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SHORT TIME-SCALE VARIABILITY OF CHROMOSPHERIC Ca II IN LATE-TYPE STARS

S. L. BALIUNAS,[1,2,3] L. HARTMANN,[2,3] A. H. VAUGHAN,[4] W. LILLER,[2,3] AND A. K. DUPREE[2,3]

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ABSTRACT

We have investigated short time-scale variability of singly ionized calcium chromospheric emission in a few late-type stars. Emission-line variations with time scales of a few minutes to hours are seen in α Tau (K5 III), λ And (G8 III–IV), and ε Eri (K2 V). The existence of substantial chromospheric flux changes (10^{30}–10^{32} ergs) over short periods of time suggests that the calcium emission arises from a few small, coherent regions. Frequencies present in the data are discussed in the context of acoustic wave predictions and estimated acoustic cutoff frequencies for giants and dwarfs.

Subject headings: Ca II emission — stars: chromospheres — stars: late-type

I. INTRODUCTION

The emission cores of the Ca II H and K doublet are important optical indicators of chromospheric activity in late-type stars. While a great deal of effort has been directed toward the observation and analysis of time-averaged Ca II emission, relatively little work has been done on stellar chromospheric variability on short time scales. Previous studies have presented evidence for changes in the relative intensities of the violet and red peaks of the emission cores of some cool stars (Wilson and Bappu 1957; Griffin 1963; Liller 1968). Variable emission fluxes have also been observed over periods of hours to months in some late-type giants (Liller; Baliunas and Dupree 1979). The long-term survey of chromospheric activity in nearby dwarfs, which was begun by Wilson to search for solar cycles, indicates some short-period fluctuations superposed on the long-term variation (Wilson 1976; Vaughan, Preston, and Wilson 1978; Wilson 1978). Flares and related activity have been observed on many cool dwarfs, although there are relatively little data on emission-line variation (Kunkel 1973; Schneeberger *et al.* 1979).

Chromospheric variability cannot be understood without precise measurements of the amplitude and time scales of the changing emission. The validity of time-independent, homogeneous chromospheric models may be compromised by the nature of this variability. For these reasons, we have begun a program to obtain Ca II H and K flux measurements from late-type stars over many time scales. In this paper, we report the first results of these line-strength variability measurements for four giants, α Boo, α Tau, α Aur, and λ And, for a dMe flare star, YZ CMi, and for an "active-chromosphere" K-type dwarf, ε Eri. There are two different experiments reported here. First, we present high-resolution spectra of the giants with a time resolution on the order of an hour and extending over several days; second, we examine spectrophotometry with a time resolution on the order of a few minutes of some of the giants and the two dwarfs listed above. The spectra are used to investigate profile variations accompanying substantial (larger than about 10%) flux changes which might occur over several nights. From the spectrophotometry, we search for relative changes in the chromospheric emission strength at a lower level (about 5%) which may occur on short time scales. These two approaches are complementary and necessary. Although the precision and time resolution are better for the spectrophotometry, it is only from the spectra that we can determine the nature of profile variations.

II. DATA

a) Spectra of the Giants

High-resolution (~ 0.2 Å) spectra of all four giants were obtained in the Ca II H and K regions in order to search for flux and profile variations. Spectra were recorded each night, 1978 January 19–22. These spectra were obtained prior to the spectrophotometry obtained in 1978 November which is discussed in § II*b*, below.

The Mount Wilson 100 inch (2.54 m) telescope was used with a two-slit spectrograph and dual-lined (936 × 2)-element Reticon array plus a three-stage image tube at the coudé focus. For the bright stars observed here, neutral density filters were employed to slow the photon-counting rate below that of the onset of coincidence effects. The spectra thus were integrated over 40–60 minute intervals to achieve photon statistics of $\lesssim 1\%$.

The procedure was to observe a star in one slit and sky background in the other slit for half the integration time, and then to reverse the positions of the slits. Flat fields produced by an incandescent lamp were divided into the spectra to remove the fixed pattern in the detector. Sky backgrounds were subtracted and the stellar spectra from each slit were added together.

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[1] Amelia Earhart Fellow, Zonta International.

[2] Guest Investigator, Mount Wilson and Las Campanas Observatories.

[3] Harvard-Smithsonian Center for Astrophysics.

[4] Mount Wilson and Las Campanas Observatories.

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In our Reticon spectra, the photospheric absorption features agree with other high-resolution spectra to within 10% in relative strength. We attribute the difference to scattered light in the spectrograph system and to other causes discussed below. Observed time variations (real or otherwise) of integrated emission-line strengths do not exceed 10%. The relative strengths of the emission cores compared to the surrounding photospheric spectra of α Aur, α Tau, and α Boo are similar to those published by Kelch *et al.* (1978) and by Griffin (1968). Baliunas and Dupree (1979) found, over a comparable period of time, some variations larger than 10% in the integrated flux of the K and H cores of λ And.

The spectra are noisier than would be expected from photon statistics. The additional random errors are likely to arise from: (1) small, incoherent shifts in the position of the fixed-pattern spectrum (occurring over the course of the night, these shifts will modify the flat-field correction derived from incandescent exposures obtained during the day); and (2) an inability to reregister exactly the distorted, image-intensified spectrum onto the linear Reticon detector each night after resetting the grating tilt.

We attribute the lack of observed variability in the spectra, as compared with the variability found by the spectrophotometry below, to the lesser accuracy of the spectra (10% versus 1.5%) and to the much longer integration times (40–60 m versus 2 m). In addition, these results may be indicative of the relative infrequency of substantial chromospheric flux variations in these stars.

b) *Spectrophotometry*

We used the spectrophotometer (HKP2), described by Vaughan, Preston, and Wilson (1978), on the 60 inch (1.5 m) reflector on Mount Wilson to search for short time-scale variations in α Tau, λ And, YZ CMi, and ϵ Eri on 1978 November 4–6. The instrument measures the fluxes in four spectral windows sequentially at a chopping frequency of ∼ 30 Hz: two reference channels, 20 Å wide, located shortward of K (centered ∼ 3900 Å) and longward of H (centered ∼ 4000 Å); and two channels, 1 Å wide, centered on the H and K cores. These narrow passbands encompass most of the emission cores in the program stars. The passbands can be tuned by offsetting the entrance slit to compensate for the Doppler effect. The zero-point wavelength is calibrated by a hollow cathode lamp emitting Ca II H and K. In the case of the spectroscopic binary λ And, offsets appropriate for the times of observation were computed from orbital elements given by Walker (1944).

