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Search for activity-induced variability in AR Lac, KT Peg, KZ And, II Peg and EI Eri in autumn 1997

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Abstract. We report on a search for activity-induced variability in the SB2 systems AR Lac, KT Peg and KZ And as well as in the SB1 systems II Peg and EI Eri in the September 1997 season. The study of Hα line profiles, Na I 5889Å doublet, Ca II IRT lines and TiO 7055Å absorption band is presented. The spot properties were estimated for the systems AR Lac and II Peg. The former possesses spots at intermediate stellar latitudes on the primary component while the latter shows these surface inhomogeneities at low latitudes. In both cases, the spots cooler than the surrounding photosphere were revealed. Significant variability in the hydrogen Hα line profile was observed on II Peg and EI Eri, and the evidence of a rotational modulation was found in KT Peg and II Peg.

Key words: late-type stars – activity – spots

1. Introduction

This study aims at probing the presence of magnetic activity, its level and orbital modulation in a sample of SB2 and SB1 binary systems by using selected activity indicators. Solar-like activity manifestations such as photospheric spots and chromospheric emission lines are known to be present on a variety of late-type stars as the result of underlying magnetic fields and yet little understood dynamo processes. In particular, in this paper the activity level is derived from Hα line profiles, from Na I 5889Å doublet and Ca II IRT spectroscopic lines and from the TiO 7055Å absorption band, while basic spots properties are estimated from broad band UBV photometry and TiO spectroscopy.

2. Observations

Between September 15 and September 22 1997, we used the fiber-fed echelle spectrograph MUSICOS at the 2.5m INT telescope at La Palma, Canary Islands, Spain, to obtain relatively high resolution (~0.1Å) spectra in the spectral interval from 4335Å up to 9700Å for a sample of active binaries (see Table 1). The present study is based on the data collected during the nights of September 17, 18, 19 and 21.
The instrumental setup was chosen in such a way to have the spectral features of interest approximately at the center of the echelle order, where the typical signal reached 3000-10 000 counts per pixel depending on the echelle order. The spectroscopic data set (selected echelle orders) is available in an electronic form at the http://www.astro.sk/caosp/Eedition/FullTexts/vol35no1/pp23-34.dat/ address.

This spectroscopy was complemented by contemporary UBV photometry obtained at the Catania Astrophysical Observatory by the 80-cm Automatic Photometric Telescope on Mt. Etna (Messina et al. 2002).

Table 1. Programme stars.

Star	m_V (mag)	p_{orb} (=p_{rot}) (d)	i_{orb}	Sp.	lum. ratio	$v \sin i$ km s^{-1}	L_X (Watt)
AR Lac	6.1	1.98	87°	G2IV/K0IV	3:7∇	46/73	1.050
KT Peg	7.0	6.20	49°	G2V/K5V	1:8	10/9	0.015
KZ And	7.9	3.03	60°	K2V/K2V	1:1	11/11	0.073
II Peg	7.4	6.72	—	K2IV	—	~ 23	0.606
EI Eri	7.1	1.95	—	G5IV	—	~ 51	1.380

Note: ∇ out of eclipse, X-ray luminosity L_X in 10^{24} Watts.

3. Analysis

The spectra were routinely analysed and the Hα line profiles, after correction for orbital motion, stellar luminosities and eclipses (if necessary) were subsequently subtracted from stellar theoretical line profiles (composite profiles were used in the case of SB2 systems) to determine the residual flux emission (see Zboril et

al. 2004). Moreover, all spectral features were fitted by a Gaussian function to obtain the radial velocities, central intensities and the equivalent widths (EW). Due to a high noise level, the numerical integration process for estimating EWs was eventually leaved out. The results are shown in Figures 1 and 2 and summarised in Tables 2 and 3.
Programme stars were photoelectrically observed differentially with respect to nearby non-variable comparison stars. Instrumental differential magnitudes, after correction for atmospheric extinction, were transformed into absolute values of the UBV Johnson standard system. Finally, the observed V light curves and colour indexes were fitted with the theoretical ones. Specifically, Djurasevic's code (1992) based on the Roche model was applied to AR Lac system and the code SpotMod for SB1 systems to II Peg. The SpotMod code uses several iterative procedures (free of analytical derivatives), the Barnes-Evans surface flux relationship and black-body fluxes to produce synthetic light curves (Zboril 2003). The basic properties of the programme stars are listed in Table 1.

