

# STELLAR ACTIVITY IN BARIUM STARS. I. ANALYSIS OF $H$ AND $K$ Ca II LINES IN TEN BARIUM STARS

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Received 15 July 1991; revised 5 November 1991

## ABSTRACT

High dispersion spectra have been obtained in order to study the activity level of ten barium stars by means of the Ca II  $H$  and  $K$  emission flux, looking for a relation between barium intensity index and activity. Absolute magnitudes obtained from the Wilson-Bappu relationship disagree, in some cases, with the magnitudes computed from parallaxes, but this fact is not due to barium nature. Total emission fluxes,  $F(H + K)$  or  $R_{HK}$  index, plotted versus effective temperature show a distribution similar to that of cool giant stars. The asymmetry of  $K$  emission line,  $[F(K_{2v})/F(K_{2r})]$ , has been analyzed in relation with effective temperature, in this sense barium stars behave as expected of late-type giants with the only exception of two stars.

## 1. INTRODUCTION

Barium stars represent an interesting group within low-mass cool giants. This kind of giants were first acknowledged as a class by Bidelman & Keenan (1951), who considered the enhancements that the Ba II, Sr II, and some carbon molecules presented. Barium stars are classified in the basis of a qualitative index of barium  $\lambda 4554$  Å line strength, introduced by Warner (1965), in a scale ranging from 1 to 5 on low-dispersion spectrograms. Morgan & Keenan (1973) considered a group of stars which presented the barium line mildly enhanced in spectrograms of low or moderate dispersion, these are the so-called Ba 0 stars and further subdivisions such as Ba 0.3 are also used.

It is generally believed that, very likely, barium stars could be binary systems. According to an analysis of the radial velocities in these stars McClure & Woodsworth (1990) have concluded that all barium stars are binaries, with orbital periods ranging from 80 days to 10 yr. Furthermore, the mass function indicates that the secondaries have masses of about  $0.6 M_{\odot}$  and these values are typical of white dwarfs.

In the context of a program under development about abundance analysis (Fernández-Villacañas *et al.* 1990) and Stroemgren photometry (Reglero *et al.* 1991) in barium stars, observations of  $H$  and  $K$  Ca II lines have also been carried out. The emission cores of the Ca II appear superimposed on the typical absorption and are the most remarkable characteristics, in the optical domain, of the existence of active chromospheres in late-type stars.

The main purpose of the present work is to study the possible relation between stellar activity and barium index, as well as to verify whether the behavior of these stars is similar to that of the normal giants or, on the contrary, the barium stars present some anomaly in relation to stellar activity.

For a large number of barium stars the physical parameters are poorly known, specially the absolute magnitude obtained from trigonometric parallax is known only in few cases; therefore it has been necessary to use indirect methods such as that based on the  $H\alpha$  width (Kemper 1975). This method is not applicable to active stars because several au-

thors noted significant filling in of the cores of  $H\alpha$  (Fekel *et al.* 1986). Barium stars, as evolved late-type stars, should exhibit Ca II  $H$  and  $K$  emissions, so we can compute absolute magnitudes by using the well-known Wilson-Bappu relationship which we consider a more appropriate method for these stars than that based on  $H\alpha$  width due to the possible activity of these stars.

The classification according to luminosity classes is not clear in most cases, making it rather difficult to discern the effects of luminosity from those typical of the anomalous chemical composition. For this reason many barium stars have no luminosity class assigned.

The sample studied in this paper comprises thirteen stars: one marginal, three mild, and six strong barium stars together with three (nonbarium) giants, the latter being used as comparison stars. Table 1 includes the observed parameters and the barium type (column 4). We have carefully checked spectral types using different catalogs (Hoffleit & Jaschek 1982; Keenan & Yorka 1985; Yamashita & Norimoto 1981). Two stars of the sample had no luminosity class assigned and we have assumed luminosity class III, because this is the most frequent among strong Ba stars (Jaschek *et al.* 1985). Effective temperatures have been computed with the temperature calibration of Böhm-Vitense (1981).