Sky background and instrumental dark current levels were smaller than 1 count s^{-1} in any channel. For all stars except YZ CMi, photon statistics of $\lesssim 1\%$ were achieved in 2 minutes or less in the channel with the faintest signal. For YZ CMi, λ And, and ϵ Eri, sky background counts were measured and subtracted from the stellar signal.

The data were used to construct several quantities for each observation, and the results are shown in Figures 1–3. We define a color index,

$$C = 2.5 \log (N_R/N_V) = -C_{RV} , \qquad (1)$$

where N_R and N_V are the total count rates (exclusive of the sky brightness) in the monitor channels longward of H and shortward of K, respectively. The color index C_{RV} is defined by equation (4) of Vaughan, Preston, and Wilson (1978). Also calculated were the instrumental magnitudes of the ratios of photon counts in the emission cores to photon counts of the monitor channels interpolated to the wavelength of the emission cores:

$$\mathrm{mag}\,(r_{\mathrm{K}}) = -2.5 \log \times \left\{ N_{\mathrm{K}} \Big/ \left[N_V + \left(\frac{\lambda_{\mathrm{K}} - \lambda_V}{\lambda_R - \lambda_V} \right) (N_R - N_V) \right] \right\} , \qquad (2)$$

$$\mathrm{mag}\,(r_{\mathrm{H}}) = -2.5 \log \times \left\{ N_{\mathrm{H}} \Big/ \left[N_V + \left(\frac{\lambda_{\mathrm{H}} - \lambda_V}{\lambda_R - \lambda_V} \right) (N_R - N_V) \right] \right\} , \qquad (3)$$

where N_{K} and N_{H} denote the count rates (corrected for background, if necessary) in the K and H channels, and λ's refer to the central wavelengths of each of the passbands.

The relation between the values of $r_{\mathrm{K}}/r_{\mathrm{H}}$ and the optical thickness of the emitting gas is not simple. These instrumental values contain a scale factor to account for wavelength-dependent instrumental sensitivity, atmospheric extinction, and differing amounts of line blanketing in different stars, and they also contain a photospheric contribution. In addition, calculations suggest that the H and K cores are optically thick, so that the ratio of K to H should vary with changing temperature gradients, thermalization depths, and other radiative transfer effects.

Differential atmospheric extinction causes a reddening of *C* with increasing air mass, as can be seen in Figures 1–3. For all the stars, this effect appears to be small, approximately 0.015 mag per unit air mass; no correction has been applied to our data. The recurrence of similar values of *C*, both throughout each night and between nights, indicates that systematic errors are small in this quantity. The effect of differential extinction is less pronounced in the line ratios r_{K} and r_{H}.

In the following discussion, we have assumed that the photosphere is constant while any variations in r_{K} and r_{H} are attributable to changes in the emission lines, either in integrated flux or radial velocity of the core with respect to the instrumental passband. Instrumental drifts in the zero-point wavelength can cause changes in the recorded flux at H and K. Although the radial velocity offset can be made to a precision of about 1 km s^{-1}, drifts of 3–6 km s^{-1} in the zero point caused by temperature changes in the equipment can occur in the course of some nights. We have determined, by scanning the emission profiles of λ And and α Tau, that a 10% decrease in flux requires about a 10 km s^{-1} shift of the profile. Wavelength errors due to possible temperature fluctuations are too small to affect the measured H and K fluxes by more than a few percent. Furthermore, drifts of the passbands of the emission cores that cause decreases in the measured signal at H and K are expected to occur only in one direction along the spectrum. Thus, flux decreases followed by brightenings are probably not due to instrumental drifts.

We have ruled out stellar radial velocity shifts as the cause of the observed variations. The emission cores of H and K in λ And, as recorded in the spectra of Baliunas and Dupree (1979), do not show the large velocity differences relative to the nearby photospheric absorption lines that would be required. For the dwarf ϵ Eri, the requisite velocities would be significantly larger because of the narrower widths of the Ca emission lines.

The assumption that the continuum remains constant and that changes occur in the emission lines may be a poor approximation in the case of the flare star YZ CMi. In this case, further analysis must be made to distinguish between line and continuum variability.

III. RESULTS

The HKP2 photometer is used routinely in another program in which the measurements, reduced as described by Vaughan, Preston, and Wilson (1978), are typically found to be reproducible on the 1–2% level. For the observations of 1978 November, a rigorous procedure of observing standard stars at frequent intervals was followed, as a check of the instrumental stability.

The results for the standard stars are summarized in Table 1. The standard stars chosen show small Ca II H and K emission reversals and little variation in the long-term observing programs of Wilson (1978) and Vaughan, Preston, and Wilson (1978). Our data for HD 207978 and HD 13421 indicate flux changes at a level of about 1.5 times the photon-statistical errors in all three instrumental quantities. The star HD 76572 appears to vary by a larger amount in r_K. Furthermore, Wilson's (1978) observations show differences in the amount of scatter in various standards stars. It is difficult to avoid the inference that the standards themselves are slightly variable in H and K at the 1–2% level. Hence, the inherent accuracy of the measurements themselves is probably somewhat better than this.

The star HD 142373, also a standard in the Wilson (1978) and Vaughan, Preston, and Wilson (1978) programs, was monitored for 30 minutes on 1979 May 8. The standard deviations of any point from the mean values of C, mag (r_K) and mag (r_H) and 0.009 mag, 0.013 mag, and 0.015 mag, respectively. These errors are comparable to those determined by sampling standard stars throughout the nights in 1978 November and those of the long-term monitoring programs of Vaughan, Preston, and Wilson. We therefore adopt a conservative mean standard deviation of 1.5% in r_K and r_H, based on the average behavior of the standard stars. These small variations in the line cores of the standard stars, coupled with the recurrence of the

