

# Multiwavelength optical observations of chromospherically active binary systems

## II. EZ Pegasi<sup>\*</sup>

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**Abstract.** The star EZ Peg, long ago classified as cataclysmic variable, has been shown to be a chromospherically active binary system of the RS CVn-type. In this paper we have analysed, using the spectral subtraction technique, simultaneous spectroscopic observations of the  $H\alpha$ ,  $H\beta$ , Na I D<sub>1</sub> and D<sub>2</sub>, He I D<sub>3</sub>, Mg I b triplet, Ca II H & K, and Ca II infrared triplet lines. We have found that the hot component is the active star of the system, showing strong emission in the  $H\alpha$ , Ca II H & K,  $H\epsilon$ , and Ca II IRT lines, and a strong filling-in of the  $H\beta$  line, however the Na I D<sub>1</sub> and D<sub>2</sub> and Mg I b triplet lines do not present filled-in. The He I D<sub>3</sub> could present a total filling-in due to microflaring. The observed variations (in different epochs and with the orbital phase) of the different activity indicators, formed at different height in the chromosphere, are correlated. Very broad wings have been found in the subtracted profiles of  $H\alpha$  and Ca II IRT  $\lambda 8498$  and  $\lambda 8662$  lines. These profiles are well matched using a two-component Gaussian fit (narrow and broad) and the broad component could be interpreted as arising from microflaring. The higher luminosity class of the hot component, that our spectra seem to indicate, could explain why the hot component is the active star of the system.

**Key words:** stars: activity – stars: binaries: close – stars: chromospheres – stars: late-type – stars: individual: EZ Peg

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### 1. Introduction

EZ Peg (BD +24° 4742) has a misleading history of confused interpretation of the origin and composition of the system. The

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<sup>\*</sup> Based on observations made with the Isaac Newton, William Herschel and Jacobus Kapteyn telescopes operated on the island of La Palma by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias

spectrum of EZ Peg was originally classified by Cannon as G5 (Schlesinger et al. 1934). Vyssotsky & Balz (see Alden 1958) claimed that the star varies from B0 to G5, due to a spectrum taken in 1943 which appeared to be a B star spectrum. Later Howell & Bopp (1985) presented evidence that this erroneous interpretation of the spectrum was due to poor resolution data. Irvine (1972) proposed that EZ Peg was an U Gem system (a cataclysmic variable), but it is an unlikely explanation due to the normal UV emission of the system: in a color-color plot there is no strong UV excess typical of the dwarf novae and symbiotics (Szkody 1977). Furthermore linear polarimetry measurements of the system (Szkody et al. 1982) show that EZ Peg does not seem to be a cataclysmic variable.

Howell & Bopp (1985) observed the double-lined spectrum of EZ Peg and interpreted the color-indices (B-V) and (U-B) as that of a composite spectral type of G5 IV + K0 IV. They observed Ca II H & K,  $H\alpha$  and  $H\epsilon$  lines in emission, and they supposed that this emission originated in the cooler star, because it is the most typical case. Howell et al. (1986) suggested that both components of EZ Peg were subgiants, and pointed out a slightly asymmetric profile in  $H\alpha$ , interpreted as a vertical motion in the atmosphere of the active star of the system.

Griffin (1985) presented radial-velocity observations of the system, and he calculated the orbital elements. Recently Gunn et al. (1996) made cross-correlation radial velocity measurements of EZ Peg, showing a disagreement with the phases calculated from the ephemeris given by Griffin (1985). Vilkki et al. (1986) calculated a distance to EZ Peg of 83 pc using the trigonometric parallax method, and they suspected that EZ Peg belongs to the Hyades cluster. Barret (1996) calculated a distance of 82 pc using linear polarimetry.

Finally, recent studies in the IR band by Mitrou et al. (1996) with the IRAS satellite indicated that the system does not seem to present any circumstellar matter.

Continuing with the series of multiwavelength optical observations of chromospherically active binaries (Montes et al. 1997b, hereafter Paper I), in this paper we present simultaneous observations in different optical wavelength bands, including

**Table 1.** Observing log

Date	IDS-INT											UES-WHT			
	H $\alpha$			Na I D <sub>1</sub> , D <sub>2</sub> , He I D <sub>3</sub>			Ca II H & K			H $\beta$			Echelle		
	UT	$\varphi$	S/N	UT	$\varphi$	S/N	UT	$\varphi$	S/N	UT	$\varphi$	S/N	UT	$\varphi$	S/N
1993/07/31	-	-	-	-	-	-	-	-	-	-	-	-	02:05	0.954	315
1995/09/14	00:36	0.416	295	00:04	0.414	362	-	-	-	-	-	-	-	-	-
1995/09/15	00:23	0.501	332	00:02	0.500	343	-	-	-	-	-	-	-	-	-
1996/11/26	21:25	0.141	295	-	-	-	23:11	0.148	295	-	-	-	-	-	-
1996/11/27	20:39	0.224	295	20:49	0.225	362	19:35	0.220	295	-	-	-	-	-	-
1996/11/28	19:24	0.306	295	20:25	0.310	362	21:44	0.314	295	21:19	0.312	362	-	-	-

also a high resolution echelle spectrum. All the data seem to point out that EZ Peg is a RS CVn system with an evolved G5 active star, and a K0V or IV non-active star. We have applied the spectral subtraction technique, observing the Ca II H & K, He $\epsilon$ , H $\alpha$  and Ca IR triplet lines in emission, and a filling-in of the H $\beta$  line, proceeding from the hotter component of the system.

In Sect. 2 we give the details of our observations and data reduction. In Sect. 3 we discuss some of the stellar parameters of the binary system and in Sect. 4 the behavior of the different chromospheric activity indicators is described. Finally in Sect. 5 we present the conclusions.

## 2. Observations and data reduction

Spectroscopic observations of EZ Peg in several optical chromospheric activity indicators have been obtained during two observing runs with the 2.5 m Isaac Newton Telescope (INT) at the Observatorio del Roque de Los Muchachos (La Palma, Spain) using the Intermediate Dispersion Spectrograph (IDS). In the first run (September 13-15 1995) we have obtained two spectra: in the H $\alpha$  and Na I D<sub>1</sub>, D<sub>2</sub>, He I D<sub>3</sub> line regions, using grating H1800V, camera 500 and a 1024 x 1024 pixel TEK3 CCD as detector. The reciprocal dispersion achieved is 0.24 Å/pixel which yields a spectral resolution of 0.48 Å and a useful wavelength range of 250 Å centered at 6563 Å (H $\alpha$ ) and 5876 Å (He I D<sub>3</sub>) respectively. In the second run (November 26-28 1996) we used the same configuration but two different gratings H1200R and H1200B, for the red and blue spectral regions respectively. Using the same configuration a reciprocal dispersion of 0.39 Å was obtained which yields a spectral resolution of 0.94 Å and a useful wavelength range of 385 Å centered at 6563 Å (H $\alpha$ ), 5876 Å (He I D<sub>3</sub>), 4861 Å (H $\beta$ ), 3950 Å (Ca II H&K) respectively.

In Table 1 we give the observing log. For each spectral region observed we list the date, UT, orbital phase ( $\varphi$ ) and signal to noise ratio (S/N) obtained.

We also analyse here echelle spectra obtained with the 4.2 m William Herschel Telescope (WHT) and the Utrecht Echelle Spectrograph (UES) on July 31 1993 that we have retrieved from La Palma Data Archive (Zuiderwijk et al. 1994). These WHT/UES spectra were obtained with echelle 31 (31.6 grooves

per mm) and a 1280 x 1180 pixel EEV6 CCD as detector. The central wavelength is 6127 Å and covers a wavelength range from 4845 to 8805 Å over 53 echelle orders. The achieved reciprocal dispersion ranges from 0.045 to 0.080 Å/pixel. In order to improve the S/N ratio and to avoid cosmic ray events, the final spectrum analysed here is the resulting from combine 28 CCD images with exposure times of 240 s each, obtaining a final spectrum with a S/N of 315 in the H $\alpha$  line region. In Table 2 we give the wavelength range and the spectral lines of interest in each echelle order.

In addition we also use one spectrum in the region of the Ca II IRT lines taken on January 16 1997 with the 1.0 m Jacobus Kapteyn Telescope (JKT) using the Richardson-Brealey Spectrograph (RBS) with a grating of 1200 grooves per mm, and a 1024 x 1024 pixel TEK4 CCD as detector. The reciprocal dispersion achieved is 0.85 Å/pixel which yields a spectral resolution of 1.7 Å and a useful wavelength range of 865 Å centered at 8765 Å.

The spectra have been extracted using the standard reduction procedures in the IRAF<sup>1</sup> package (bias subtraction, flat-field division, and optimal extraction of the spectra). The reduction of the JKT/RBS spectrum was carried out using the reduction package RED<sub>m</sub><sup>UC</sup>E (Cardiel & Gorgas 1997, see also <http://www.ucm.es/OTROS/Astrof/reduceme/reduceme.html>). The wavelength calibration was obtained by taking spectra of a Cu-Ar lamp in the INT/IDS spectra, a Th-Ar lamp in the WHT/UES spectrum and a Cu-Ne lamp in the JKT/RBS spectrum. Finally, the spectra have been normalized by a polynomial fit to the observed continuum.