The SB2 system **AR Lac** (HD 210334) is the only eclipsing binary system in our sample. The phases covered by our spectroscopic observations allowed us to study only the orbital eclipses. The level of activity of the system has been monitored over many years; for instance Frasca et al. (2000) investigated the long-term chromospheric activity and radial velocities derived from the Hα line profiles. Gehren et al. (1999) deduced photospheric abundances and stellar parameters of the system during the total eclipse of the primary G2 IV component. In modelling the light curve, the stellar size is described by the filling factors for the critical Roche lobes $F_{\rm h,c}$ of the hotter primary and cooler secondary component, respectively, which tell us to what degree the stars in the system fill their corresponding critical lobes. For synchronous rotation of the components, these factors are expressed as the ratio of the stellar polar radii, $R_{\rm h,c}$, and the corresponding polar radii of the critical Roche lobes, i.e., $F_{\rm h,c} = R_{\rm h,c}/R_{\rm Roche_{h,c}}$. Tidal effects are expected to contribute to synchronisation of the rotational and orbital periods. Therefore, in the inverse problem we adopted $f_{\rm h,c} = \omega_{\rm h,c}/\omega_{\rm K} = 1.0$ for nonsynchronous rotation coefficients, where $f_{\rm h,c}$ is the ratio of the angular rotation rate ($\omega_{\rm h,c}$) to the Keplerian ($\omega_{\rm K}$) orbital revolution rate.
The mass ratio of the components was fixed in the inverse problem at $m_{\rm h}/m_{\rm c} = 0.894 \pm 0.006$, estimated by Frasca et al. (2000) from a radial velocity solution. Based on the spectral type G2 IV, the temperature of the hotter and less massive component, $T_{\rm h}$, was set at 5100 K (Gehren et al. 1999).
Following Lucy (1967), Rucinski (1969) and Rafert & Twigg (1980), the gravity-darkening coefficients of the stars, $\beta_{\rm h,c}$, and their albedos, $A_{\rm h,c}$, were set at the values of 0.08 and 0.5, respectively, appropriate for stars with convective envelopes.

The following ephemeris (Marino et al. 1998)