TABLE 1

STANDARD STAR DATA FOR MOUNT WILSON 1978 NOVEMBER

Date	mag r_K	mag r_H	C
	HD 207978		
4 Nov.	3.038	2.981	0.086
	3.054	2.979	0.079
5 Nov.	3.067	2.981	0.082
	3.063	2.995	0.074
6 Nov.	3.045	2.977	0.085
	3.028	2.979	0.079
	mag (r_K) = 3.049 ± 0.015	mag (r_H) = 2.98 ± 0.007	(C) = 0.081 ± 0.004
	HD 13421		
4 Nov.	3.203	3.186	0.008
	3.214	3.174	0.004
5 Nov.	3.193	3.193	0.013
	3.182	3.175	0.009
6 Nov.	3.202	3.190	−0.011
	3.199	3.176	−0.010
	mag (r_K) = 3.199 ± 0.011	mag (r_H) = 3.182 ± 0.008	(C) = 0.002 ± 0.010
	HD 76572		
4 Nov.	3.020	3.011	0.050
5 Nov.	3.029	3.057	0.058
	3.054	3.025	0.065
	3.066	3.029	0.058
6 Nov.	3.086	3.035	0.052
	3.088	3.022	0.060
	3.064	3.000	0.059
	mag (r_K) = 3.058 ± 0.026	mag (r_H) = 3.016 ± 0.018	(C) = 0.057 ± 0.005

Mean Error Determined from all Three Stars

$\sigma(r_K) = 0.017$ mag $\sigma(r_H) = 0.011$ mag $\sigma(C) = 0.006$ mag

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TABLE 2

Ca II H AND K CHROMOSPHERIC LOSSES

Star	Spectral Type	Estimated Surface Loss in (H + K)[a] (ergs s^{-1} cm^{-2})	Luminosity in (H + K) Fluctuation (ergs s^{-1})	Total Energy in Fluctuation (ergs)
ε Eri[a]	K2 V	2×10^6	1×10^{29}	2×10^{30}
λ And[a]	G8 III–IV	8×10^5	1×10^{30}	7×10^{31}
α Tau[a]	K5 III	6×10^4	4×10^{30}	2×10^{32}
Solar Flare A[b]	...	...	2.3×10^{25} (H + K) 5.4×10^{26} (Total)	...
Solar Flare B[c]	...	...	$\sim 10^{27}$ (H + K) $\sim$few $\times 10^{28}$ (Total)	...

[a] See text for each estimate. References for absolute fluxes are: ε Eri, Kelch 1978; λ And, Baliunas 1980; α Tau, Kelch *et al.* 1978.

[b] 1973 Sept. 5 (Canfield *et al.* 1980). Observed, see text.

[c] 1972 Aug. 4 (Tanaka and Zirin 1973). Estimated, see text.

values of C to 1–2% throughout the observations of our program stars, is indicative of the stability of our system.

We discuss in the following the observations for the program stars. In addition, we also estimate the energy present in some of the rapid flux variations in ε Eri, α Tau, and λ And. These estimates are listed in Table 2 and discussed further in § IV.

a) *ε Eridanus* (*K2 V*)

The active chromosphere star ε Eri is a single star showing bright Ca II emission. Changes of 10% in time scales less than a month are apparent in the H and K fluxes in Wilson's (1978) survey. Our data for 1978 November 4, 5, and 6 (Fig. 1) show correlated fluctuations of up to 7% in both r_K and r_H, over characteristic time scales of 15 minutes. The mean of r_K and r_H is brighter on November 5 than November 4 by 5%. These changes are much greater than those recorded in C at similar air masses or in the values of r_K and r_H in the standard stars. The magnitude of the observed variation is of the same order as those typically seen by Wilson (1978). In the Wilson data, the observed scatter may be due to much shorter time-scale variations than can be resolved in his program.

From Kelch (1978) we estimate the average losses in H and K for ε Eri to be $\sim 1 \times 10^{29}$ ergs s^{-1}. A 5% variation into 2π steradians in 15 minutes results in a change in chromospheric energy losses of $\sim 2 \times 10^{30}$ ergs. This change is similar to the total energy in an average flare in the U-passband of the dMe flare star AD Leo

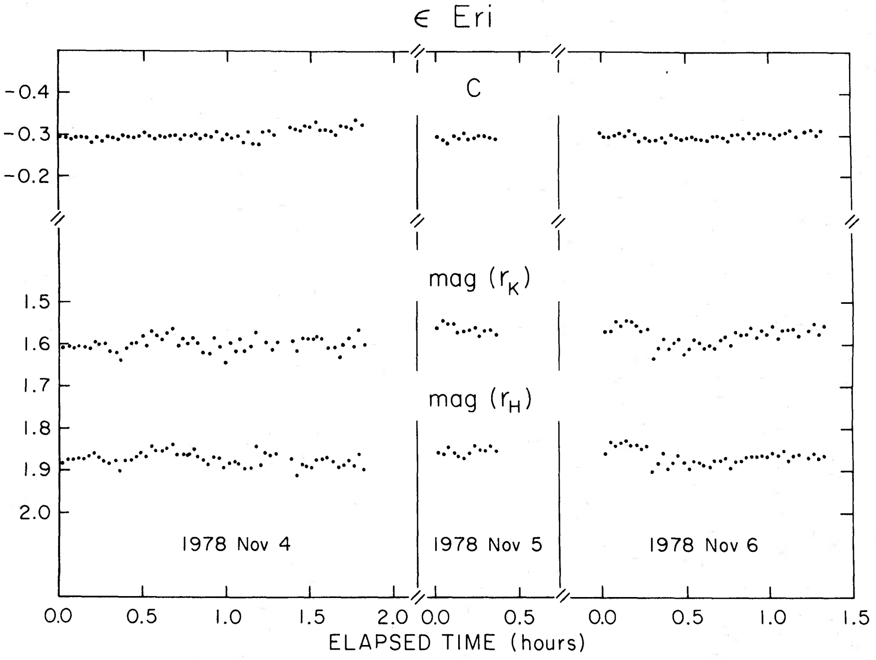

FIG. 1.—Observations of ε Eri for 1978 November 4, 5, and 6. Note variations in mag (r_K) and mag (r_H) and the relative stability of C.

