each bin is shown in Figure 9. Also shown in Figure 9 is the average distribution of points from 10 simulations, using the same bins.

We first ask whether the overall statistical properties of the diagram are reproduced by the model. For example, suppose bins 5-9 contain the “low-emission” stars, bins 13-16 represent the “high-emission” stars, and bins 10-12 cover the “gap.” The numbers of stars in these three categories in the survey data are 135, 40, and 24, respectively, while the corresponding numbers in the simulations are 135.2, 34.8, and 31.2. A reduced \( \chi^2 \) test applied to these results yields a value of 2.4, so that there is no significant difference between the survey and the simulation on this large scale. This result indicates that the large-scale properties of the Vaughan-Preston “gap” do not require a discontinuous change in chromospheric properties.

On a finer scale, the distributions are statistically separable.
For example, the low-emission distribution of the simulation is offset from the survey. There is little point to adjusting this part of the simulation, however, because there is no isochrone information available for old stars.

If we treat the eight bins 9-17 separately, one calculates $\chi^2 = 27$ using the simulation to test the observations, which indicates a highly significant difference between the two populations. However, if bin 14 is left out, we find $\chi^2 = 9$, which is significant at only the 75% level. This suggests that the data set may contain a significant increase in the density of points at bin 14.

Wilson’s (1970) observations showed that the Hyades stars occupy a locus of points close to the position of the density enhancement observed in the Vaughan-Preston diagram. The Hyades $S$ values, averaged over many observations in order to eliminate the effects of rotational modulation (about 0.07 in log $S$), show a scatter $\sim \pm 0.025$ in log $S$ (or log $R_{\text{HK}}$) from the mean cluster relation as a function of $B-V$. This suggests that we should not look for meaningful structure in logarithmic flux intervals less than about 0.05 when analyzing the survey, in which most stars have been observed only two or three times.

We have tried several other binning schemes, which all give essentially the same result as above. For example, we also used the isochrones assumed in our simulations to form bins, counting the number of stars in the observed survey within given time intervals. Using a uniform birthrate and the Twarog scale height correction, we would expect on the average to observe 27.4 stars with ages from 0 to $1 \times 10^9$ yr, 25.7 stars with ages from 1 to $2 \times 10^9$ yr, and 146 stars with ages greater than $2 \times 10^9$ yr. These age groupings correspond to bins roughly above, in, and below the gap, using the emission model combining the exponential and Skumanich emission decay laws (Fig. 4). The number of stars in the survey observed to lie within the indicated bins are 33, 18, and 148, respectively. A $\chi^2$ test shows that the difference between this model and the survey is not statistically significant.

The observed distribution of points appears to have significant fluctuations on a finer scale, as shown in Table 3. However, most of the deviation of the observations from the model comes from one age bin. As found in the previous binning method, a fluctuation is observed which would correspond to about a factor of 2 increase in the local birthrate of stars on a time scale of $< 5 \times 10^8$ yr. In view of the existence of nearby star clusters such as the Pleiades and the Hyades, it is likely that local star formation is not constant on such time scales.

### Table 3

**Survey Stars Binned by Estimated Age**

<table>
<thead>
<tr>
<th>Age (10^9 yr)</th>
<th>Expected*</th>
<th>Observed</th>
<th>Expected*</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.5</td>
<td>16.5</td>
<td>8</td>
<td>17.0</td>
<td>31</td>
</tr>
<tr>
<td>0.5-1.0</td>
<td>15.7</td>
<td>25</td>
<td>16.2</td>
<td>19</td>
</tr>
<tr>
<td>1.0-1.5</td>
<td>15.2</td>
<td>10</td>
<td>15.6</td>
<td>8</td>
</tr>
<tr>
<td>1.5-2.0</td>
<td>15.0</td>
<td>8</td>
<td>15.4</td>
<td>14</td>
</tr>
<tr>
<td>2.0-2.5</td>
<td>14.3</td>
<td>17</td>
<td>14.8</td>
<td>12</td>
</tr>
<tr>
<td>2.5-3.0</td>
<td>13.7</td>
<td>21</td>
<td>14.2</td>
<td>9</td>
</tr>
<tr>
<td>3.0-3.5</td>
<td>13.2</td>
<td>14</td>
<td>13.6</td>
<td>14</td>
</tr>
<tr>
<td>3.5-4.0</td>
<td>12.7</td>
<td>11</td>
<td>13.1</td>
<td>11</td>
</tr>
<tr>
<td>4.0-4.5</td>
<td>11.8</td>
<td>14</td>
<td>12.1</td>
<td>14</td>
</tr>
</tbody>
</table>

* Slight differences exist between the expected number of stars in the different emission laws, because the total number of stars in the survey observed to lie within the age bins of the two emission law models is slightly different.
We can also use a pure $r^{-1/2}$ emission decay law to bin the survey stars (Fig. 10). As shown in Table 3, the result once again appears to indicate an increase of a factor of 2 in the local birthrate about $5 \times 10^8$ yr ago. By deleting the single bin containing this fluctuation, the Skumanich law with the uniform birthrate can be used to fit the rest of the survey very well.