## 3. Stellar parameters of the binary system EZ Peg

EZ Peg is a double-lined spectroscopic binary with an orbital period of 11.6598 days (Griffin 1985), classified as G5V-IV/K0IV. It is in synchronous rotation with a photometric period of 11.6626 days (Howell et al. 1986). In Table 3 we show the

<sup>1</sup> IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

**Table 2.** UES spectral orders

No.	$\lambda_i$	$\lambda_f$	Chromospheric Lines	Other lines
1	4845.80	4897.29	H $\beta$	
2	4887.53	4939.46		
3	4929.98	4982.35		
4	4973.16	5026.00		
5	5017.11	5070.41		
6	5061.85	5115.62		
7	5107.38	5161.63		
8	5153.74	5208.48	Mg i b $\lambda$ 5167-72-83	
9	5200.94	5256.19		
10	5249.02	5304.77		
11	5297.99	5354.27		
12	5347.89	5404.69		Ti i $\lambda$ 5366
13	5398.73	5456.07		Ti i $\lambda$ 5426
14	5450.54	5508.43		
15	5503.36	5561.81		
16	5557.21	5616.23		
17	5612.13	5671.73		
18	5668.14	5728.34		
19	5725.28	5786.09		
20	5783.58	5845.01		
21	5843.08	5905.14	Na i D <sub>1</sub> , D <sub>2</sub> , He i D <sub>3</sub>	Ti i $\lambda$ 5866
22	5903.82	5966.53		
23	5965.84	6029.20		
24	6029.17	6093.21		
25	6093.87	6158.59		
26	6159.96	6225.39		
27	6227.51	6293.66		
28	6296.55	6363.44		
29	6367.15	6434.78		Fe i $\lambda$ 6411.66
30	6439.35	6507.75		Fe i $\lambda$ 6495
31	6513.20	6582.39	H $\alpha$	
32	6588.77	6658.76		
33	6666.11	6736.93		Fe i $\lambda$ 6678
”				Li i $\lambda$ 6708
”				Ca i $\lambda$ 6718
34	6745.30	6816.95		
35	6826.39	6899.90		O <sub>2</sub> $\lambda$ 6867
36	6909.45	6982.85		
37	6994.56	7068.87		
38	7081.80	7157.03		
39	7171.24	7247.43		
40	7262.98	7340.14		
41	7357.09	7435.25		
42	7453.68	7532.86		
43	7552.84	7633.08		B-band $\lambda$ 7600
44	7654.68	7736.00		K i $\lambda$ 7665, 7699
45	7759.30	7841.73		
46	7866.82	7950.40		
47	7977.38	8062.12		
48	8091.08	8177.03		
49	8208.08	8295.27		
50	8328.51	8416.99		Ti i (M.33)
51	8452.54	8542.33	Ca ii IRT $\lambda$ 8498, 8542	Ti i $\lambda$ 8468
”				Fe i $\lambda$ 8514
”				Ti i $\lambda$ 8518
52	8580.32	8671.46	Ca ii IRT $\lambda$ 8662	Fe i $\lambda$ 8621
53	8712.02	8804.56		

adopted stellar parameters from Strassmeier et al. (1993) except for  $T_{\text{conj}}$  (see below).

### 3.1. Radial velocities

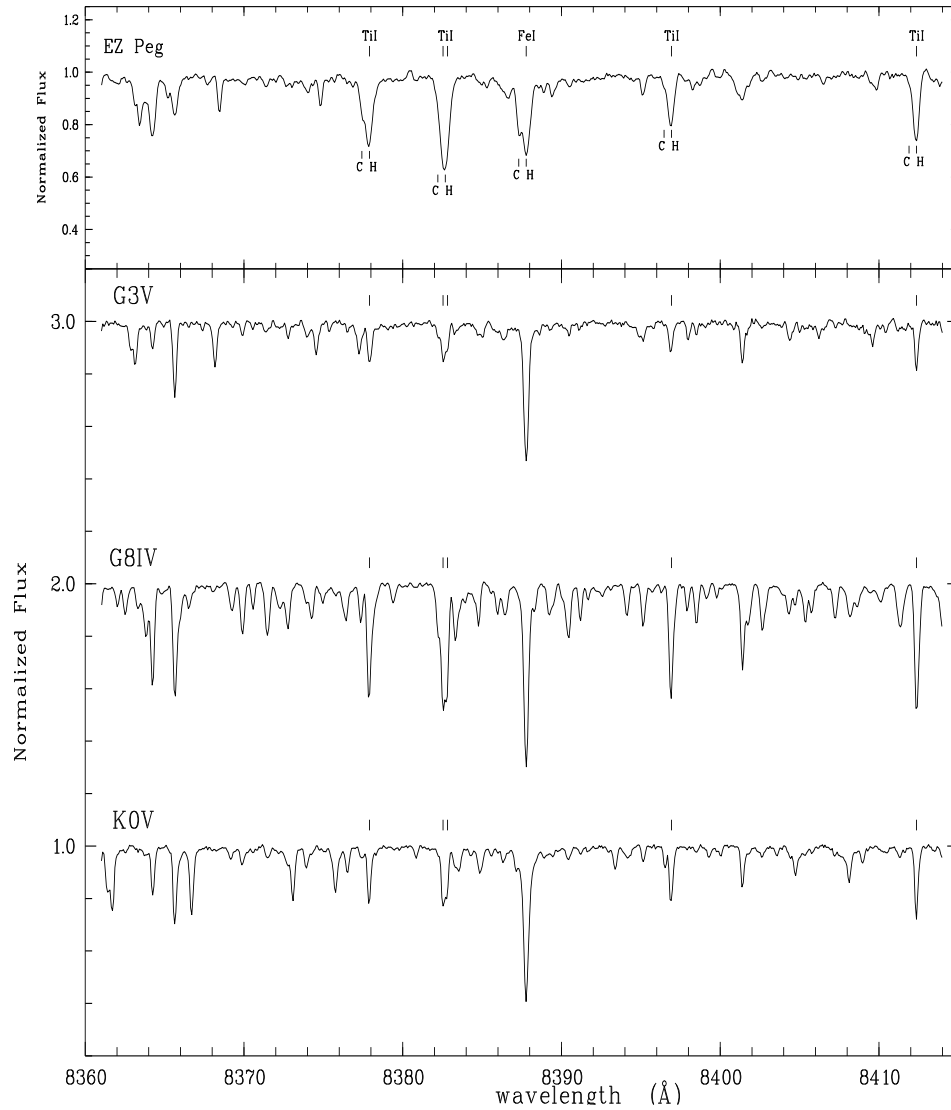
In our high resolution echelle spectrum we can resolve both components in all the orders. We have calculated the radial velocity difference for this observation using 39 lines clearly seen in the echelle spectrum as double lines. The value obtained is  $16.17 \pm 0.72 \text{ km s}^{-1}$  which results in a value for the orbital phase of  $0.944 \pm 0.002$ .

According to the ephemeris given by Strassmeier et al. (1993) the calculated phase for this spectrum is 0.997, which is clearly in disagreement with our observation, since at this phase the radial velocity difference is  $0.92 \text{ km s}^{-1}$  which yields a difference in wavelength between both components of only  $0.02 \text{ \AA}$ . This  $\Delta\lambda$  is lower than the resolution of the spectrum and then the lines from both components should be blended. Similar problems have been found in the other spectra when we use this ephemeris. The phase deviation is the same for all the observations and is very large to be ascribed to orbital period variations, so we thought of an error in the heliocentric Julian date on conjunction ( $T_{\text{conj}}$ ). In effect, we have found a mistake in the  $T_{\text{conj}}$  given in the Strassmeier et al. (1993) catalog where the orbital data by Griffin (1985) are compiled. In the original paper the epoch is determined using Modified Julian Date (MJD) and so a difference of 0.5 days must be added to the Strassmeier et al. (1993) date which used 2440000.0 Julian day as reference date. The orbital phase of the echelle spectrum obtained using the corrected value of  $T_{\text{conj}}$  (2445737.165) is 0.954. Now, the difference with the orbital phase that we deduce from our spectrum is only 0.01, which is within the uncertainties given by Griffin (1985). We would notice that the large discrepancies in the radial velocities which Gunn et al. (1996) found could be reduced using the corrected  $T_{\text{conj}}$ . Therefore we have used the corrected  $T_{\text{conj}}$  given in Table 3 to calculate the orbital phases of all the observations reported in this paper.

### 3.2. Spectral type and luminosity class

Several Ti I lines can be used as a luminosity classification criterion (Keenan & Hynek 1945; Kirkpatrick et al. 1991; Ginestet et al. 1994; Jashek & Jashek 1995) because they present a positive luminosity effect (i.e. they are stronger in giants than in dwarfs). We have analysed the behaviour of the Ti I lines that appear in our echelle spectrum in order to improve the luminosity classification of the EZ Peg components.