$$HJD = 2450692.5174 + 1^{d}.983188 \times E \tag{1}$$

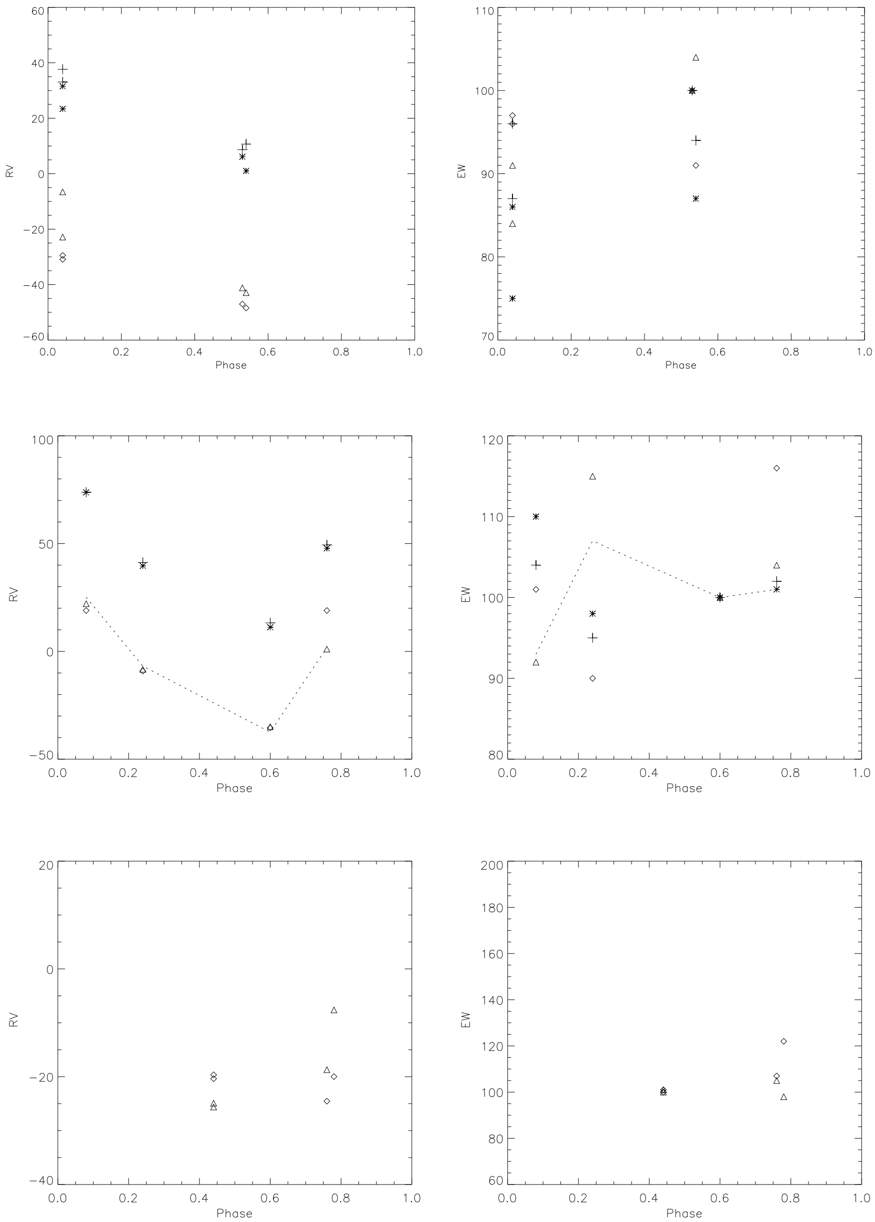

Figure 1. The radial velocities and equivalent widths for AR Lac (upper panel), KT Peg (middle panel) and KZ And (bottom panel): symbols (+) and (∗) refers to Na I doublet while (△) and (◇) to Ca II IRT lines; the Hα data with dotted line.

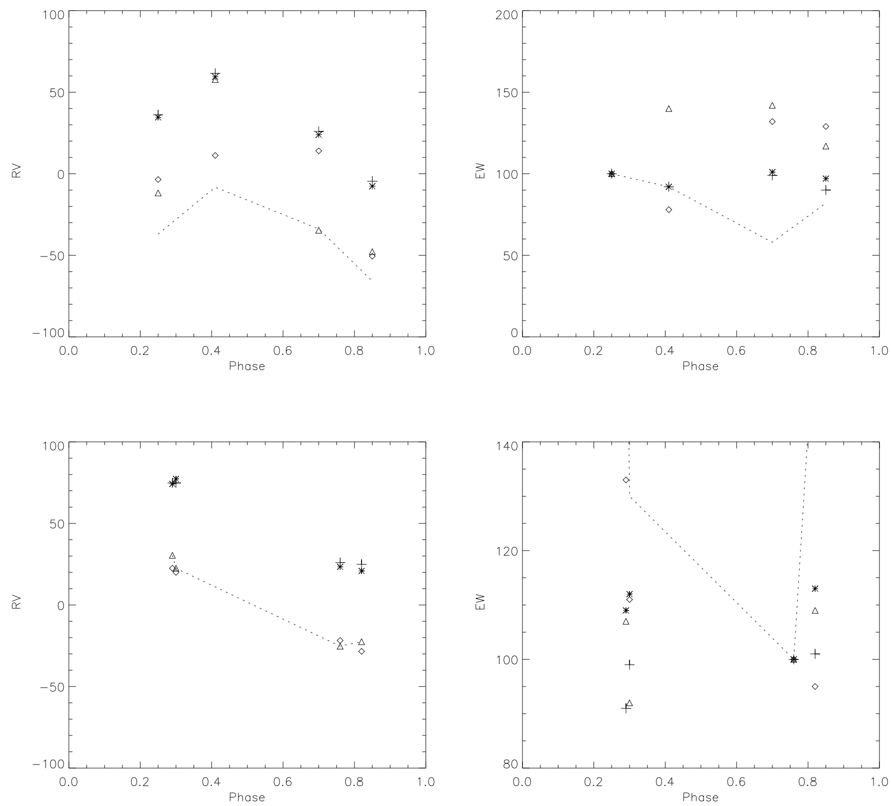

Figure 2. The radial velocities and equivalent widths for II Peg and EI Eri.

was used to obtain the phased light curves in Fig. 3. For instance, we want to point out that the AR Lac spectra we collected could be inter-compared with the set of spectra in Gehren et al. (1999), which, though obtained with a different instrument set-up, revealed a discrepancy of only $\sim 3\%$ in the hydrogen Hα line core while the line profiles resulted to be identical. Thus, this extended dataset is suitable for the relative analysis process at least (e.g. orbital phases etc.).