## 2. OBSERVATIONS AND DATA REDUCTION

The observational program has been carried out in July 1988 with the 2.2 m telescope at the German-Spanish Astronomical Observatory in Calar Alto (Almería, Spain), using the coude B&C spectrograph and a CCD as detector. The configuration allowed a resolution of  $0.2 \text{ Å/pixel}$  in the Ca II region covering a spectral range from  $\lambda 3920$  to  $\lambda 3980 \text{ Å}$  approximately. The wavelength-calibrated spectra are extracted from CCD images using the standard reduction procedures for these kinds of images in MIDAS package. The spectra were then corrected from atmospheric extinction by means of the semiempirical method by Hayes & Latham (1975). We have compared this method with the photometric extinction coefficients obtained for Calar Alto Observa-

TABLE 1. Observed parameters.

HD	Star	Spectral type	Ba type	$V$	$B - V$	$V - R$	$(V - R)_0$	$d$ (pc)	$T_{\text{eff}}$
131873	$\beta$ UMi	K4 III	0.3	2.08	1.47	1.11	1.06	26	3900
163770	$\theta$ Her	K1 IIa	—	3.86	1.35	0.90	0.86	500	4260
164349	93 Her	K0.5 IIb	—	4.67	1.26	0.87	0.75	250	4750
168532	105 Her	K3 III	0.4	5.27	1.53	—	0.96	500	4100
178717	—	K3.5 III	5	7.5	1.4	—	1.06	320	4050
185958	$\beta$ Sge	G8 IIIa	—	4.37	1.05	—	0.70	91	4900
198809	31 Vul	G7 III	m	4.59	0.83	0.68	0.70	28	4950
199939	—	G9 III	4	8.00	1.28	0.82	0.74	—	4850
201657	—	G9 III	4	8.1	—	—	0.84	—	4850
206778	$\epsilon$ Peg	K2 Ib	1	2.39	1.53	1.05	0.89	167	4000
211594	—	K0 (III)	4	8.09	1.00	—	0.77	—	4780
215665	$\lambda$ Peg	G8 III	0.3	3.95	1.07	0.76	0.66	24	4900
218356	56 Peg	G8 Ib	2	4.76	1.34	0.97	0.81	164	4500

m: marginal barium star.

tory by Fabregat (1989), having found no significative deviations.

The flux calibration is performed using spectra of standard stars from Oke & Gunn (1983) and from Barnes & Hayes (1984); after this calibration the flux units are  $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ . Night to night discrepancies found for the standard stars are within a 5%.

The calibrated spectra are displayed in Fig. 1. The emission in at least  $K$  line is apparent in all of our spectra, among them it stands out the emission in 56 Peg (Ba 2).

The  $H$  and  $K$  emission fluxes were measured reconstructing the absorption profile below the emission peaks following the method of Blanco *et al.* (1974); these authors suggest that the wing profiles can be extrapolated smoothly toward the line center in order to define the photospheric level. The measurements are less exact in the  $H$  line because of the presence of  $\text{He}$ , for  $\theta$  Her and 56 Peg, the  $\text{He}$  emission has been subtracted by a Gaussian fit. In spite of that some authors (Linsky & Ayres 1978) regard that the method of Blanco *et al.* seems to overestimate the radiative photospheric contribution; we have adopted it in all our papers where the chromospheric emission has been analyzed (Fernández-Figueroa *et al.* 1986) because  $H_1$  and  $K_1$  minima have essentially nonzero intensity in our spectra. We have plotted in Fig. 2 the flux in the  $K_1$  feature [given in Table 3(a)]. The solid line represents the radiative equilibrium flux predicted by Linsky *et al.* (1979) and it can be seen that all of the observational points lie above the theoretical curve. In this sense, our measurements represent the  $H$  and  $K$  chromospheric emission above the contribution of the upper photosphere where some nonradiative heating processes may be present. From semiempirical solar models, departures from radiative equilibrium has been derived, also for upper photosphere and minimum temperature region, which can be the result of convective motions, oscillation, or wave dissipation (Avrett 1990). Similar phenomena may drive an upper-photospheric heating in the giant cool stars.

To convert the Earth-observed fluxes into stellar surface fluxes we have used the Barnes & Evans (1976) relationship which involves the unreddened color index  $(V - R)_0$ . In our sample there are several bright giants and supergiants for which the interstellar reddening has to be taken into account. The color indices were obtained from the observed ones and corrected for interstellar reddening (Landolt-Börnstein 1982). In the case of stars whose observed color

index,  $(V - R)$ , is not available in literature, the intrinsic one has been adopted from spectral types and luminosity class provided by Johnson (1966). It is difficult to estimate the total error in the surface fluxes but a reasonable upper limit could be around 25%. The surface fluxes are given in Table 2.