($\sim$ 2–3 × 10^{30} ergs; Lacy 1976). Our results argue that the *contrast* of photospheric flux for different effective temperatures is very important in determining the impression of flare activity and can cause misleading assessments of the level of chromospheric flare activity in stars of an earlier spectral type.

b) α *Taurus* (*K5 III*)

Changes of the asymmetric Ca II K profile of α Tau have been reported previously (Kelch *et al.* 1978). The K core shows a strong red emission peak, while a relatively narrow absorption component, perhaps caused by circumstellar material, appears to suppress the blue emission peak (Vaughan and Skumanich 1970). The circumstellar absorption is variable on time scales as short as a few days (Kelch *et al.* 1978). Previous photometric work of Liller (1968) has shown not only a 19% change in the intensity of the violet emission peak of K within 17 minutes, but also nights when this feature remained constant to 4%. Figure 2 shows our data for 1978 November 5 and 6. Excluding long-term drifts produced by differential extinction in *C*, changes in *C* were $\lesssim 0.02$ mag. For α Tau on November 5, the maximum excursion of the points in r_K is $\sim$ 10% and $\sim$ 5% in r_H, indicating variability in this range. On November 6 the scatter in r_K is 4–5%, while r_H does not vary significantly, except possibly near elapsed time 0.83 hours. However, the average level has increased by $\sim$3%

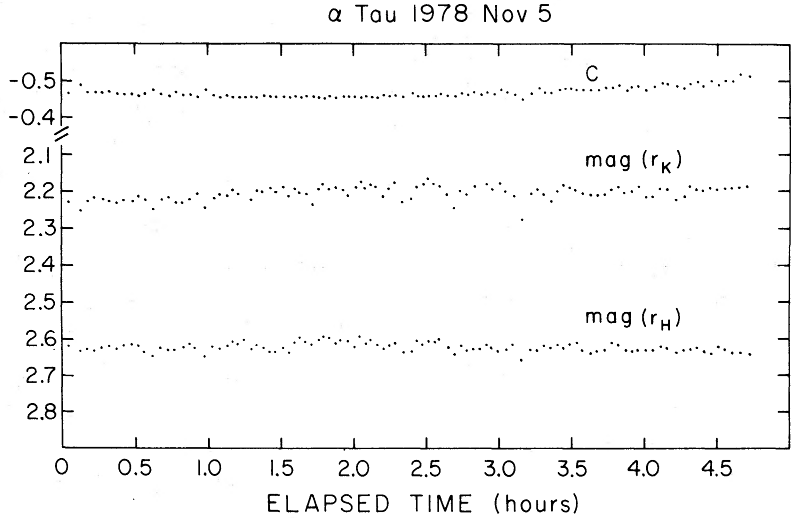

FIG. 2*a*

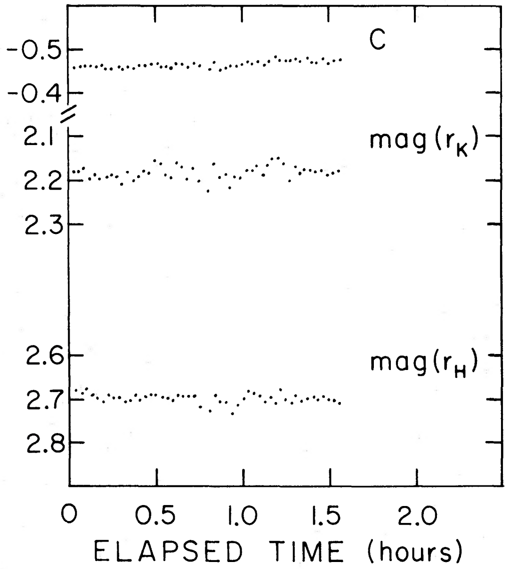

FIG. 2*b*

FIG. 2.—Observations of α Tau for (*a*) 1978 November 5 and (*b*) November 6. The quantity *C* remained smooth, but mag (r_K) and mag (r_H) vary erratically, by up to 0.10 mag and 0.07 mag. Some fluctuations occur within a few minutes, a time scale which is similar to solar active-region and flare phenomena.

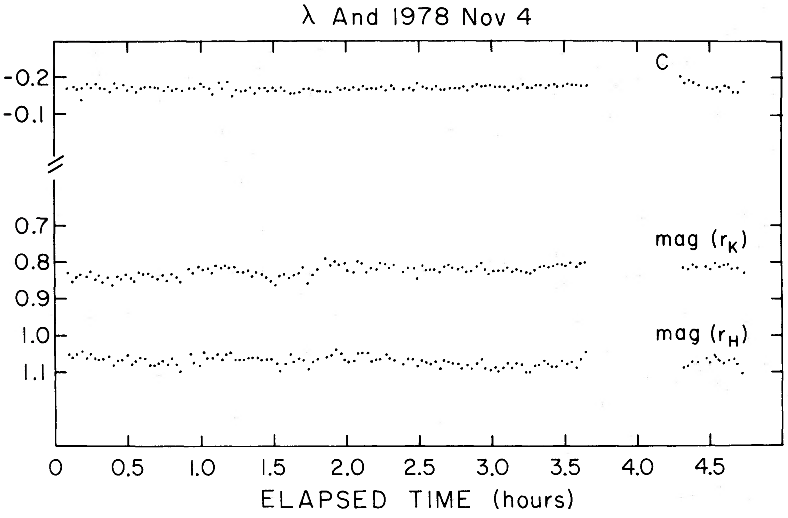

FIG. 3*a*

FIG. 3.—The instrumental magnitudes of λ And on (*a*) 1978 November 4, (*b*) November 5, and (*c*) November 6 show fluctuations in r_K and r_H of 0.10 mag on time scales as short as 10 minutes. Instantaneous variations in C are $\lesssim 0.02$ mag.

in r_K and decreased by $\sim 7\%$ in r_H from November 5 to 6. The change in r_H is clearly significant compared with the 1–2% agreement in C measured at similar air masses for the two nights.

On the assumption that chromospheric emission variations (rather than circumstellar absorption changes) are responsible for the observed flux variations on these short time scales, we have used the flux calibration for chromospheric models (Kelch *et al.* 1978) to estimate the flux in the K core of α Tau. The change in energy in an "event" at about 2.5 hours elapsed time on November 5, encompassing an 8% change over 12 minutes, is 2×10^{32} ergs in both H and K. The amount of energy involved is about two orders of magnitude larger than that seen in ε Eri; the change in *surface* flux is $\sim 10^{-1}$ of that in ε Eri.

c) λ *Andromeda* (*G8 III-IV*)

This member of the long-period RS CVn group is a spectroscopic binary with a period of ~ 20 days and an unseen companion (Hall 1976). The star λ And is a source of soft X-ray emission (Walter *et al.* 1980) and a source of variable continuum radio emissions (Bath and Wallerstein 1976; Spangler, Owen, and Hulse 1977). The intense Ca cores vary in shape and integrated flux. The largest rate of variability that has been reported is a 40% increase in the flux of the K core in spectra separated by one day (Baliunas and Dupree 1979). The system λ And shows cyclic, broad-band V-magnitude variations of ~ 20–30% with periods of 50–60 days (Landis *et al.* 1978). This light variation is attributed to the rotational modulation of a lower-luminosity hemisphere exhibiting starspots (Hall 1976). These long-period fluctuations in integrated light, however, will not contribute to the short-term variations seen here.