Note to Table 4: n - number of observations, $\Sigma(\mathrm{O}-\mathrm{C})^2$ - final sum of squares of residuals between observed (LCO) and synthetic (LCS) light curves, σ - standard deviation of the observations, $m_\mathrm{h}/m_\mathrm{c}$ - mass ratio of the components, $f_{\mathrm{h,c}}$, $\beta_{\mathrm{h,c}}$, $\mathrm{A}_{\mathrm{h,c}}$ - nonsynchronous rotation coefficients, gravity-darkening coefficients and albedo of the components, $T_{rmh,c}$ - temperature of the hotter G2 IV primary and cooler K0 IV secondary, A_S, θ_S, λ_S and φ_S - spots' temperature

Table 2. Programme stars-central wavelengths.

Star	phase	Hα	Na I1	Na I2	Ca II IRT1	Ca II IRT2
AR Lac	0.53	—	5889.17	5895.12	8540.80	8660.98
AR Lac	0.04	—	5889.65	5895.46	8541.30	8661.98
AR Lac	0.04	—	5889.74	5895.62	8541.26	8661.51
AR Lac	0.54	—	5889.21	5895.02	8540.76	8660.93
KT Peg	0.60	6561.99	5889.26	5895.22	8541.13	8661.16
KT Peg	0.76	6562.85	5889.97	5895.94	8542.08	8662.20
KT Peg	0.08	6563.36	5890.45	5896.45	8542.68	8662.81
KT Peg	0.24	6562.66	5889.81	5895.78	8541.90	8661.93
KZ And	0.44	—	—	—	8541.58	8661.43
KZ And	0.78	—	—	—	8541.57	8661.95
KZ And	0.44	—	—	—	8541.56	8661.45
KZ And	0.76	—	—	—	8541.44	8661.63
II Peg	0.25	6562.00	5889.71	5895.68	8542.04	8661.83
II Peg	0.41	6562.63	5890.21	5896.17	8542.46	8663.84
II Peg	0.70	6562.07	5889.51	5895.47	8541.54	8661.17
II Peg	0.85	6561.37	5888.91	5894.85	8540.70	8660.79
EI Eri	0.76	6562.47	5889.51	5895.46	8541.27	8661.44
EI Eri	0.29	6563.76	5890.47	5896.46	8542.78	8663.05
EI Eri	0.30	6563.75	5890.47	5896.52	8542.71	8662.82
EI Eri	0.82	6562.54	5889.49	5895.41	8541.33	8661.52

Note: Na I1-5889Å, Na I2-5895Å, Ca II IRT1-8540Å, Ca II IRT2-8660Å

coefficient, angular dimension, longitude and latitude (in arc degrees), $\mathrm{F_{h,c}}$ - filling factors for the critical Roche lobe of the hotter (less-massive) and cooler (more-massive) star, i [°] - orbit inclination (in arc degrees), $a_1^{\mathrm{h,c}}$, $a_2^{\mathrm{h,c}}$, $a_3^{\mathrm{h,c}}$, $a_4^{\mathrm{h,c}}$ - nonlinear limb-darkening coefficients of the components (Claret's formula), $\Omega_{\mathrm{h,c}}$ - dimensionless surface potentials of the primary and secondary, $R_{\mathrm{h,c}}$ - polar radii of the components in units of the distance between the component centres, $\mathrm{L_h/(L_h + L_c)}$ - luminosity of the hotter star (including spot on the cooler one), $M_{\mathrm{h,c}[\mathrm{M}_\odot]}$, $R_{\mathrm{h,c}[\mathrm{R}_\odot]}$ - stellar masses and mean radii of stars in solar units, log $g_{\mathrm{h,c}}$ - logarithm (base 10) of the mean surface acceleration (effective gravity) for system stars, $M^{\mathrm{h,c_{bol}}}$ - absolute bolometric magnitudes of AR Lac components, and $a_{\mathrm{orb}}[\mathrm{R}_\odot]$ - orbital semi-major axis in units of solar radius.

The **KT Peg** (HD 222317) is also a chromospherically active system recognised mainly from Ca II H & K profiles (Rutten 1986). The binary possesses synchronous rotation (orbital vs. rotational) and the spectrum of the secondary component contributes for 3-4% of the total continuum level (Stockton & Fekel

Table 3. Programme stars-the equivalent widths.