Tables 3(a) and 3(b) show the monochromatic surface flux, following the usual notation:  $H_1$  and  $K_1$  refer to the minima outside the line cores,  $H_2$  and  $K_2$  correspond to the emission peak, and  $H_3$  and  $K_3$  refer to the central minima; as usual,  $V$  and  $R$  correspond to the violet and red sides of the line profiles, respectively.

### 3. RESULTS AND DISCUSSION

The first step was to use the Wilson-Bappu relationship (Wilson & Bappu 1957), which relates the measurable quantity, FWHM of the emission  $K$  line core, to  $M_v$ . Instead of using the original Wilson-Bappu formula, we adopted the updated version given by Lutz (1970), which is the same adopted by Linsky *et al.* (1979), and it can be written as

$$M_v = -15.55 \log W_0 + 28.49,$$

where  $W_0$  is the FWHM and is the full width measured between the flux levels halfway between the mean flux at  $K_1$  and  $K_2$  on each side of the  $K$  line (Linsky *et al.* 1979); for  $H$  line the same definition holds. In Table 2 the FWHM of  $H$  and  $K$  lines are given as well as the absolute magnitudes obtained from above equation,  $M_v(WB)$ , and from trigonometric parallaxes,  $M_v(\pi)$ , when available.

For  $\epsilon$  Peg and 56 Peg, the  $M_v(WB)$  values agree very well with the results obtained by Pasquini *et al.* (1990). The disagreement with the luminosity class is only noticeable in the case of HD 168532, HD 185958 (a nonbarium star), and HD 201657. Absolute magnitudes derived from parallax are out of keeping with luminosity class. In any case, the discrepancies do not seem to be related with the barium index.

The total emission fluxes of Ca II,  $F(H + K)$ , which can describe chromospheric activity, are plotted in Fig. 3 versus effective temperature. Despite wide scatter a decline toward cooler effective temperature can be observed. We have also plotted in Fig. 4 Ca II  $H$  and  $K$  emission flux in units of the bolometric flux  $R_{HK}$  versus effective temperature. In the lat-