In Figure 3, the data from 1978 November 4, 5, and 6 show fluctuations of up to 0.10 mag in r_K and r_H on time scales of a few minutes. On November 6, λ And shows correlated variations in r_K and r_H. On the same night, α Tau shows a fairly flat r_H, thus arguing against persistent instrumental fluctuations as the cause of these changes. After about 4 hours of elapsed time on November 6, activity in r_K and r_H diminishes considerably in λ And.

The flux in the K core is determined from the absolute spectrophotometry of Baliunas (1980). Using parameters of the primary star in the λ And system listed in Baliunas and Dupree (1979), we find that the energy in an event on 1978 November 6 (a 10% change in 10 minutes) is $\sim 7 \times 10^{31}$ ergs, summed in H and K. This variation is larger by a factor of 30–40 in luminosity than that for ε Eri; surface flux changes are comparable.

d) *YZ Canis Minor* (*dM4.5e*)

YZ CMi is a flare star with a flaring rate of about 1.2 per hour (Moffett 1974). Since the star is faint, there is greater scatter in the data. In addition, because of the strength of the emission lines, the photon statistical errors are due almost entirely to the continuum fluxes.

YZ CMi shows no variability larger than that expected from photon statistical counting rates for the continuum channels, ~ 0.1 mag in r_H and r_K during 2.5 hours on 1978 January 4 and 1.5 hours on 1978 January 6.

Unfortunately, the analysis for this star is complicated by the possibility of continuum and line-emission flares occurring on similar time scales and by approximately compensating in r_H and r_K. With the HKP2 instrument, we cannot obtain spectrophotometric data that would enable us to investigate variations appearing in the individual passbands. Further observations of flare stars should be pursued with similar time resolutions and with apertures that permit such photometry.

IV. DISCUSSION

The physical significance of the chromospheric variability observed here can be investigated by estimating the

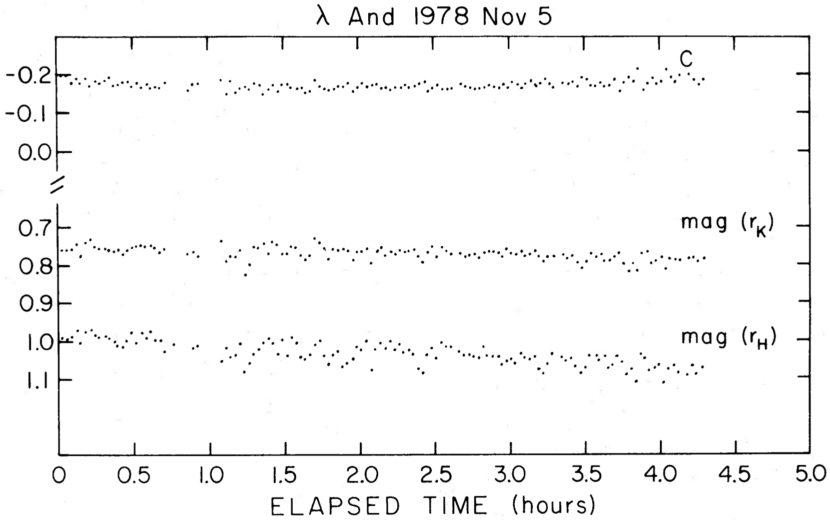

FIG. 3*b*

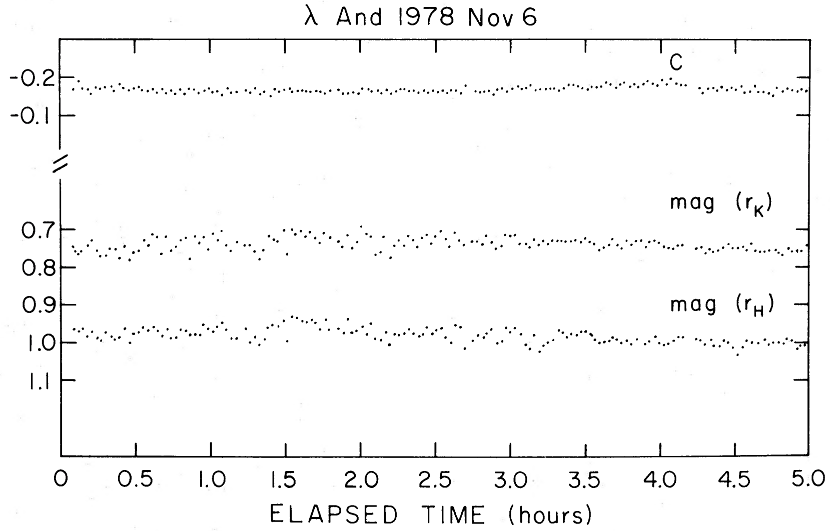

FIG. 3*c*

amounts of energy involved, the sizes of the emitting regions implied by the variation time scales, and by searching for any periodicities in the data.

a) *Energies and Time Scales of the Variations of the* Ca II *Emission*

In assessing the energy present in the Ca II H and K line fluxes, we point out that significant chromospheric emission is undoubtedly present in other lines (for example, the Ca II infrared triplet, Mg II, Lyα) which were not observed here. Since much of the variability we see occurs on time scales of a few minutes, and detector systems for the ultraviolet lines do not yet have this temporal-resolution capability, it is difficult to tally the total changes in the chromospheric losses implied by these observations. The losses we determine from Ca II H and K (see § III and Table 2) should thus be lower bound to the total chromospheric losses. Further work incorporating simultaneous measurements of several chromospheric lines is necessary to find the total amounts of energy involved in these events.

For a comparison of the Ca II H and K brightenings to solar flare energetics, we have included in Table 2 the radiative output in two solar flares of differing strengths. The radiative losses in the spectral range 1 Å to 1 m have been measured for the flare of 1973 September 5 (Canfield *et al.* 1980). The radiative losses at Ca II H and K represent 4% of the total measured power, 5.4×10^{26} ergs s^{-1}. From the power observed at Hα in the exceptionally large flare of 1972 August 4 (Tanaka and Zirin 1973), we have estimated both the total losses and those at Ca II H and K from the fractional contributions of spectral features measured by Canfield *et al.* The total radiative energy output of this bright flare is estimated to be approximately a few times 10^{28} ergs s^{-1}. The power present in the brightenings observed at Ca II H and K in ϵ Eri, λ And, and α Tau is several orders of magnitude larger than the *total* radiative output of typical solar flares.