In Fig. 1 we can notice the enhancement of the multiplet 33 Ti I lines for the system in comparison with main sequence stars of spectral type similar to the components of EZ Peg. It is worth mentioning the case of the Ti I  $\lambda$ 8382 line which is even more intense than the Fe I  $\lambda$ 8388 line, showing a behaviour different from that in the subgiant reference star (see Fig. 1 lower panel). This behaviour can be also observed in other Ti I lines like  $\lambda$ 5366.651 (Multiplet 35),  $\lambda$ 5446.593 (M. 3),  $\lambda$ 5866.453,  $\lambda$ 5937.806 and  $\lambda$ 5941.755 (M. 72),  $\lambda$ 6554.226 and  $\lambda$ 6556.066



**Fig. 1.** WHT/UES (Jul 1993), spectra in the region of several lines of Ti I (M.33). In the upper panel we plot EZ Peg and in the lower panel three reference stars: HD 186427 (G3V), HD 44867 (G8IV), HD 185144 (K0V).

**Table 3.** Stellar parameters

$T_{\text{sp}}$	SB	R ( $R_{\odot}$ )	d (pc)	B-V	V-R	$T_{\text{conj}}$ (H.J.D.)	$P_{\text{orb}}$ (days)	$P_{\text{rot}}$ (days)	$V \sin i$ ( $\text{km s}^{-1}$ )
G5V-IV/K0IV:	2	-	83	0.73/0.91	0.58/0.71	2445737.165	11.6598	11.6626	9/7

(M.102),  $\lambda 6599.112$  (M.19). These results suggest a clear difference in luminosity class between the two components of the system, being the G5 primary star more evolved than a subgiant, meanwhile the K0 star is probably a luminosity class V star.

As is explained in the following section all the activity indicators analysed here show that the hot component is the active star of the system, contrary to the usual behaviour observed in chromospherically active binaries. Only in some BY Dra stars the hot component tends to be the most active star of the system or even the only active component (Montes et al. 1996a). So we have used our Ca II K spectra to determine the absolute

visual magnitude,  $M_V$  of the active component by the application of the Wilson-Bappu effect (Wilson & Bappu 1957). The mean emission line width measured in our Ca II K spectra is  $1.229 \text{ \AA}$ , which come out to  $60.39 \text{ km s}^{-1}$  after the quadratic correction of the instrumental profile. We have used the relation found for chromospherically active binaries by Montes et al. (1994) obtaining  $M_V = 2.27$ . This value is lower than the  $M_V$  that corresponds to a G5V ( $M_V(T_{\text{sp}}) = 5.1$  from Landolt-Börnstein (Schmidt-Kaler 1982)) but higher than for a G5III ( $M_V(T_{\text{sp}}) = 0.9$ ). This result indicates that the active component of EZ Peg may be of luminosity class IV or higher.

**Table 4.**  $H\alpha$  line measures in the observed and subtracted spectrum

Obs.	$\varphi$	Observed $H\alpha$ Spectrum			Subtracted $H\alpha$ Spectrum			
		$W_{\text{obs}}$ (Å)	$R_c$	$F(1.7\text{Å})$	$W_{\text{sub}}$ (Å)	I	EW (Å)	$\log F_S$
UES 1993	0.954	0.96	1.325	1.987	1.62	0.882	2.085	7.06
INT 1995	0.416	0.65	1.139	1.695	1.70	0.655	1.488	6.91
"	0.501	0.54	1.059	1.657	1.69	0.639	1.400	6.89
INT 1996	0.141	1.48	1.131	1.779	2.43	0.604	2.272	7.10
"	0.224	1.55	1.157	1.812	2.30	0.634	1.862	7.01
"	0.306	1.35	1.134	1.784	2.16	0.638	1.677	6.96

The difference in luminosity class between the hot and cool components that our spectra indicate could explain why the hot component is the active star (see below), since if the hot component is a more evolved star it could have developed a deep convective zone and therefore, according to the dynamo mechanism, should present a higher activity level. Anyway the cooler K0V component could also be active and present a faint emission in the H & K lines, but due to the small contribution of that star to the combined spectrum of the system, this emission is very difficult to be observed.

### 3.3. The $\text{Li I } \lambda 6707.8$ line

We also analyse here the Lithium abundance of EZ Peg using the  $\text{Li I } \lambda 6707.8$  line. This line appears in the order 33 of the WHT/UES echelle spectrum together with the  $\text{Fe I } \lambda 6678$  and  $\text{Ca I } \lambda 6718$  lines. In Fig. 2 we can clearly see the  $\text{Fe I}$  and  $\text{Ca I}$  lines from both components, the expected positions of these features for the hot (H) and cool (C) are given in this figure. However, the absorption  $\text{Li I}$  line appears centered in the wavelength-position corresponding to the hot component, so we can suppose that the absorption line comes only from this star or that the contribution of the cool component to the observed  $\text{Li I}$  is very small. This assumption seems to be reasonable because, as we show below, the hot component is the active star of the system and a high  $\text{Li I}$  abundance is found in chromospherically active binaries (Fernández-Figueroa et al. 1993; Barrado et al. 1997). In order to obtain the  $\text{Li I}$  equivalent width (EW), we have corrected the total EW measured,  $\text{EW}(\text{Li I} + \text{Fe I}) = 50.4$  (mÅ) from the relative contribution to the continuum (0.65). Then the contribution from the blend with the  $\text{Fe I } \lambda 6704.41$  line must be subtracted. The EW of the  $\text{Fe I}$  line was calculated from the empirical relationship with (B-V) given by Soderblom et al. (1990), obtaining  $\text{EW}(\text{Fe I}) = 15.8$  (mÅ), the same value is found with the relationship given by Favata et al. (1993) using the effective temperature. Finally, the corrected  $\text{EW}(\text{Li I})_{\text{corr}} = 61.7$  (mÅ) was converted into abundances by means of the curves of growth computed by Pallavicini et al. (1987), obtaining  $\log N(\text{Li I}) = 2.15$  (on a scale where  $\log N(\text{H}) = 12.0$ ) with an accuracy of  $\approx 0.30$  dex. This high  $\text{Li I}$  abundance is similar to that obtained for other chromospheri-

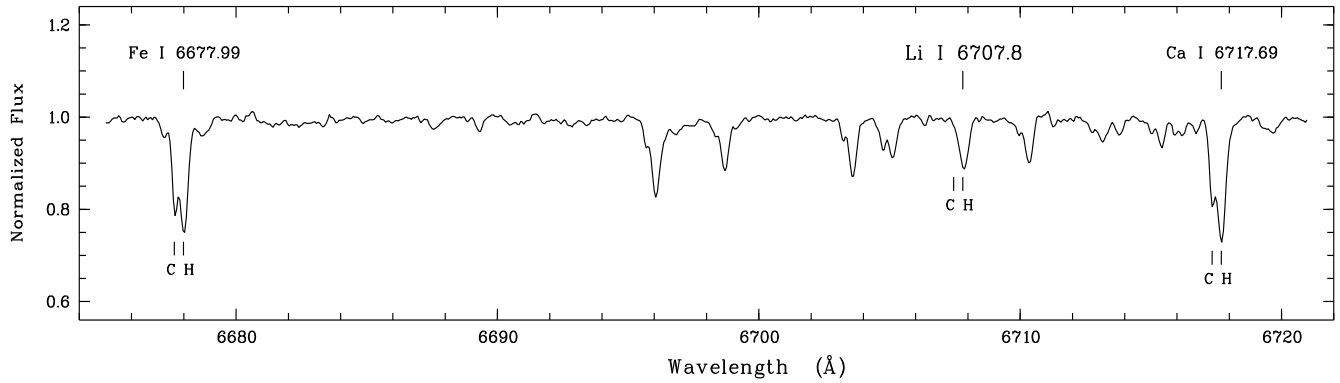
cally active binaries by Fernández-Figueroa et al. (1993) and Barrado et al. (1997) and it is related to the high activity level of EZ Peg.

## 4. Chromospheric activity indicators

In the following we describe the behaviour of the different optical chromospheric activity indicators (formed at different atmospheric heights) observed for EZ Peg:  $\text{Na I } D_1, D_2$ , and  $\text{Mg I } b$  triplet (upper photosphere and lower chromosphere),  $\text{Ca II IRT}$  lines (lower chromosphere),  $H\alpha, H\beta$ ,  $\text{Ca II H \& K}$  (middle chromosphere), and  $\text{He I } D_3$  (upper chromosphere). The chromospheric contribution in these features has been determined using the spectral subtraction technique described in detail by Montes et al. (1995a, b, c), (see also Paper I). The synthesized spectrum has been constructed with reference stars of spectral types G5V and K0IV, taken from the spectral library of Montes et al. (1997a), in the case of the INT/IDS spectra. For the WHT/UES spectrum we have used a G3V and K0V taken during the same observing run, and for the JKT/RBS spectrum a G5III-IV and K0V have been used. The use of reference spectra of spectral type slightly different for each observing run and different also from the system component spectra introduce some residual in the absorption lines, but it does not affect significantly the excess emission equivalent width measures in the subtracted spectra. The uncertainties are within similar order to that obtained in the reduction, synthesis and fitting procedures. Furthermore, we have considered a clear detection of excess emission or absorption lines only when these features in the difference spectrum are larger than  $3\sigma$ .

The contribution of the hot and cool components to the total continuum that yields a better fit between the observed and subtracted spectra is 0.65/0.35.

The line profiles are displayed in Figs. 1 - 8. For each spectrum we plot the observed (solid-line), the synthesized (dashed-line) and the subtracted one, additively offset for better display (dotted line).