Star	phase	Hα	Na I1	Na I2	Ca II IRT1	Ca II IRT2	TiO
AR Lac	0.53	—	100	100	100	100	3%
AR Lac	0.04	—	96	86	97	84	2%
AR Lac	0.04	—	87	75	96	91	1%
AR Lac	0.54	—	94	87	91	104	1%
KT Peg	0.60	100	100	100	100	100	1%
KT Peg	0.76	101	102	101	116	104	2%
KT Peg	0.08	93	104	110	101	92	2%
KT Peg	0.24	107	95	98	90	115	1%
KZ And	0.44	—	—	—	100	100	1%
KZ And	0.78	—	—	—	122	98	2%
KZ And	0.44	—	—	—	101	101	2%
KZ And	0.76	—	—	—	107	105	1%
II Peg	0.25	100	100	100	100	100	2%
II Peg	0.41	92	92	92	78	140	2%
II Peg	0.70	58	99	101	132	142	2%
II Peg	0.85	82	90	97	129	117	1%
EI Eri	0.76	100	100	100	100	100	1%
EI Eri	0.29	185	91	109	133	107	2%
EI Eri	0.30	130	99	112	111	92	2%
EI Eri	0.82	163	101	113	95	109	0%

Note: TiO-7055Å, first night=reference point (100%), EW=$\sqrt{(\pi/2)}\frac{A_0}{A_2}$.

1992). Our present analysis suggests a modest activity in Hα in September 1997 season. Stockton & Fekel's ephemeris was adopted to compute the orbital phases

$$HJD = 2446996.904 + 6^d.20198 \times E \qquad (2)$$

It is the only system where the four orbital phases (eclipses and quadratures) were fully resolved.

The **KZ And** (HD 218738) is a binary system where the contribution of both components to the composite spectrum is effectively equal. Hall & Wolovitz (1998) found the activity of the secondary component highly variable in a five-year interval. Again, our present analysis confirms the presence of activity on both components, one of them being significantly more active. The following ephemeris (Bopp & Fekel 1975)

$$HJD = 2442370.722 + 3^d.032867 \times E \qquad (3)$$

was used to compute the orbital phases in Table 2 and 3.

The SB1 system **II Peg** (HD 224085) is a well-known chromospherically active star of the RS CVn type. This system shows multi-wavelength line variability, broad-band photometric variability, and significant variability of the hydrogen profile yielding from chromospheric, transiton and coronal activity. The star is often used to demonstrate the existence of activity cycles on stars other than Sun and a very large total spot coverage on the entire stellar surface (Rodonó et al. 2000). The following ephemeris (Rodonó et al. 2000):

$$HJD = 2442025.5 + 6^{d}.720 \times E \tag{4}$$

was used to calculate the rotational phases in Fig. 4 and Fig. 5.

The **EI Eri** (HD 26337) is a SB1 active binary system with a relatively short rotational period and synchronous rotation. The Hα line profile was studied by Montes et al. (1995). Due to the high rotational velocity of this star numerous Doppler images have been constructed (for a summary see Strassmeier 2002). The following ephemeris was used (Strassmeier 1990)

$$HJD = 2444635.65 + 1^{d}.945 \times E \tag{5}$$

for determining the rotational phases in Table 2 and 3.

4. Results

4.1. Spots

Applying the formula for the flux combination (e.g. Neff et al. 1995):

$$F_{tot} = \frac{f_S R_\lambda F_S + (1 - f_S) F_Q}{f_S R_\lambda + (1 - f_S)} \tag{6}$$

one can arrive at the total spot coverage on a stellar surface. Adopting the effective temperatures from the spectral type, a canonical temperature difference of $T_{\rm Q}$-$T_{\rm S}$=1000K between the quiet and spotted photosphere and the corresponding fluxes ratio from black-body radiation, the flux difference in TiO 7055Å band-head suggests a total spot coverage of $f_{\rm S}$=1-3% for the systems analysed. All flux differences were assigned to the spot contribution. In fact, the above reference uses the calibration for unspotted standard late-type stars and demonstrates clearly that the flux difference is essentially zero down to the K5 spectral type. This result is supported by the light curve modelling of two systems, namely AR Lac and II Peg. The final spot properties obtained from the SpotMod code are the following: two spots circular in outline with the radii 19.5 and 19.0 degrees, longitudes (at phase) -0.029 and -0.028, latitudes 12.0 and 31.0 degrees and both 1000 K cooler than the surrounding photosphere. The single spot model suggests the values 27 degrees for the radius and 20 degrees for the latitude ('Powell' iterative method). The light curve modelling is presented in Figures 4 and 5. In particular, the very low values of spot coverage (5.6% of stellar surface) on II Peg suggests the presence of a very small fraction of spots distributed on the system in the 1997 season (in contrast with some other epochs).