The time scales of a few minutes of some of the fluctuations indicate that much of the variability derives from an organized region on each of the stars. Adopting sound speeds of 10–20 km s^{-1}, appropriate for the region of the formation of the Ca II emission cores, and using observed time scales of the fluctuations, we arrive at sizes that are a few percent of a stellar radius for the dwarfs and a few times 10^{-4} of a stellar radius for the giants. The derived sizes could be increased by using a larger velocity, for example, an Alfvén velocity. In this case, in order to increase the signal velocity appreciably, the magnetic field strength would have to be much larger than $\sim 10^2$ gauss, which is the equipartition strength inferred from the chromospheric gas pressure.

The time scales for variability are similar to a variety of solar flare and active-region phenomena recorded in the extreme ultraviolet, at Hα and at Ca II K (Zirin 1974; Svestka 1976). Some of the observed events show sharp rises followed by slow declines, reminiscent of solar and stellar flare phenomena. Often, however, variations are seen with behavior opposite that of flare activity and with no direct counterpart to solar activity. The quiescent level can be persistently bright, and sharp declines in the data followed by slow recoveries are present.

The stars we observed show strong Ca II K emission, between 3 and 5 on the Wilson and Bappu (1957) scale of 0 (Ca II K emission reversal absent) and up to 5 (emission as bright as the surrounding continuum). The large range of variability in our program stars is consistent with Wilson's (1978) observation that dwarf stars with the strongest Ca emission cores exhibit the most variability.

Variations are observed in both K and H, although K generally varies to a greater extent than H. Since the opacity of K is larger than that of H, K is formed higher in the atmospheres, indicating that larger variations occur higher in the atmospheres. This effect is also seen in model calculations of two different intensity components of the quiet Sun, which show that K brightens more than H (Vernazza, Avrett, and Loeser 1981).

b) *Frequency Analysis*

The data which shows variability in the Ca II fluxes were analyzed for frequency components. The periodicities that are apparent are discussed below for each star. For the period analysis, we used Fast Fourier Transforms (FFT) to obtain the power spectra. A description of this method in application to solar chromospheric featues is given by White and Athay (1979).

We have imposed the requirements of FFT analysis on the data samples. Since the flux measurements were not obtained at quite equally spaced time intervals, the data have been rebinned using linear interpolation. The rebinning intervals are less than 3 minutes for all data, and the average integration times per point are listed in Table 2. If breaks appear in the data (for example, λ And, November 4), only the longest data train is analyzed. The data window is contained within 2^N points, where N is an integer, and the remaining points outside the data window are zero. The mean of the data is subtracted from each point and the 10 edge points on each side of the data window have been multiplied by the ascending or descending branch of a cosine bell function. This procedure lessens the effect of the abrupt onset and end of the observing interval.

The quantities C, mag (r_K), and mag (r_H) have been analyzed with FFT. Peaks in the power spectra of mag (r_K) are identified if they are strong and the corresponding power peaks in C are negligible. We do not show power spectra of mag (r_H). The power spectra of r_H show peaks at frequencies similar to those in r_K, although the peaks for r_H are weaker than for r_K. Generally, r_H can fall below the experimental limits of detectability. Changes in r_H and r_K, however, are strongly correlated in our observations, as evidenced both in the linear correlation coefficient calculated between r_H and r_K and in the Figures 1–3. For example, for λ And on 1978 November 5 the correlation coefficient is 0.78; the standard error in the measurement of 0.1 indicates a highly significant correlation. In contrast, C is not significantly correlated with r_K or r_H. Since the uncertainties in C and mag (r_K) are similar, the spectrum analysis of C compared to r_K suggests that we have not identified instrumental fluctuations in r_K. The periods corresponding to the strong peaks in the power spectra of C and mag (r_K) for λ And and α Tau are shown in Figure 4, and power spectra for all stars are discussed further below.

Peaks can also occur near the frequency corresponding to the data window if, for example, the trend of the data has an overall curvature. To determine the effect of these onset frequencies upon the higher-frequency components, cosine functions with periods corresponding to the data windows are subtracted from the data. The resulting power spectra show greatly reduced low-frequency components but essentially unchanged power in the identified peaks. In the power spectra shown in Figure 4, however, no cosines are subtracted, and the low-frequency spikes remain.

The presence of significant power at specific frequencies in stellar data which are disk-averaged suggests that a small number of coherent emitting regions dominate the chromospheric emission. In the case of the Sun, observations of solar active regions reveal oscillations in the Ca II and Mg II cores with maxima in the power spectra occurring near periods of ~ 200 s (Jensen and Orral 1963; Orrall 1966; Bonnet *et al.* 1978). The solar observations monitor velocity shifts of the features in the profiles, over a fraction of the solar disk, while our observations are flux measurements of disk-integrated emission. It is thus difficult to make comparisons between the solar and stellar data. However, it is plausible that velocity shifts will affect the solar emission strengths. For example, Bonnet *et al.* parametrized the Mg II line profiles in a manner which suggests that the emission flux is modulated with the period of oscillation, but the strong correlation with other parameters makes this difficult to assess (cf. their Fig. 14). Furthermore, studies of the chromospheric Si II (λ 1817) lines show fluctuations both