**Fig. 2.** WHT/UES (Jul 1993), spectrum in the region of the Li I 6707.8 Å line including also the Fe I 6677.99 Å and Ca I 6717.69 Å. The expected positions of this features for the hot (H) and cool (C) components are given.

**Table 5.** Parameters of the broad and narrow Gaussian components used in the fit of the H $\alpha$  subtracted spectra

Obs.	$\varphi$	H $\alpha$ broad component				H $\alpha$ narrow component			
		I	FWHM (Å)	EW <sub>B</sub> (Å)	EW <sub>B</sub> /EW <sub>T</sub> (%)	I	FWHM (Å)	EW <sub>N</sub> (Å)	EW <sub>N</sub> /EW <sub>T</sub> (%)
UES 1993	0.954	0.273	3.935	1.143	54.8	0.648	1.367	0.942	45.2
INT 1995	0.416	0.152	4.035	0.651	43.7	0.535	1.470	0.837	56.3
"	0.501	0.129	4.096	0.562	40.1	0.535	1.470	0.838	59.9
INT 1996	0.141	0.123	9.418	1.209	53.2	0.493	2.028	1.064	46.8
"	0.224	0.124	5.622	0.740	39.7	0.520	2.028	1.122	60.3
"	0.306	0.091	5.528	0.536	32.0	0.572	1.876	1.142	68.0

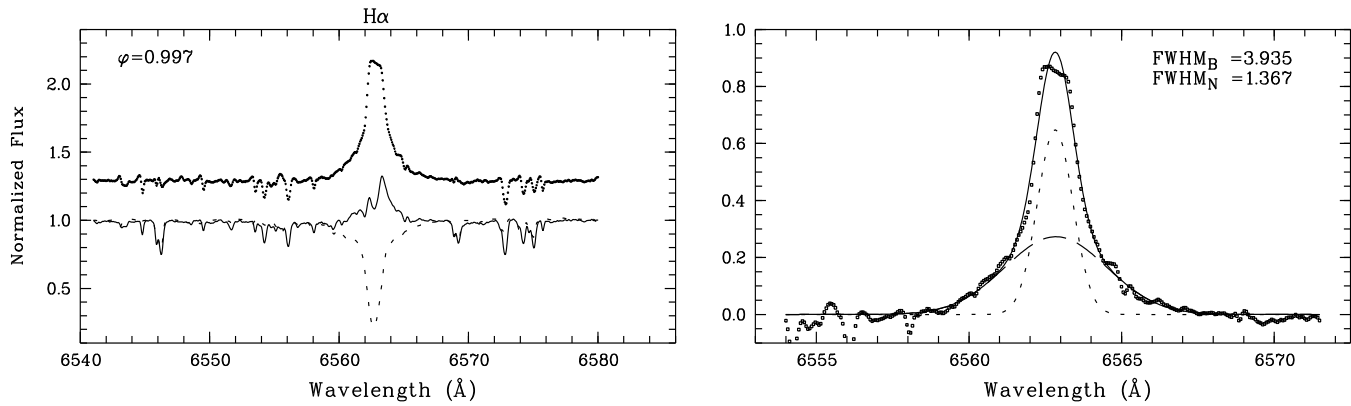
#### 4.1. The H $\alpha$ line

We have taken several spectra of EZ Peg in the H $\alpha$  line region in three different epochs. One WHT/UES spectrum in July 1993 at the orbital phase 0.954 (Fig. 3), two INT/IDS spectra in September 1995 at the phases 0.416 and 0.501 (Fig. 4) and three more INT/IDS spectra in November 1996 at the phases 0.141, 0.224 and 0.306 (Fig. 5). In all the spectra we can see the H $\alpha$  line in emission above the continuum with an asymmetry in the wavelength position corresponding to the H $\alpha$  absorption line of the cool component. The spectral subtraction reveals that the hot star is responsible for the excess H $\alpha$  emission.

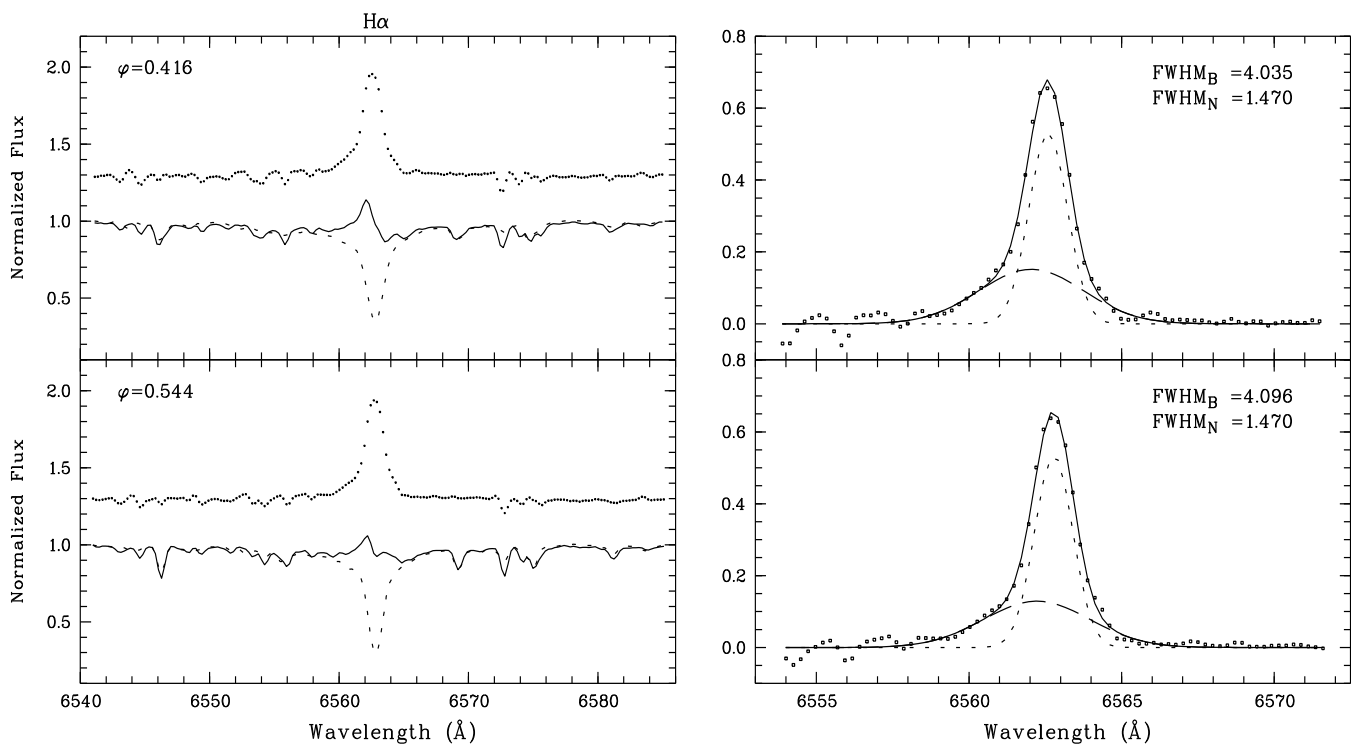
Table 4 gives the H $\alpha$  line parameters, measured in the observed and subtracted spectra of EZ Peg as follows: column (1) the observing run, column (2) the orbital phase ( $\varphi$ ) and columns (3), (4), (5) the following parameters measured in the observed spectrum: the full width at half maximum ( $W_{\text{obs}}$ ); the residual intensity,  $R_c$ ; and the H $\alpha$  core flux,  $F(1.7\text{\AA})$ , measured as the residual area below the central 1.7 Å passband. The last four columns give the following parameters measured in the subtracted spectrum: the full width at half maximum ( $W_{\text{sub}}$ ), the peak emission intensity (I), the excess H $\alpha$  emission equivalent width (EW(H $\alpha$ )), and absolute fluxes at the stellar surface  $\log F_S(\text{H}\alpha)$  obtained with the calibration of Pasquini & Pallavicini (1991) as a function of (V - R), very similar values of  $F_S(\text{H}\alpha)$  are obtained

using the more recent calibration of Hall (1996) as a function of (V - R) and (B - V). As can be seen in Table 4 and Figs. 3, 4 and 5 the excess H $\alpha$  emission of EZ Peg show small variations with the orbital phase and also seasonal variations from Jul 93 to Nov 96. The higher H $\alpha$  EW has been reached in the first night of the 1996 run and in the 1993 observation. The higher values correspond to the orbital phases closer to the conjunction (0.0).

The H $\alpha$  subtracted profiles present at all the epochs broad wings which are not well matched using a single-Gaussian fit. These profiles have therefore been fitted using two Gaussian components. The parameters of the broad and narrow components used in the two-Gaussian fit are given in table 5 and the corresponding profiles are plotted in the left panel of Figs. 3, 4 and 5. In some cases the blue wing is noticeable stronger than the red wing and the fit is better matched when the broad component is blue-shifted with respect to the narrow component. The cool component of EZ Peg cannot account for this effect since any emission from that star would be on the red side of the observed line for these orbital phases. We have also observed broad components in the most active systems of the sample of Paper I which we interpreted as microflaring that occurs in the chromosphere by similarity with the broad components also found in the chromospheric Mg II h & k lines (Wood et al. 1996) and in several transition region lines of active stars (Linsky & Wood



**Fig. 3.** WHT/UES  $H\alpha$  spectrum (Jul 1993). In the left panel we plot the observed spectrum (solid-line), the synthesized spectrum (dashed-line), the subtracted spectrum, additively offset for better display (dotted line). In the right panel we plot the subtracted  $H\alpha$  profile (dotted line), and the two Gaussian components fit (solid-line). The sort-dashed-line represents the broad component and the large-dashed-line the narrow one.