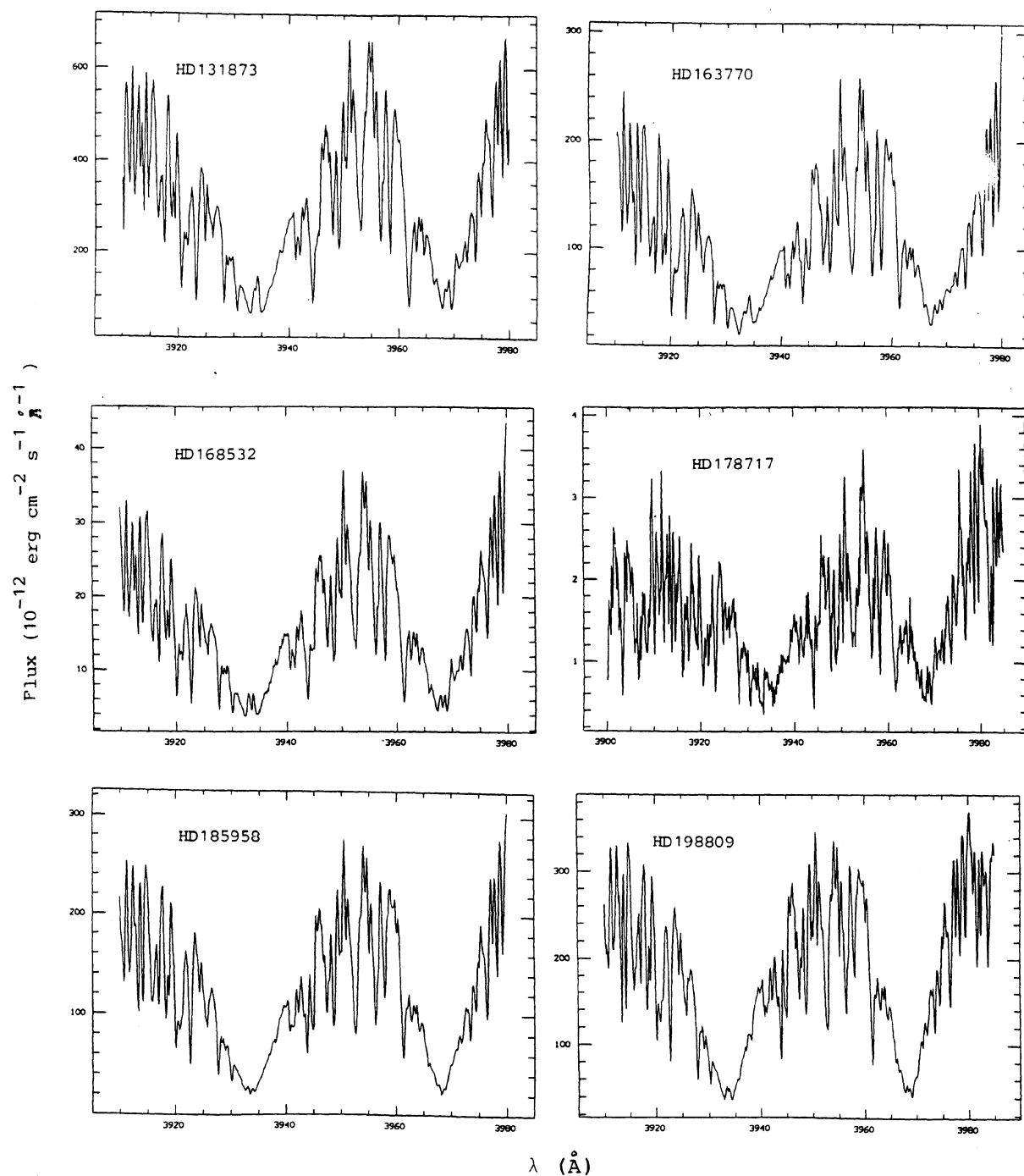


FIG. 1. Ca II H and K profiles for the sample of the program stars.