The stars included in the high-density fluctuation do not exhibit an obvious common proper motion, which might be expected if they originated in a single cluster or group. The truncated survey does include six known members of the Ursa Major group, five of which fall into the first bin in Table 3. The existence of nearby examples of fluctuations in local star formation (e.g., Ursa Major, Hyades) further suggests that nonuniform star formation on short time scales must be considered in any analysis of the Vaughan-Preston diagram.

We cannot rule out the possibility of fine-scale discontinuities or rapid transitions in chromospheric behavior. However, the observed structure corresponds to time scales of order a few times $10^8$ yr, which can be accounted for by variations in the local star formation rate. There is no need to invoke rapid chromospheric evolution, i.e., the gap does not require a discontinuous change in chromospheric emission at a statistically significant level.

**b) Chromospheric Emission Decay**

The distribution of Ca II H and K chromospheric emission in the solar neighborhood is produced by the combined effects of the rate of decay of emission with increasing age and the stellar birthrate. Therefore, it is not possible to determine the decay of chromospheric emission uniquely from the Vaughan-Preston survey. If we make the assumption, however, that star formation has proceeded relatively uniformly over the last several billion years, it is possible to estimate the form of the decay of emission with age. As shown in Figure 4, the emission decay derived in this way departs from the form suggested by Skumanich (1972), in the sense that the Ca II fluxes from very young stars are lower than predicted by the $r^{-1/2}$ relation. It was shown earlier that fragmentary data for Pleiades stars support the decay function used in the simulations.

We can make one further test of the emission decay relation. Skumanich (1972) indicated that the rotational velocities of solar-type stars also decreases as $r^{-1/2}$; more recent observations are in reasonable agreement with this result (Soderblom 1983). Noyes et al. (1983) have derived the relationship between $R_{HK}$ and rotational period for various spectral types on the main sequence, based on measurements of the Ca II rotational modulation (Vaughan et al. 1981; Baliunas et al. 1983). Although this sample includes only field stars, and not cluster members, if we adopt the $r^{-1/2}$ variation for rotational velocity, we can assign ages to field stars. This permits the implied variation of $R_{HK}$ with age to be determined.

We have used the dependence of $R_{HK}$ on rotational period determined by Noyes et al. (1983) for $B-V = 0.66$, combined with the assumption that the Sun is rotating normally for its age of $4.5 \times 10^9$ yr, to produce the emission decay as a function of age shown in Figure 11. The result is encouragingly similar to the emission decay form used in the simulations.

**V. CONCLUSIONS**

Our preliminary investigation of the chromospheric emission properties of stars in the solar neighborhood survey of Vaughan and Preston (1980) has resulted in the following conclusions and inferences.

1. Photospheric emission contributes significantly to the "floor" of Ca II chromospheric emission as measured by the $S$ index.
2. The observed upper limit of chromospheric emission in the chromospheric emission-color diagram is roughly consistent with the existence of an upper limit, or possible saturation, of Ca II fluxes, as indicated by the recent Pleiades observations of Vaughan (1983). The small difference in emission levels between the Pleiades and Hyades F-G stars is inconsistent with the Skumanich (1972) $t^{-1/2}$ relationship, unless the solar-type stars are much older than the age indicated by the upper main-sequence turnoff point.

3. The presence of an upper limit to emission, coupled with a photospheric "floor" to emission measured by the S index for F-G stars, tends to produce an enhanced density of stars in the Vaughan-Preston diagram at very large and at low emission levels. This creates the impression of a "gap" or an underdensity of stars at intermediate emission levels.

4. It is possible to construct a smooth function representing the decay of chromospheric emission with time in agreement with cluster observations which produces the large-scale structure of the "gap" as a statistical fluctuation. The data suggest small-scale fluctuations of the local star formation rate.

Although we have left many questions unresolved, there are a number of observational projects which can yield a better understanding of the nature of chromospheric emission decay as a function of age and of the distribution of points in the Vaughan-Preston diagram. A significant improvement would result from cluster observations defining emission isochrones. Further work on the Pleiades and Hyades clusters is under way at Mount Wilson. Other young clusters should be studied in order to explore possible problems associated with noncoeval star formation. It is important to observe old clusters as well; for example, M67 appears to be within reach of the largest telescopes.

We have neglected the effects of metal abundance on the S index and the calibration. For old stars, low metal abundances may change the intrinsic chromospheric response as well as the blanketing in the continuum bandpasses; studies of these effects should be pursued.

As our knowledge of cluster emission isochrones in the Vaughan-Preston diagram improves, we will have an increasingly powerful tool for determining the ages of late-type dwarfs. This type of information should assist in the determination of stellar velocity dispersion and scale height changes with age, particularly for low-mass stars. The ultimate importance of chromospheric emission surveys such as that of Vaughan and Preston may lie in studies of the time evolution of the formation rates of low-mass stars.

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