**Fig. 4.** INT/IDS  $H\alpha$  spectra (Sep 1995), as in Fig. 3

1994; Linsky et al. 1995; Wood et al. 1996, 1997; Dempsey et al. 1996a, b; Robinson et al. 1996). The contribution of the broad component to the total EW of the line of EZ Peg ranges between 32% and 55% which is in the range observed to the stars analysed in Paper I. The larger changes in the excess  $H\alpha$  emission appear to occur predominantly in the broad component and its contribution is related to the degree of stellar activity. It is noticeable the change in the wings of the  $H\alpha$  line from the 1st to the 2nd night of the 1996 run, the two Gaussian components fit reveals that the contribution of the broad component changes from 53.2% to 39.7% (see Fig. 5).

#### 4.2. The $H\beta$ line

Two spectra in the  $H\beta$  line region are available. The WHT/UES spectrum (July 1993) and other in the INT/IDS 1996 run. In both spectra the  $H\beta$  line appears in absorption and the application of the spectral subtraction technique reveals a clear excess emission in this line (see Fig. 6). Again the relative velocity shift shows that the emissions belong to the hotter component. Contrary to the case of the  $H\alpha$  line the  $H\beta$  subtracted profiles do not present broad wings and they are well matched using a single-Gaussian fit.

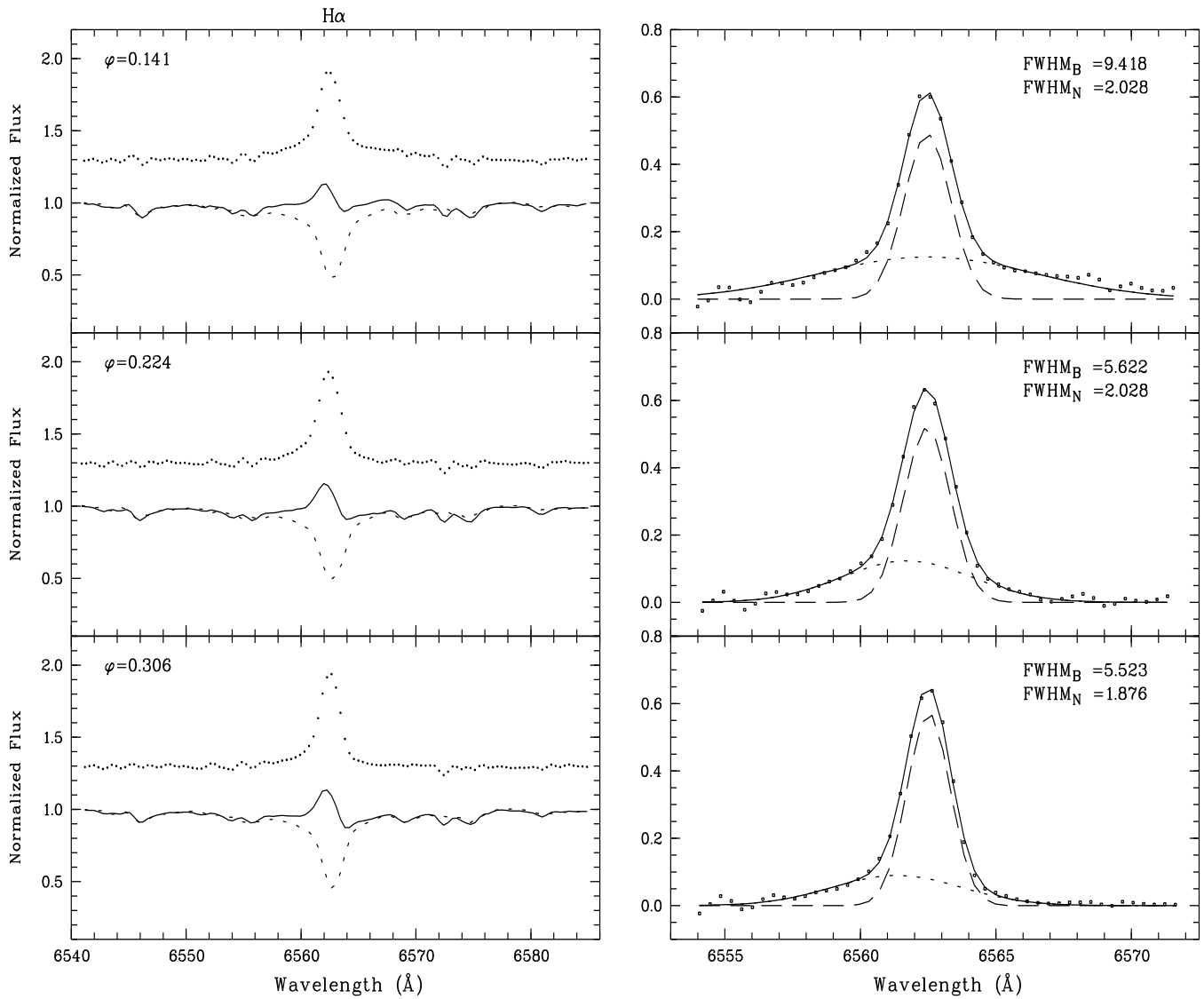


Fig. 5. INT/IDS H $\alpha$  spectra (Nov 1996), as in Fig. 3

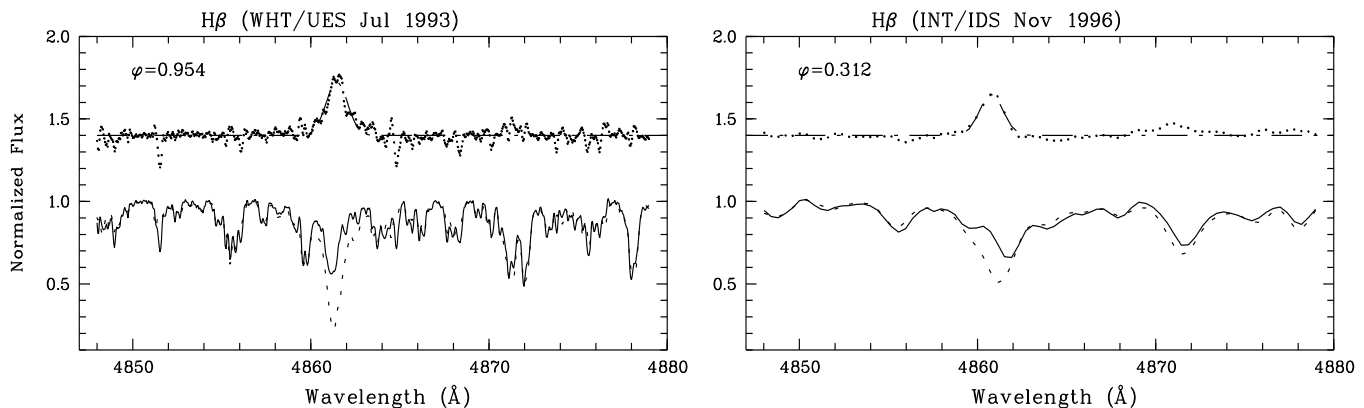


Fig. 6. WHT/UES H $\beta$  (Jul 1993) and INT/IDS H $\beta$  (Nov 1996) spectra. For each spectrum we plot the observed spectrum (solid-line), the synthesized spectrum (dashed-line), the subtracted spectrum, additively offset for better display (dotted line), and the Gaussian fit to the subtracted spectrum (dotted-dashed line)



Table 6 gives the  $H\beta$  line parameters, measured in the observed and subtracted spectra as in the case of the  $H\alpha$  line, see also our previous study of the excess  $H\beta$  emission in active binaries (Montes et al. 1995d).

In Table 6 we also give the ratio of excess emission  $EW$ ,  $\frac{EW(H\alpha)}{EW(H\beta)}$ , for the two  $H\beta$  observations of EZ Peg, and the ratio of excess emission  $\frac{E_{H\alpha}}{E_{H\beta}}$  with the correction:

$$\frac{E_{H\alpha}}{E_{H\beta}} = \frac{EW(H\alpha)}{EW(H\beta)} * 0.2444 * 2.512^{(B-R)},$$

given by Hall & Ramsey (1992) that takes into account the absolute flux density in these lines and the color difference in the components.

We have used this ratio as a diagnostic for discriminating between the presence of plages and prominences in the stellar surface, following the results of Hall & Ramsey (1992) who found that low  $E_{H\alpha}/E_{H\beta}$  ( $\approx 1-2$ ) can be achieved both in plages and prominences viewed against the disk, but that high ratios ( $\approx 3-15$ ) can only be achieved in extended regions viewed off the limb. The high ratio ( $E_{H\alpha}/E_{H\beta} > 3$ , see Table 6) that we have found in EZ Peg indicates that the emission would arise from extended regions (prominences).