Table 4. Results of the analysis of the AR Lac light curves obtained by solving the inverse problem for the Roche model with active cool area on the more-massive (cooler) component.

Quantity	$B - filter$	$V - filter$
n	81	81
$\Sigma(\mathrm{O-C})^2$	0.0308	0.0180
σ	0.0196	0.0150
$\mathrm{q = m_h/m_c}$	0.894	
$\mathrm{f_{h,c}}$	1.0	
$\beta_{\mathrm{h,c}}$	0.08	
$\mathrm{A_{h,c}}$	0.5	
$\mathrm{T_h}$	5100	
$\mathrm{A_S = T_S/T_c}$	0.70	
θ_{S}	25.0 ± 1.2	24.3 ± 1.0
λ_{S}	350.2 ± 4.5	351.4 ± 3.5
φ_{S}	52.0 ± 2.4	53.0 ± 2.0
$\mathrm{T_c}$	4652 ± 14	4650 ± 15
$\mathrm{F_h}$	0.493 ± 0.008	0.496 ± 0.006
$\mathrm{F_c}$	0.803 ± 0.006	0.797 ± 0.006
$i\ [^\circ]$	89.4 ± 2.6	89.9 ± 2.0
$a_1^{\mathrm{h,c}}$	$+0.6220, +0.6152$	$+0.6524, +0.6852$
$a_2^{\mathrm{h,c}}$	$-0.8347, -0.8769$	$-0.6627, -0.8608$
$a_3^{\mathrm{h,c}}$	$+1.8304, +1.7262$	$+1.5420, +1.7210$
$a_4^{\mathrm{h,c}}$	$-0.6978, -0.5244$	$-0.6750, -0.6590$
Ω_{h}	6.951	6.917
Ω_{c}	4.711	4.740
$\mathrm{R_h}[D=1]$	0.171	0.172
$\mathrm{R_c}[D=1]$	0.294	0.291
$\mathrm{L_h/(L_h+L_c)}$	0.420	0.377
$\mathrm{M_h[M_\odot]}$	1.12 ± 0.02	
$\mathrm{M_c[M_\odot]}$	1.26 ± 0.02	
$\mathrm{R_h[R_\odot]}$	1.53 ± 0.03	
$\mathrm{R_c[R_\odot]}$	2.68 ± 0.05	
$\log g_{\mathrm{h}}$	4.12 ± 0.02	
$\log g_{\mathrm{c}}$	3.68 ± 0.02	
$\mathrm{M_{bol}^h}$	4.41 ± 0.03	
$\mathrm{M_{bol}^c}$	3.59 ± 0.04	
$a_{\mathrm{orb}}[\mathrm{R_\odot}]$	8.862 ± 0.009	

Note: BaSeL approximation of the stellar atmospheres, (Basel Stellar Library for model flux distributions) and $[\mathrm{Fe/H}]_{\mathrm{h,c}} = 0.0$ - accepted metallicity of the components.