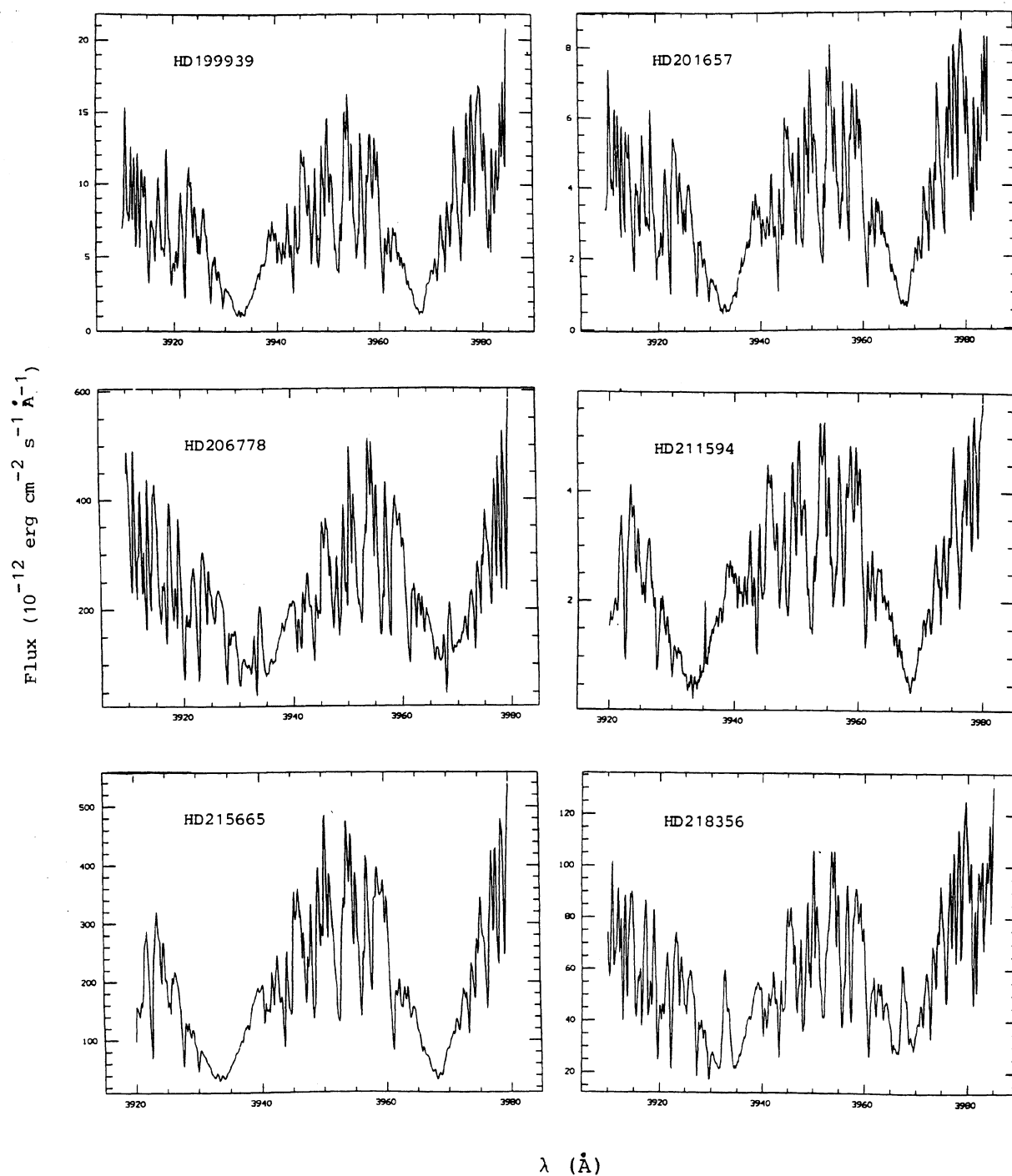


FIG. 1. (continued)

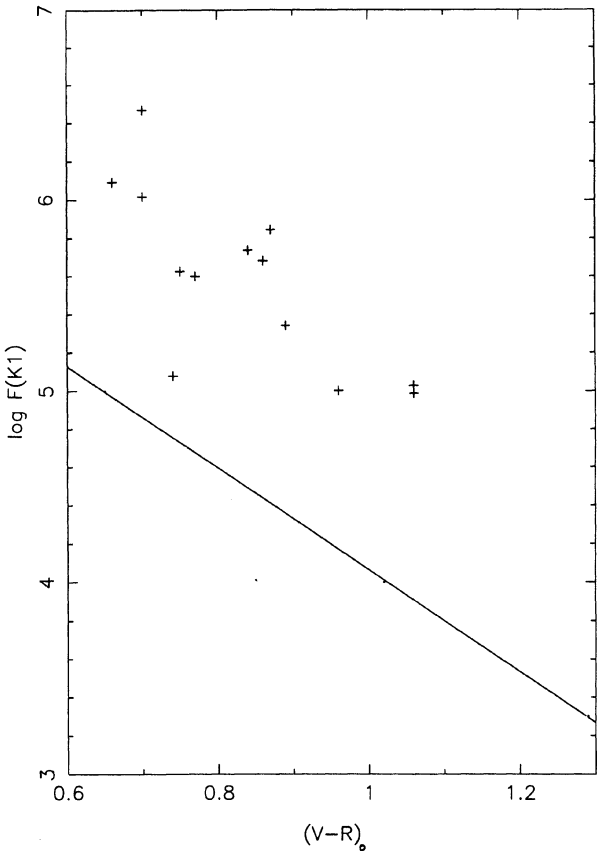


FIG. 2. Monochromatic flux at the  $K_1$  minimum as a function of  $(V - R)_0$ . The solid line indicates the radiative equilibrium flux predicted by Linsky *et al.* (1979).

ter figure the dashed lines display the limits of the gap used by Strassmeier *et al.* (1990) to divide the stars up into quite an active chromosphere. This horizontal gap can be identified with the Vaughan–Preston gap (Vaughan & Preston 1980). In this sense, our sample of barium stars does not show an anomalous behaviour.