The excess  $H\beta$  emission is somewhat larger in the 1993 observation than in the last night observation of the 1996 run, in agreement with the behaviour observed for the  $H\alpha$  line.

#### 4.3. The Na I D<sub>1</sub> and D<sub>2</sub> and He I D<sub>3</sub> lines

We have five spectra of EZ Peg in the region of Na I D<sub>1</sub> and D<sub>2</sub> and He I D<sub>3</sub> lines: one WHT/UES spectrum in July 1993 at the orbital phase 0.954 (Fig. 7), two INT/IDS spectra in September 1995 at the phases 0.414 and 0.500 and two spectra in INT/IDS November 1996 at the phases 0.225 and 0.310 (Fig. 8). We have not detected any significant absorption or emission for He I D<sub>3</sub>.

Saar et al. (1997) in their study of He I D<sub>3</sub> in G and K dwarfs found that while for few active stars the He I D<sub>3</sub> line behaves "normally", increasing in absorption with increasing rotation, and showing consistent correlations with other activity indicators, the behavior clearly diverges when stars become very active. They found a large filling-in He I D<sub>3</sub> line in some very active K stars. On the other hand, they also found He I D<sub>3</sub> EW significantly lower than the theoretical maximum value given by Andretta & Giampapa (1995), suggesting that the line could be filling-in due to frequent low-level flaring.

Both facts could explain the absence of emission or absorption due to a total filling-in of the He I D<sub>3</sub> line that we have found in EZ Peg and also in other dwarfs and subgiants chromospherically active binaries (see Paper I), since these stars are very active and also present low-level flaring (microflares) as indicated by the  $H\alpha$  broad component that we have found (see sect. 4.1 and Paper I). In some cases He I D<sub>3</sub> goes into emission due to flares (Huenemoerder & Ramsey 1987; Huenemoerder et al. 1990; Montes et al. 1996b; Paper I). However, in the most evolved stars the behaviour is different as consequence of the lower chromospheric densities of these stars, as it is suggested

by Saar et al. (1997) and as it is indicated by the presence of the He I D<sub>3</sub> in absorption that we have reported in Paper I for several chromospherically active binaries with giant components.

In the Na I D<sub>1</sub> and D<sub>2</sub> lines the spectra are too noisy to distinguish a clear filled-in. Once again we can observe (see Fig. 7) that the redward lines of the double-lined spectrum usually are the deepest, but in the Na I D blueshifted components are the deepest ones. As it is well known, the Na I D lines are very sensitive to the temperature; this behaviour of the lines confirms that the hot star of the system is the redshifted one, which, as mentioned above, shows very high activity in  $H\alpha$ .

#### 4.4. The Mg I b triplet lines

The Mg I b triplet lines  $\lambda 5167.33$ ,  $\lambda 5172.68$ , and  $\lambda 5183.61$  are formed in the lower chromosphere and the region of temperature minimum and they are good diagnostics of photospheric activity (Basri et al. 1989). A small filling-in of these lines have been recently found in some RS CVn system (Gunn & Doyle 1997; Gunn et al. 1997). As in the case of the Na I D<sub>1</sub> and D<sub>2</sub> lines, in the subtracted spectrum corresponding to the echelle images no clear filled-in has been found. Thus the photospheric activity in EZ Peg is very low.

#### 4.5. The Ca II H & K and He I lines

We have taken three spectra in the Ca II H & K line region during the 1996 run (see Fig. 9). These spectra exhibit strong Ca II H & K emission lines and a small bump in the wavelength-position corresponding to the He I line. The H & K emission lines appear blue-shifted with respect to the observed absorption lines in agreement with the orbital phase, which confirms that the emission originates in the hot component. The spectral subtraction yields a satisfactory fit and reveals a small but clear emission in the He I line.

The excess Ca II H & K and He I emissions equivalent widths (EW) have been measured by reconstruction of the absorption line profile (described by Fernández-Figueroa et al. 1994) and using the spectral subtraction technique (explained by Montes et al. 1995c, 1996a). The Ca II H & K surface flux,  $F_S(\text{Ca II H \& K})$  has been obtained by means of the linear relationship between the absolute surface flux at 3950 Å (in  $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$ ) and the colour index (V-R) by Pasquini et al. (1988).

Table 7 gives the Ca II H & K and He I line parameters, measured in the observed and subtracted spectra. Column (1) gives the observing run. Column (2) gives the orbital phase ( $\varphi$ ). In columns (3) and (4) we list the EW for the K and H lines, obtained by reconstruction of the absorption line profile, in columns (5) to (7) we give the EW for the K, H and He I lines, measured in the subtracted spectrum, and in columns (8) to (10) the corresponding surface fluxes are listed.

The excess Ca II H & K and He I emissions change with the orbital phase during the three nights of the 1996 run in the same way as the corresponding excess  $H\alpha$  emissions.

**Table 6.**  $H\beta$  line measurements in the observed and subtracted spectrum

Obs.	$\varphi$	Observed $H\beta$ Spectrum			Subtracted $H\beta$ Spectrum			$\frac{EW(H\alpha)}{EW(H\beta)}$	$\frac{E_{H\alpha}}{E_{H\beta}}$
		$W_{obs}$ ( $\text{\AA}$ )	$R_c$	$F(1.7\text{\AA})$	$W_{sub}$ ( $\text{\AA}$ )	I	EW ( $\text{\AA}$ )		
UES 1993	0.954	0.91	0.561	1.235	0.94	0.364	0.489	4.27	3.49
INT 1996	0.312	2.13	0.660	1.237	1.54	0.244	0.411	4.08	3.33

**Table 7.** Ca II H & K and H $\epsilon$  lines measures in the observed and subtracted spectrum

Obs.	$\varphi$	Reconstruction		Spectral subtraction			Absolute flux		
		EW (K)	EW (H)	EW (K)	EW (H)	EW (H $\epsilon$ )	log F (K)	log F (H)	log F (H $\epsilon$ )
INT 1996	0.148	0.982	0.718	1.246	0.931	0.292	6.91	6.79	6.28
"	0.220	0.975	0.671	1.191	0.910	0.194	6.82	6.78	6.10
"	0.314	0.948	0.628	1.142	0.907	0.185	6.87	6.77	6.08

**Table 8.** Ca II IRT lines measured in the observed and subtracted spectra

Obs.	$\varphi$	Reconstruction			Spectral subtraction			Absolute flux		
		EW $\lambda 8498$	EW $\lambda 8542$	EW $\lambda 8662$	EW $\lambda 8498$	EW $\lambda 8542$	EW $\lambda 8662$	log F $\lambda 8498$	log F $\lambda 8542$	log F $\lambda 8662$
UES 1993	0.954	0.256	-	0.238	0.680	-	0.892	6.43	-	6.55
JKT 1997	0.511	-	-	-	0.397	0.471	0.453	6.19	6.26	6.25

#### 4.6. The Ca II IRT lines

The Ca II infrared triplet (IRT)  $\lambda 8498$ ,  $\lambda 8542$ , and  $\lambda 8662$  lines are other important chromospheric activity indicators (Linsky et al. 1979; Foing et al 1989; Dempsey et al. 1993). These lines share the upper levels of the Ca II H & K transitions (see for example Mihalas 1978), but unlike the blue Ca II lines, the IRT lies in a region of the spectrum with a well-defined continuum, making the calibration simpler. The IRT is formed in the lower chromosphere. Shine & Linsky (1972, 1974) observed solar IRT plage profiles concluding that the emission results from a steepening of the temperature gradient in the chromosphere. This forces the temperature, electron density, and Ca II density population to be higher for a given optical depth, compared to the quiet chromosphere, thus increasing the source function thereby producing emission in the line cores.

In the observations carried out by Dempsey et al. (1993) only one star of the sample (BY Dra) showed emission above the local continuum in only the  $\lambda 8498$  line, and other seven stars revealed emission rising above the shallow line core.