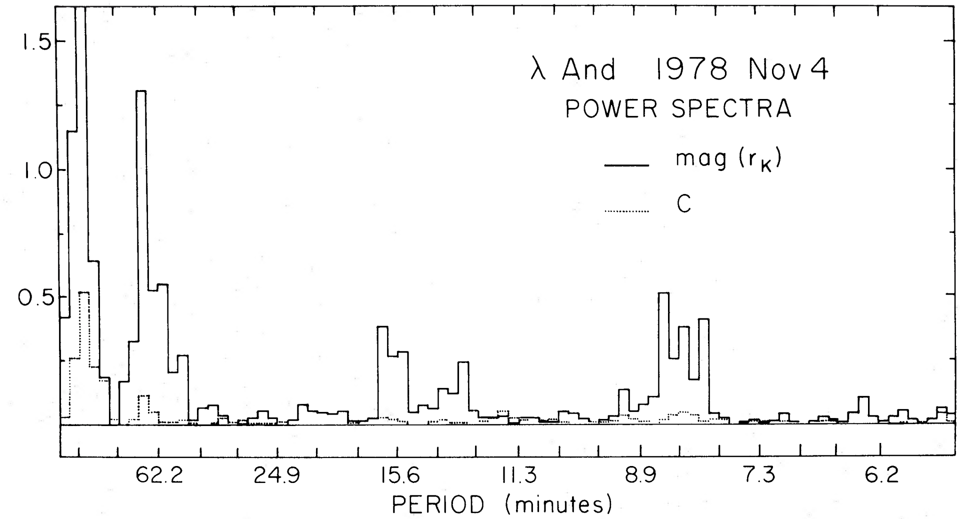

FIG. 4*a*

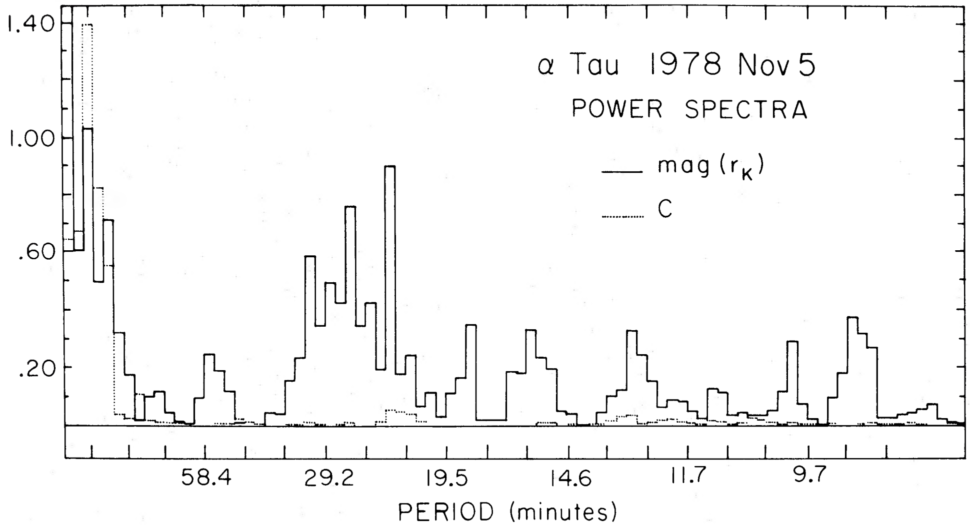

FIG. 4*b*

FIG. 4.—Power spectra of *C* and mag (r_K) for (*a*) λ And and (*b*) α Tau on 1978 November 5. Frequency components are listed in Table 3. The ordinates for the plots are in units of square magnitudes.

of the intensity at a given wavelength in the line (Chipman *et al.* 1976; White and Athay 1979) and of the integrated line intensity (Athay and White 1979). The peak periods are near 200 s, and this period increases slightly from the quiet Sun to active regions. Active regions show a 300 s oscillation in velocity and intensity in the chromospheric C II (λ 1336) emission line (Chipman 1977).

If the ~ 200 s period results from the establishment of standing waves, which in turn depends upon the atmospheric scale height, then we would expect oscillatory periods in other stars to scale approximately inversely with gravity. Ando (1976) has performed a linear analysis of the stability of acoustic waves in late-type model atmospheres. The results of those calculations show that the wave periods for which exponential growth is most rapid in giants is in good agreement with the periods obtained by scaling the solar chromospheric period inversely with gravity.

Other acoustic wave periods may also be present. Although the dominant solar chromospheric oscillation is ~ 200 s, shorter periods are possibly indicated by the broad width of the peaks in the power spectra (White and Athay 1979) and by short-period photospheric oscillations which are observed (Deubner 1976). The heating of the solar chromosphere may be due to waves with periods about an order of magnitude smaller than the ~ 200 s period (Ulmschneider and Kalkofen 1978, Stein and Leibacher 1974). The acoustic flux calculations of Renzini *et al.* (1978) show that this period of maximum acoustic flux generation, $P_{\max}$, also scales inversely with gravity. In Table 3 we list the values of $P_{\max}$ obtained for the stars observed here from the analysis of Renzini *et al.* The

TABLE 3

STRONG FREQUENCY COMPONENTS IN mag (r_K)

Star	log g (cm s^{-2})	$P_{\max}$	Date	FFT Frequency Components (periods in minutes)	Duration of Observing Interval Used in FFT Analysis (hours)	Average Sampling Time during Observations (minutes)
λ And	3.0[a]	10 min.	1978 Nov. 4	8, 15, 65	3.6	1.9
			1978 Nov. 5	15	3.0	1.9
			1978 Nov. 6	10, 30	5.6	1.9
ϵ Eri	4.5[b]	20 s	1978 Nov. 4	6–8	1.6	1.9
α Tau	1.4[c]	7 hr	1978 Nov. 5	25–30	4.6	2.7

[a] Baliunas 1980.

[b] Kelch 1978.

[c] Kelch *et al.* 1978.

values of P_0, the standing-wave or maximum exponential growth period, are approximately 10 times longer than the values of $P_{\max}$. Our sensitivity to detecting either of these periods depends upon where P_0 and $P_{\max}$ occur for a given star relative to the observing span and the integration times.

i) λ *Andromeda*

Figure 4*a* shows the power spectra for both C and mag (r_K) on 1978 November 4. We have identified frequency components at periods of ~ 8, 15, and 65 minutes. The power spectra of C do not show strong peaks at these frequencies, which suggests that the peaks in the spectrum of mag (r_K) are significant. From the power spectra of the remaining data, we list the frequencies for λ And in Table 3. In general, the peaks are several percent of the periods in width, and the frequency components in these limited strings of data appear to change at least nightly, suggesting some impulsive activity is present. All the observed periods are smaller than $P_0 \sim 100$ minutes, although the 65-minute peak is not far from P_0. The periods near 10 minutes are similar to that estimated from $P_{\max}$. The possible effects of aliasing and overtones in the data are difficult to treat; the 15-minute and 8-minute periods are suspected to be related to the 65-minute period in this way.

ii) α *Taurus*

The power spectrum for 1978 November 5 (Figure 4*b*) shows a strong, broad peak between 25 and 30 minutes in mag (r_K), along with smaller peaks at higher frequencies. The low gravity of α Tau results in much longer values of $P_{\max}$ (~ 7 hours) and P_0 than the observed periods. However, we are severely limited in detecting P_0 and $P_{\max}$ by the comparatively short span of observing time.

iii) ϵ *Eridanus*

A strong, broad peak at periods of 6–8 minutes appears in the power spectrum of mag (r_K) in the dwarf star ϵ Eri on 1978 November 5. These periods are similar to those seen in solar oscillations.