Asymmetries in  $H$  and  $K$  lines, which provide information about velocity gradients in the line formation region, are

referred as blue asymmetry if  $F(K_{2v}) > F(K_{2r})$  and similarly red asymmetry if  $F(K_{2v}) < F(K_{2r})$ . Stencel (1978) noted that the locus of the change in asymmetry occurs in the early K-type giants and supergiants and it is similar to the locus computed by Mullan (1978) for the onset of massive winds in stellar chromospheres. In order to study this question in our sample, we plot in Fig. 5 the ratio  $F(K_{2v})/F(K_{2r})$  [given in Table 3(a)] versus effective temperature. From the inspection of the diagram we can see that only HD 201657 and HD 178717 deviate from the systematic trend above mentioned. These stars show circumstellar features which can mutilate the  $H$  and  $K$  lines, so that it is difficult to measure the intensity of the line asymmetries. All these circumstances can lead to severe errors in the parameters which could explain the bad location in the diagram of the two stars. For the same reasons, both stars are also misplaced in the diagram  $M_v$  vs  $(V - R)_0$  with respect to the Stencel (1978) dividing line for giants.

As noted by Linsky *et al.* (1979), if the asymmetries of the  $H$  and  $K$  lines are due to chromospheric velocities, then the ratio  $F(K_{2v})/F(K_{2r})$  must be correlated with the wavelength shift of the central reversal  $K_3$ . We measure this shift ( $\Delta\lambda_3$ ) with respect to the minimum of the absorption computed by a polynomial fit of the  $K$  line wings. The computed shifts ( $\Delta\lambda_3$ ) are given in Table 3(a). In Fig. 6 we plot  $F(K_{2v})/F(K_{2r})$  with respect to  $\Delta\lambda_3$ . In this plot  $\theta$  Her has been omitted because of its hybrid nature. The best-fit line exhibits a positive correlation as predicted by Chiu *et al.* (1977) on the assumption of conservative mass flux.

4. FINAL REMARKS

Our primary result is the presentation of new  $H$  and  $K$  Ca II emission fluxes of ten barium stars. No relation was found between the chromospheric flux, described by  $F(H + K)$  or  $R_{HK}$  index, and the barium intensity index. From the point of view of stellar activity the behavior of barium stars is not anomalous. Absolute magnitudes computed from parallaxes and from the Wilson–Bappu relationship disagree, but these discrepancies do not seem to be related with the barium nature.

The change in asymmetry of the  $K$  line occurs in the early K-type giants, in our sample two stars, HD 201657 and HD 178717, show the contrary behavior as expected from this systematic trend. This cannot be attributable to the barium nature but to the fact that these stars show circumstellar

TABLE 2. Surface fluxes and absolute magnitudes.

HD	$F_K$	$F_H$	$R_{HK}$	FWHM		$M_v(\pi)$	$M_v(WB)$
				$K$	$H$		
131873	1.41 E5	1.31 E5	2.07 E-5	1.17	1.10	−0.16	−1.84
163770	8.07 E5	4.06 E5	6.49 E-5	1.63	1.99	−4.8	−4.1
164349	1.93 E5	2.14 E5	1.41 E-5	1.24	1.24	−2.7	−2.23
168532	9.81 E4	1.00 E5	1.24 E-5	1.31	1.22	−3.2	−2.6
178717	7.5 E4	5.7 E4	8.65 E-6	1.18	1.00	−0.45	−1.9
185958	2.61 E5	2.22 E5	1.48 E-5	1.28	1.20	−0.42	−2.45
198809	1.21 E6	8.56 E5	6.07 E-5	1.00	0.88	2.37	−0.78
199939	1.79 E5	1.43 E5	1.03 E-5	0.70	0.98	—	1.63
201657	1.17 E5	1.70 E5	9.14 E-6	0.52	0.78	—	3.63
206778	3.77 E5	1.94 E5	3.93 E-5	1.77	1.58	−4.4	−4.6
211594	2.21 E5	3.68 E4	8.70 E-6	0.83	0.99	—	0.48
215665	3.45 E5	2.96 E5	1.96 E-5	1.05	1.13	2.07	−1.11
218356	1.66 E6	1.50 E6	1.36 E-4	1.52	1.30	1.99	−3.4

$F_K$  and  $F_H$  in  $\text{ergs cm}^{-2} \text{s}^{-1}$ .



TABLE 3(a). Monochromatic surface flux for the *K* line.