The  $\lambda 8498$  and  $\lambda 8662$  lines are included in the 1993 WHT/UES echelle spectrum of EZ Peg (see Fig. 10), and both

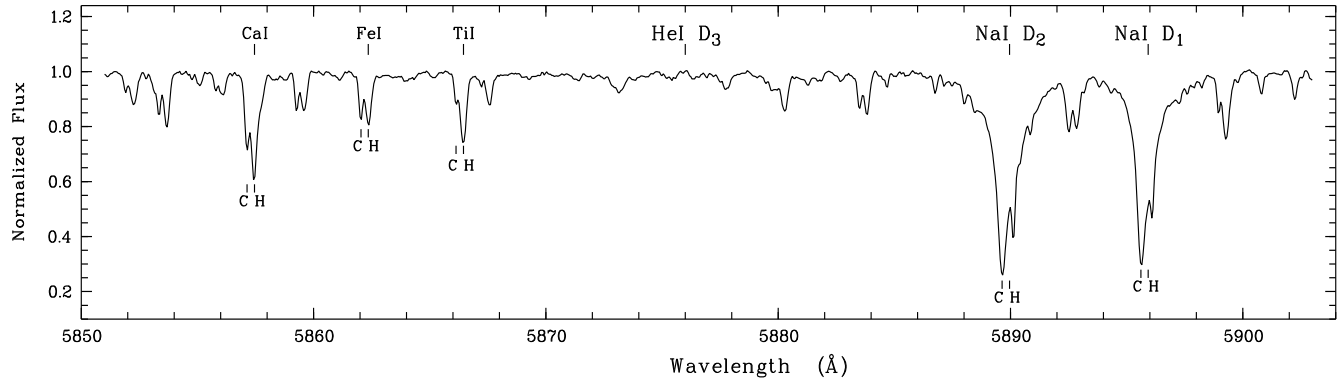
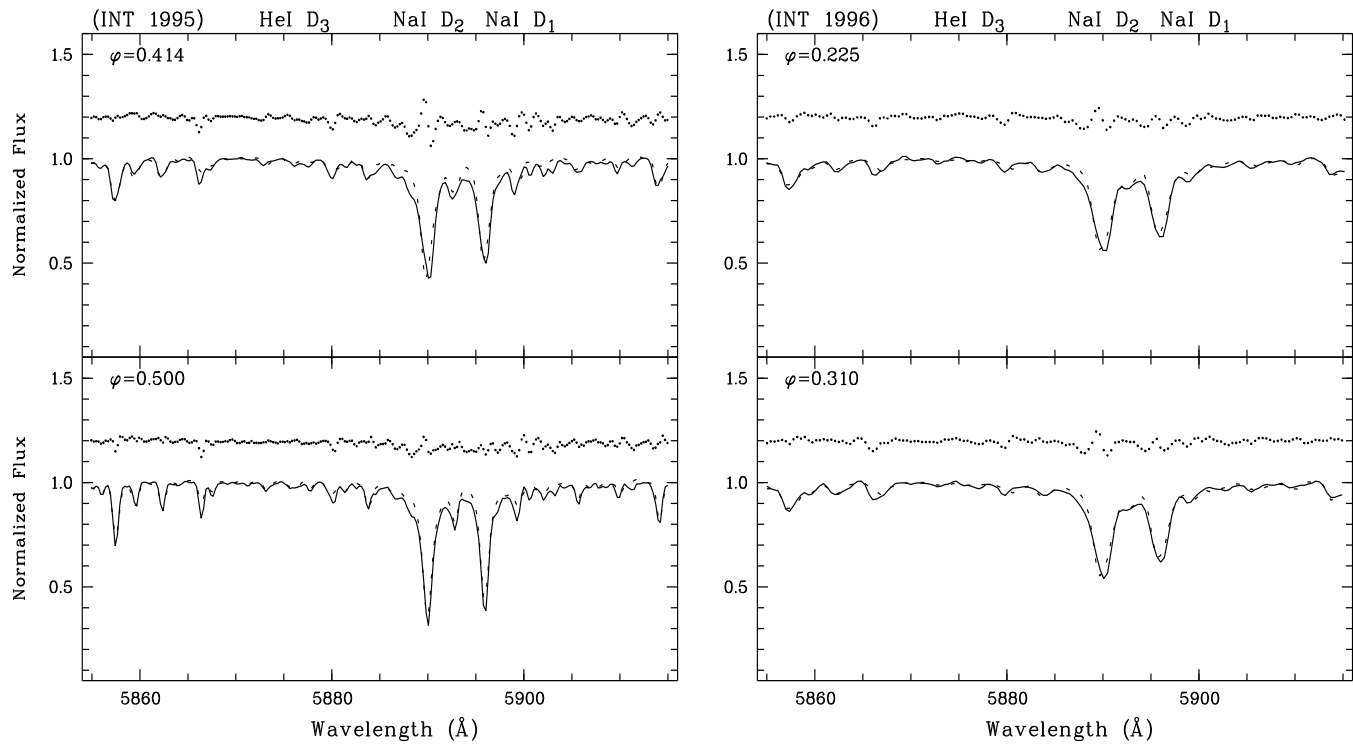
lines exhibit a strong emission superposed to the red wing of the corresponding absorption line, in agreement with the orbital phase (0.954). In the 1997 JKT/RBS spectrum at orbital phase 0.511 the three Ca II IRT lines are included (see Fig. 11). In this case the lines show a small emission reversal centered at the absorption line in the observed spectrum and a clear excess emission in the difference spectrum.

Table 8 gives the Ca II IRT line parameters, measured in the observed spectra by reconstruction of the absorption line profile, and using the spectral subtraction. The columns in this table have the same meaning as for the Ca II H & K lines (see Table 7). Notice that the underestimation of the reconstruction method is larger for the IRT lines than for the Ca II H & K lines. The absolute fluxes at the stellar surface have been obtained using the calibration of Hall (1996) as a function of (V - R).

As in the case of the H $\alpha$  line the subtracted profiles of the  $\lambda 8498$  and  $\lambda 8662$  lines also present broad wings. Therefore we have used, as for the H $\alpha$  profile, a two gaussian (broad and narrow) fit. In Table 9 we list the parameters (I, FWHM, EW) of the broad and narrow components. The narrow components of both lines are very similar; however, the contribution of the

**Table 9.** Parameters of the broad and narrow Gaussian components used in the fit of the Ca II IRT subtracted spectra

Obs.	$\varphi$	Broad component				Narrow component			
		I	FWHM (Å)	EW <sub>B</sub> (Å)	EW <sub>B</sub> /EW <sub>T</sub> (%)	I	FWHM (Å)	EW <sub>N</sub> (Å)	EW <sub>N</sub> /EW <sub>T</sub> (%)
Ca II IRT line $\lambda 8498$									
UES 1993	0.954	0.089	2.497	0.237	34.8	0.693	0.600	0.442	65.2
Ca II IRT line $\lambda 8662$									
UES 1993	0.954	0.086	5.393	0.452	50.7	0.564	0.733	0.440	49.3

**Fig. 7.** WHT/UES (Jul 1993), spectrum in the region of the NaI and HeI lines including also the CaI 5857.454 Å, FeI 5862.357 Å and TiI 5866.453 Å. The expected positions of these features for the hot (H) and cool (C) components are given.**Fig. 8.** INT/IDS spectra in the region of the NaI and HeI lines (Sep 1995) and (Nov 1996). For each spectrum we plot the observed spectrum (solid-line), the synthesized spectrum (dashed-line), the subtracted spectrum, additively offset for better display (dotted line).

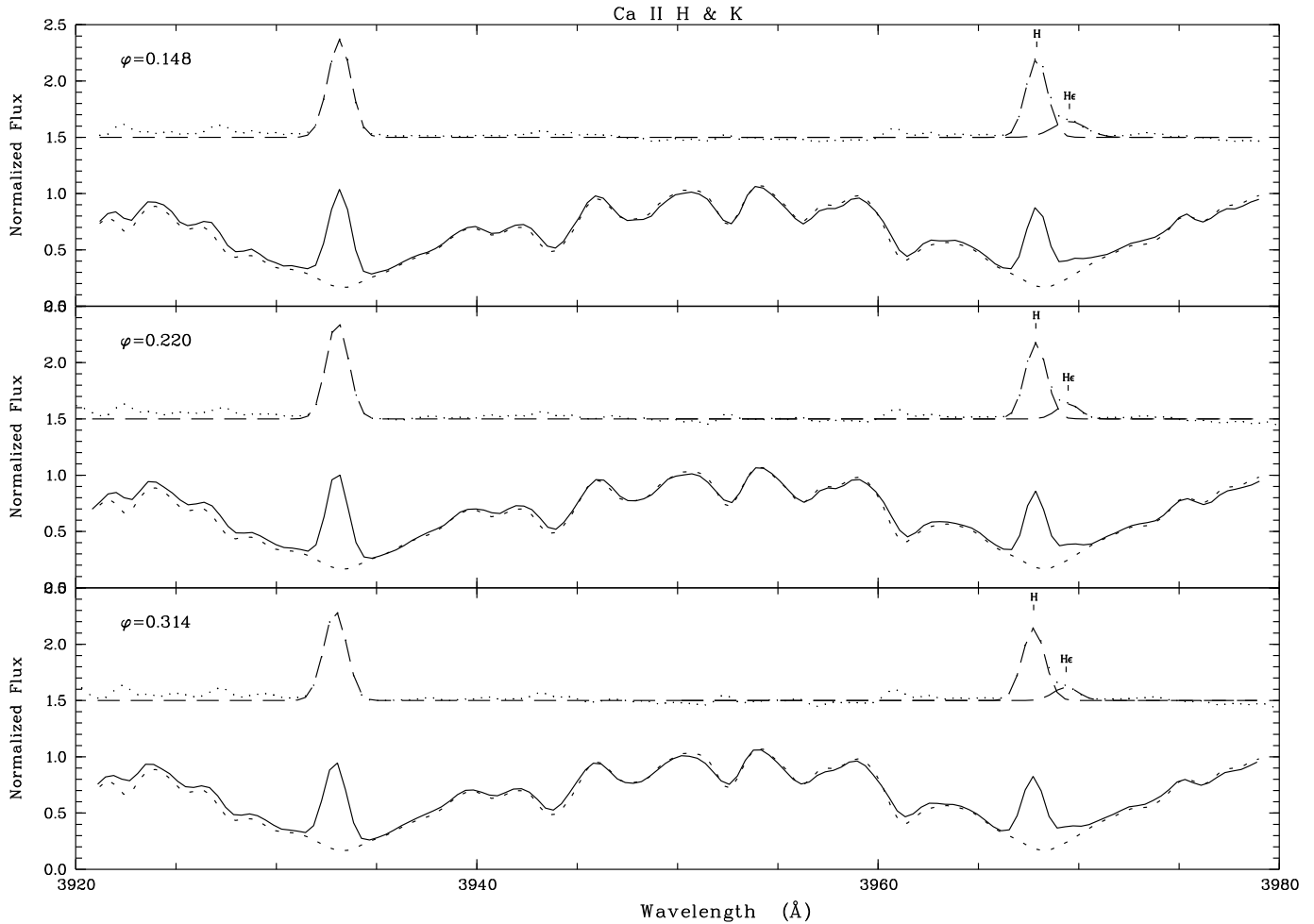


Fig. 9. INT/IDS Ca II H & K spectra (Nov 1996), as in Fig. 6

broad component to the total EW is larger in the  $\lambda 8662$  line. In the subtracted spectrum the intensity of the  $\lambda 8498$  line is higher than in  $\lambda 8662$ ; however, due to the contribution of the broad component, the total excess emission EW is larger in the  $\lambda 8662$  line.