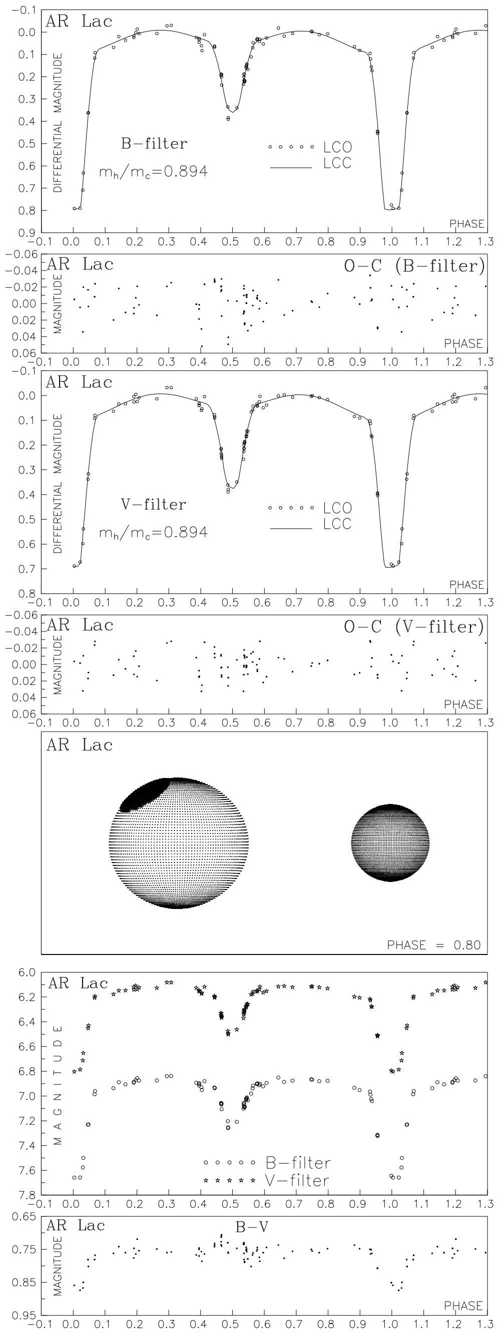

Figure 3. The AR Lac spot configuration.

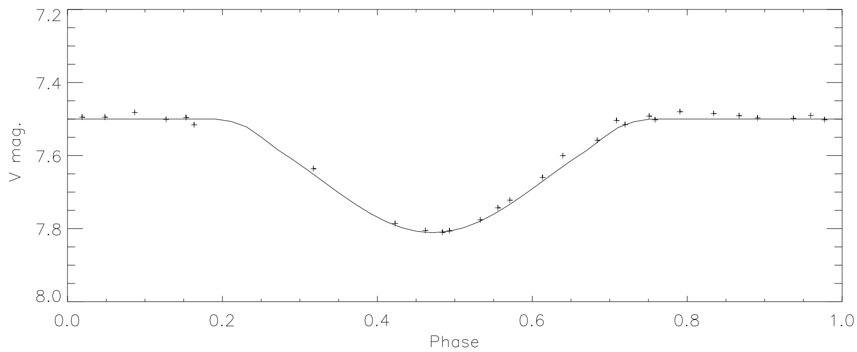

Figure 4. The II Peg light curve fit.

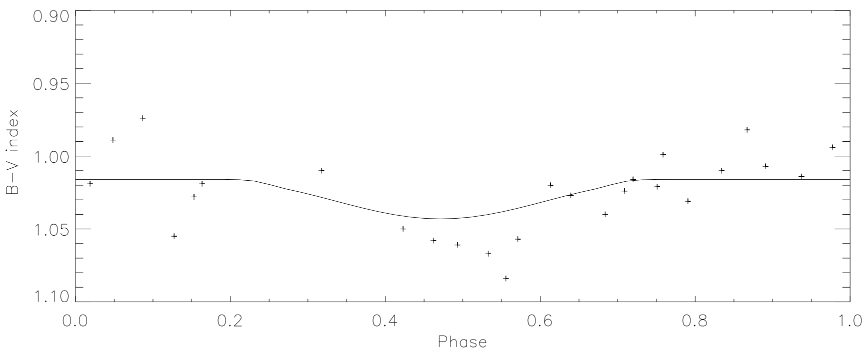

Figure 5. The II Peg *B-V* index fit.

4.2. Hα, Na I and Ca II profiles

We looked for the effect of the rotational modulation in the measured radial velocities and the equivalenth widths. Unfortunately, the phase coverage is poor but still the rotational modulation can be tentatively recognized in KT Peg and II Peg. In all systems the EW values show a level of variability within $\sim$10%, the Hα profiles display high variability in II Peg and EI Eri as expected from a high level of activity deduced from the coronal X-ray index ($L_{\rm X}$, the Simbad database).

The difference in radial velocities (Hα, CA II IRT vs. Na I) reflects interesting dynamic regime in line forming regions. Pure photospheric nearby metallic lines in corresponding echelle orders suggest a difference in radial velocities of the order 1-2 km/s (as based on few selected lines).

5. Conclusions

We presented the results of a search for magnetic activity-induced variability on a sample of known active binary systems in the September 1997 season and basic spot properties for II Peg and AR Lac. The activity level we derived from Hα, Na I and Ca II IRT spectral line profiles and EWs can be further estimated from direct semi-empirical modelling allowing to determine physical properties such as the temperature, electron density, total particle numbers and the velocity fields.

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