V. CONCLUSIONS

The data presented here show that a wide range of late-type stars possesses considerable short-term chromospheric activity. The amounts of energy involved suggest that much of the behavior is related to flaring activity and that large portions of the chromospheric emission come from coherent active regions. In addition, short timescale fadings which are distinctly dissimilar to flare behavior are observed.

The fact that definite frequency components appear in the power spectra of chromospheric variations suggests that observations of short-term Ca II variations may be valuable in probing the chromospheric structure of stars throughout the H-R diagram. Analysis of the short-period Ca II variability in many kinds of stars, including stars with varying levels of activity, may play an important role in extending the application of solar physics to the behavior of other stellar chromospheres.

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REFERENCES

Ando, H. 1976, *Pub. Astr. Soc. Japan*, **28**, 517.
Athay, R. G., and White, O. R. 1979, *Ap. J. Suppl.*, **39**, 333.
Baliunas, S. L. 1980, Ph.D. thesis, Harvard University.
Baliunas, S. L., and Dupree, A. K. 1979, *Ap. J.*, **227**, 870.
Bath, G. T., and Wallerstein, G. 1976, *Pub. A.S.P.*, **88**, 759.
Bonnet, R. M., *et al.* 1978, *Ap. J.*, **221**, 1032.
Canfield, R. C., Cheng, C.-C., Dere, K. P., Dulk, G. A., McLean, D. J., Robinson, R. D., Jr., Schmahl, E. J., and Schoolman, S. A. 1980, in *Proceedings of the Skylab Solar Workshop II*, ed. P. A. Sturrock (Boulder: Colorado Associated University Press).
Chipman, E. G. 1977, *Solar Phys.*, **55**, 277.

Chipman, E. G., Bruner, E. C., Jr., Shine, R. A., Lites, B. W., Rottmann, G. J., Athay, R. G., and White, O. R. 1976, *Ap. J.* (*Letters*), **210**, L103.

Deubner, F. 1976, in *IAU Colloquium 36, Energy Balance and Hydrodynamics of the Solar Chromosphere and Corona*, ed. R. M. Bonnet and P. Delache (Clermont-Ferrand: G. de Bussac), p. 45.

Griffin, R. F. 1963, *Observatory*, **83**, 255.

———. 1968, *A Photometric Atlas of the Spectrum of Arcturus* (Cambridge: Cambridge Philosophical Society).

Hall, D. S. 1976, in *IAU Colloquium 29, Multiple Periodic Variable Stars*, ed. W. S. Fitch (Dordrecht: Reidel), p. 287.

Jensen, E., and Orrall, F. Q. 1963, *Ap. J.*, **138**, 252.

Kelch, W. L. 1978, *Ap. J.*, **222**, 931.

Kelch, W. L., Linsky, J. L., Basri, G. S., Chiu, H.-Y., Chang, S.-H., Maran, S. P., and Furenlid, I. 1978, *Ap. J.*, **200**, 962.

Kunkel, W. E. 1973, *Ap. J. Suppl.*, **25**, 1.

Lacy, C. 1976, *Ap. J. Suppl.*, **30**, 85.

Landis, H. J., Lovell, L. P., Hall, D. S., Henry, G. W., and Renner, T. R. 1978, *A.J.*, **83**, 176.

Liller, W. 1968, *Ap. J.*, **151**, 589.

Moffett, T. J. 1974, *Ap. J. Suppl.*, **29**, 1.

Orrall, F. Q. 1966, *Ap. J.*, **143**, 917.

Renzini, A., Cacciari, C., Ulmschneider, P., and Schmitz, F. 1978, *Astr. Ap.*, **61**, 39.

Schneeberger, T. J., Linsky, J. L., McClintock, W., and Worden, S. P. 1979, *Ap. J.*, **231**, 148.

Spangler, S. R., Owen, F. N., and Hulse, R. A. 1977, *A.J.*, **82**, 989.

Stein, R. F., and Leibacher, J. 1974, *Ann. Rev. Astr. Ap.*, **12**, 407.

Svestka, Z. 1976, *Solar Flares* (Dordrecht: Reidel).

Tanaka, K., and Zirin, H. 1973, in *Proceedings Symposium on High-Energy Phenomena on the Sun*, ed. R. Ramaty and R. G. Stone (Greenbelt, Md.: NASA Goddard).

Ulmschneider, P., and Kalkofen, W. 1978, *Astr. Ap.*, **69**, 407.

Vaughan, A. H., and Skumanich, A. 1970, in *Spectrum Formation in Stars with Steady-State Extended Atmospheres*, ed. H. G. Groth and P. Wellman (Washington: National Bureau of Standards), p. 295.

Vaughan, A. H., Preston, G. W., and Wilson, O. C. 1978, *Pub. A.S.P.*, **90**, 267.

Vernazza, J. E., Avrett, E. H., and Loeser, R. 1981, *Ap. J. Suppl.*, **45**, in press.

Walker, E. C. 1944, *J.R.A.S. Canada*, **38**, 249.

Walter, F. M., Cash, W., Charles, P. A., and Bowyer, C. S. 1980, *Ap. J.*, **236**, 212.

White, O. R., and Athay, R. G. 1979, *Ap. J. Suppl.*, **39**, 317.

Wilson, O. C. 1976, in *IAU Symposium 71, Basic Mechanics of Solar Activity*, ed. V. Bumba and J. Kleczek (Dordrecht: Reidel) p. 447.

———. 1978, *Ap. J.*, **226**, 379.

Wilson, O. C., and Bappu, M. K. V. 1957, *Ap. J.*, **125**, 661.

Zirin, H. 1974, in *Vistas Astr.*, **16**, 1.

SALLIE L. BALIUNAS, ANDREA K. DUPREE, LEE HARTMANN, and WILLIAM LILLER: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

ARTHUR H. VAUGHAN: Mount Wilson Observatory, Mount Wilson, CA 91023