## 5. Conclusions

In this paper we have analysed, using the spectral subtraction technique, simultaneous spectroscopic observations of several optical chromospheric activity indicators, at different epochs, of the RS CVn binary system EZ Peg.

We have found the  $H\alpha$  line in emission above the continuum in all the spectra, with noticeable changes in the line profile, that in part are due to the superposition of the absorption line to the other component. The subtracted  $H\alpha$  profile is well matched using a two-components Gaussian fit (narrow and broad). The broad component is mainly responsible for the observed variations of the subtracted profile, and its contribution to the total EW increases with the degree of activity. We have interpreted this broad component (also observed in other active systems in

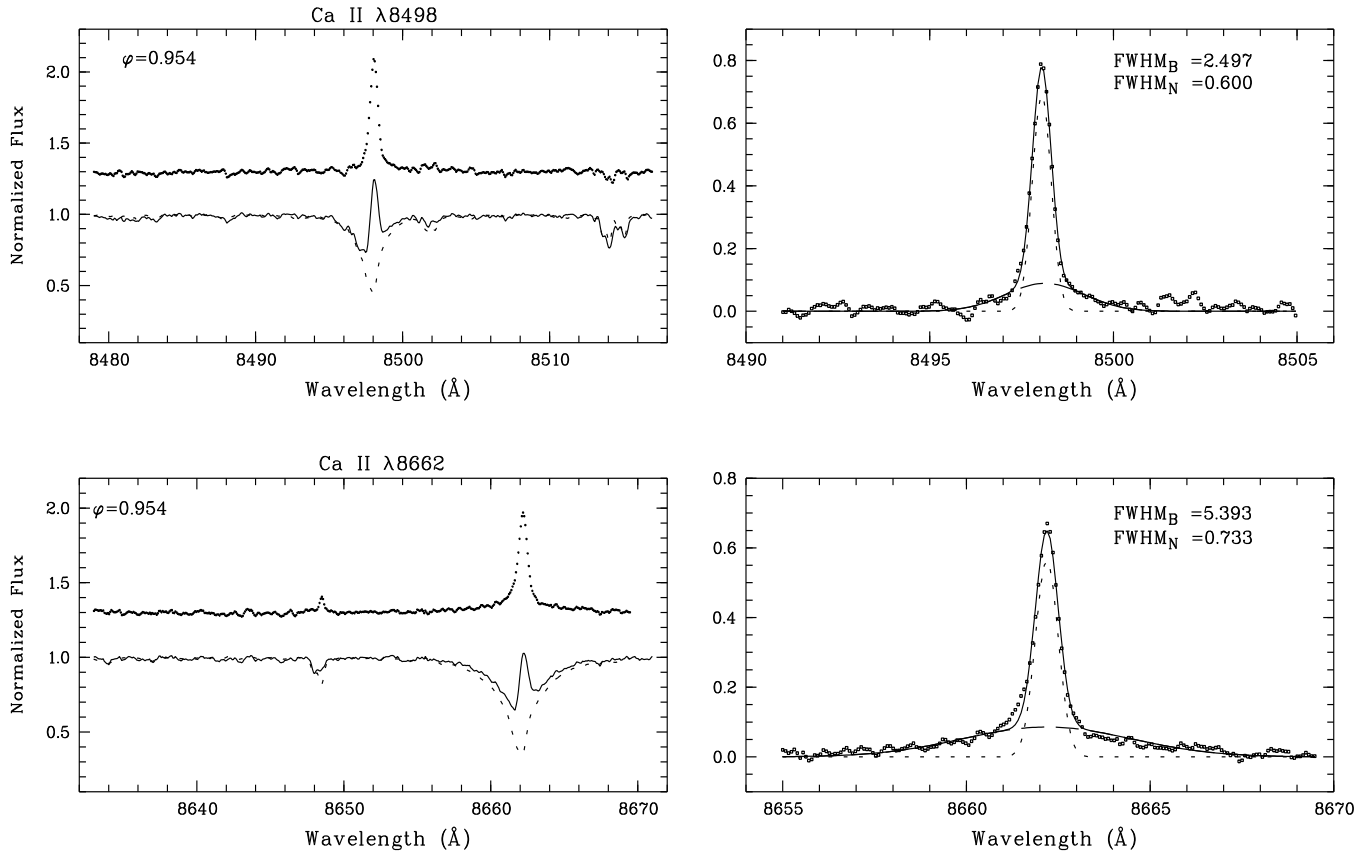
Paper I) as arising from microflaring activity that take place in the chromosphere.

A filled-in in the  $H\beta$  line has been found; however, the subtracted profiles do not present broad wings. The ratio ( $E_{H\alpha}/E_{H\beta}$ ) that we have found indicates that the emission would arise from extended regions viewed off the limb.

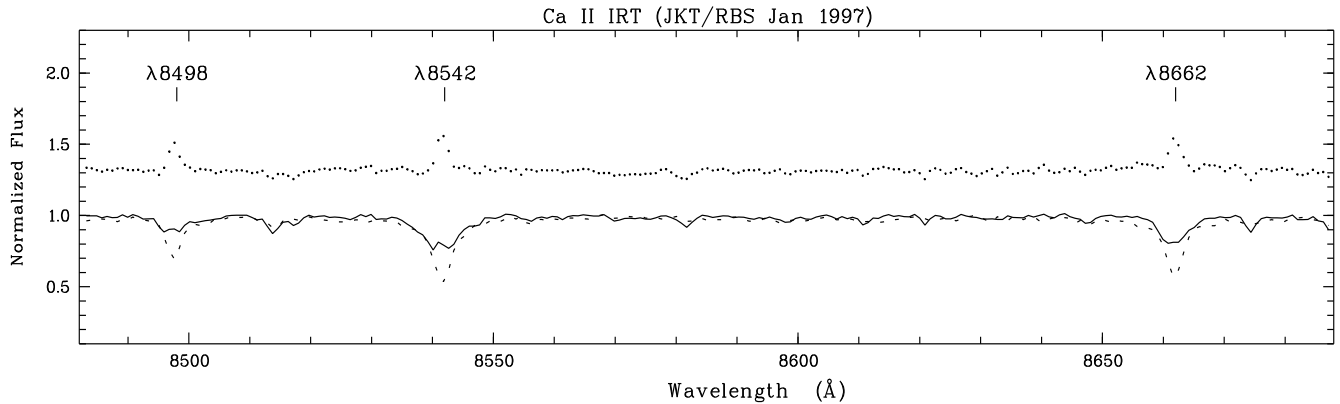
Strong Ca II H & K emission from the hot component is observed in our spectra. The spectral subtraction reveals also a small but clear emission in the  $H\epsilon$  line. The lines  $\lambda 8498$  and  $\lambda 8662$  of the Ca II IRT also show a strong emission. As in the case of the  $H\alpha$  line the subtracted profiles of these lines are well matched using a two-component Gaussian fit.

We suggest that the He I  $D_3$  could present a total filling-in due to microflaring. We have not found filled-in by chromospheric emission in the Na I  $D_1$  and  $D_2$  lines nor in the Mg I b triplet lines.

All the activity indicators analysed here indicate that the hot component is the active star of the system, contrary to the usual behaviour observed in chromospherically active binaries. The variations (in different epochs and with the orbital phase)



**Fig. 10.** WHT/UES Ca II IRT  $\lambda$  8498 and  $\lambda$  8662 spectra (Jul 1993), as in Fig. 3



**Fig. 11.** JKT/RBS Ca II IRT spectrum (Jan 1997) at orbital phase 0.511

observed in the different indicators, formed at different heights in the chromosphere, are correlated.

The analysis of several Ti I lines with a positive effect in luminosity class indicates that the hot component is not a main sequence star but a subgiant or even of higher luminosity class, in contrast with the cool component that seems to be a dwarf. This result is confirmed by the application of the Wilson-Bappu effect to our Ca II K spectra. This difference in luminosity class, and therefore in convective zone depth, between the hot and cool

components could explain why the hot component is the active star of the system.

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