HD	$F(K_{1v})$	$F(K_{1r})$	$F(K_{2v})$	$F(K_{2r})$	$F(K_3)$	$\frac{F(K_{2v})}{F(K_{2r})}$	$\Delta\lambda(K_3)$
131873	9.94 E4	1.02 E5	1.81 E5	2.25 E5	1.78 E5	0.804	- 0.04
163770	3.88 E5	5.73 E5	7.80 E5	1.03 E6	7.26 E5	0.757	0.52
164349	4.25 E5	4.19 E5	5.92 E5	5.66 E5	4.04 E5	1.046	0.01
168532	9.87 E4	1.04 E5	1.75 E5	1.74 E5	1.19 E5	1.006	0.32
178717	8.98 E4	1.05 E5	1.68 E5	1.58 E5	1.33 E5	1.063	0.33
185958	1.06 E6	1.02 E6	1.24 E6	1.14 E6	9.18 E5	1.088	- 0.10
198809	3.00 E6	2.86 E6	4.04 E6	3.82 E6	3.67 E6	1.058	0.05
199939	1.20 E6	1.20 E6	1.61 E6	1.45 E6	1.11 E6	1.110	- 0.08
201657	5.13 E5	5.80 E5	7.47 E5	8.14 E5	7.13 E5	0.918	0.05
206778	2.23 E5	2.17 E5	3.96 E5	5.43 E5	1.22 E5	0.729	- 0.20
211594	3.85 E5	4.11 E5	6.26 E5	5.82 E5	2.31 E5	1.076	0.18
215665	1.24 E6	1.25 E6	1.48 E6	1.39 E6	1.07 E6	1.065	- 0.14
218356	7.02 E5	7.02 E5	1.91 E6	1.44 E6	1.41 E6	1.326	0.28

Fluxes are expressed in  $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ .

TABLE 3(b). Monochromatic surface flux for the *H* line.

HD	$F(H_{1v})$	$F(H_{1r})$	$F(H_{2v})$	$F(H_{2r})$	$F(H_3)$
131873	1.17 E5	1.17 E5	1.85 E5	2.16 E5	1.74 E5
163770	8.55 E5	7.53 E5	9.10 E5	8.76 E5	5.63 E5
164349	5.25 E5	4.77 E5	6.31 E5	5.99 E5	4.36 E5
168532	1.17 E5	1.17 E5	1.71 E5	1.70 E5	1.31 E5
178717	9.86 E4	9.05 E4	1.76 E5	1.64 E5	1.13 E5
185958	1.37 E6	1.20 E6	1.45 E6	1.23 E6	9.90 E5
198809	3.74 E6	3.27 E6	4.22 E6	4.03 E6	3.74 E6
199939	1.67 E6	1.30 E6	1.75 E6	1.46 E6	1.30 E6
201657	7.66 E5	6.76 E5	9.91 E5	7.89 E5	7.21 E5
206778	2.78 E5	3.16 E5	3.96 E5	5.51 E5	1.29 E5
211594	5.24 E5	5.69 E5	6.12 E5	5.91 E5	3.48 E5
215665	1.55 E6	1.39 E6	1.67 E6	1.50 E6	1.15 E6
218356	9.03 E5	9.50 E5	1.99 E6	1.55 E6	1.53 E6

Fluxes are expressed in  $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ .

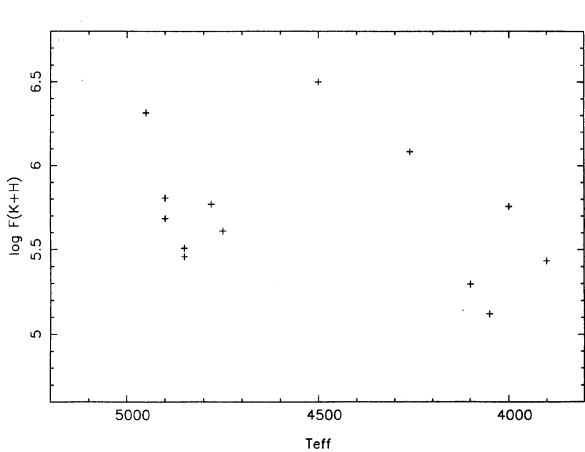


FIG. 3. Total emission flux of Ca II,  $F(K + H)$ , vs effective temperature.

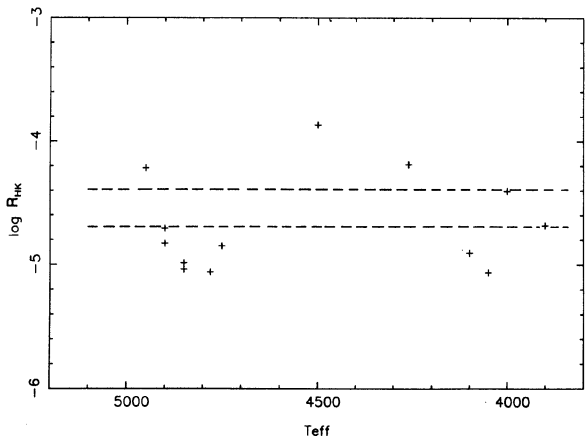


FIG. 4. Values of the index  $R_{HK}$ , the emission flux in units of the bolometric flux, plotted with respect to effective temperature.

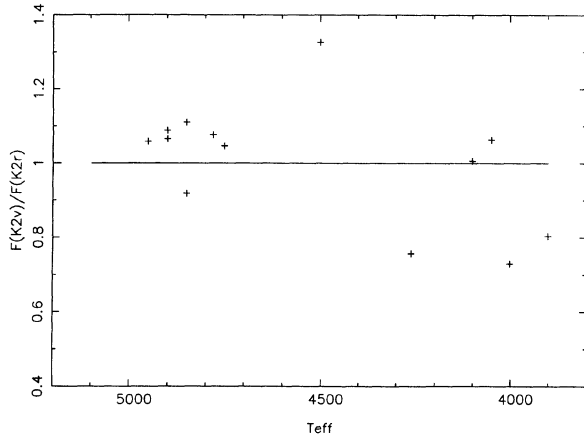


FIG. 5. Ratios of the monochromatic fluxes,  $F(K_{2v})/F(K_{2r})$ , as a function of the effective temperature.

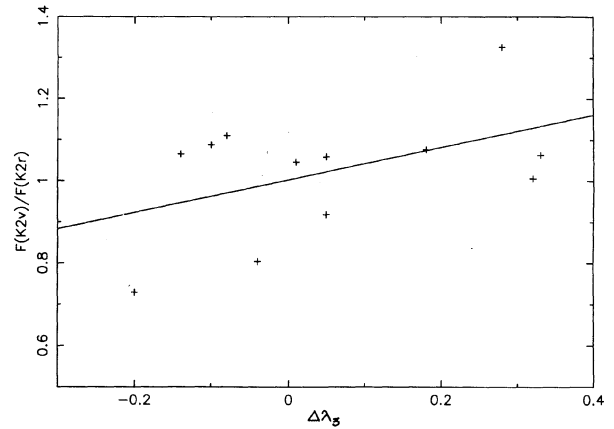


FIG. 6. Asymmetric index, represented by the ratio  $F(K_{2v})/F(K_{2r})$ , is plotted with respect to  $\Delta\lambda_3$  (see text).

features which make it difficult to measure the line asymmetries.

In relation to the binary nature of these stars it is known that the evolved stars show the same activity level, measured by the observed surface fluxes of  $H$  and  $K$  Ca II, for both single and binary stars with the same rotation period (Strassmeier *et al.* 1990). Then the binary nature of the barium stars might not influence their chromospheric activity. On the other hand, the possible mass loss from the hot companion during the previous evolutionary state could be made clear by means of a more detailed analysis of the circumstellar lines which appear in some cases overlapped with  $H$  and  $K$  lines.

We think it is necessary to make more observations of

barium stars in order to obtain definitive conclusions about the relation among stellar activity, barium intensity, and the binarity. For this reason we are planning observations of a larger sample of barium stars which include the analysis of other activity indicators such as  $H_\alpha$  and the infrared Ca II triplet.

The 2.2 m telescope at Calar Alto Observatory is operated by the Max-Planck Institut für Astronomie at the Centro Astronómico Hispano-Alemán. We want to express our gratitude to the staff of the Observatory for their help during the observational campaign. This work has been supported by the Spanish Comisión Interministerial de Ciencia y Tecnología.

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