Active stellar chromospheres: AR Lac

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Abstract. The UV Spectral Imaging method is shortly overviewed and then applied to map the active stellar chromospheres of the two components of the RS CVn-type eclipsing binary system AR Lacertae. We show the preliminary results for the Oct 1994 IUE data. From the decomposition of the series of Mg II k spectra chromospheric plages were identified and some flares were also detected. At the centre of mass of the system a bright plasma concentration was found suggesting a connection between the extended stellar magnetospheres.

1. Introduction to the UV Spectral Imaging method

Plage regions and flare events in the activity nests produce most of the UV variability of active stars. According to the solar-stellar analogy we expect these emitting centers to be physically connected with the photospheric spots. Usually, spot modelling and/or imaging techniques are applied to map the active stellar photospheres. However, comparing to the photosphere, mapping the chromospheric activity has more restrictions (cf. Neff 1992).

To map the chromospheric activity Walter et al. (1987) and Neff. et al. (1989) introduced the UV Spectral Imaging method, which is here shortly overviewed. The basic concept of this technique is, that an active stellar atmosphere produces a homogeneous, symmetric UV line profile and if there is a local additive emitting source, for instance a plage on the star, its emission component will be added to the homogeneous UV base. Since the additive component is Doppler-shifted by the stellar rotation, the sum-profile will be asymmetric and phase dependent. Thus, the UV line profile variation through the rotational cycle provides information about the spatial distribution of such individual

SOURCE	SPECTRAL MARK
homogeneous background	symmetric and constant
hemispheric inhomogeneities	symmetric, phase-dependent
global stochastic processes	symmetric, phase-independent, varying in time
large scale outflows	asymmetric, constant
plages	asymmetric, phase-dependent
flares	asymmetric, phase-dependent, varying in time

Table 1: Different kind of emitting sources with the spectral marks of their contribution.

emitting sources. To obtain this information we need to decompose the spectra to their parts.

Now let us take an additive emitting source (e.s.) above the stellar surface somewhere at β latitude! One can immediately write the Doppler shift $\Delta\lambda_D$ of its radiative contribution to the spectrum as:

$$\Delta\lambda_D = \frac{\lambda}{c}\, v_{rot,e.s.} \sin i \cos\beta, \tag{1}$$

where λ is the appropriate wavelength in vacuum, c is the speed of light, $v_{rot,e.s.}$ is the rotational velocity of the emitting source (corotation with the stellar surface is supposed), and finally, i is the inclination of the rotation angle. Measuring the Doppler shift, however, one cannot know β, only the product of $v_{rot,e.s.} \cos\beta$, because the vertical position (and vertical extension) of the emitting source is not known. These features can easily extend over the whole upper atmosphere (contrary to the photospheric spots which are *on* the stellar surface). However, a lower limit can be given to β if the measured $\Delta\lambda_D < \frac{\lambda}{c}\, v_{rot,e.s.} \sin i$ over a whole rotation, assuming, that the source is *on* the surface. Alternatively, an approximation can be given for the distance of the centre of the e.s. from the surface of the star (i.e., for the vertical extension) if it is supposed to be located in the equatorial plane (see Eq. 2 later in Section 2.3). An additional emitting source, however, can originate either from a long duration event (plage) or from a short duration one (flare) as well. Thus, to have also time resolution, one need to collect a series of spectra covering at least two rotations. As a brief summary of the different kind of emitting sources and their characteristics, in Table 1 we listed some of the most probable UV sources with their spectral marks (Neff 1992).

2. Application for AR Lac

2.1. The star

AR Lac (= HD 219334, $V = 6.1$ mag.) is an RS CVn-type eclipsing binary ($i = 87°$) with K0 IV and G2 IV components. The synchronous rotation period is near 2 days, however, this disadvantage is of no consequence using satellite measurements. AR Lac was observed by the International Ultraviolet Explorer many times during its operation between 1978-1996. IUE data on the system from 1981-1994 reflected an enhanced chromospheric activity on both stars (e.g., Rodonò et al. 1986, Neff et al. 1989, Pagano, et al. 1992, 1996). Spectral images from the past showed numerous plage regions on the cooler component, sometimes elongating towards the hotter star. Furthermore, a strong bright arch on the reconstructed X-ray image of the system from 1993 (Siarkowsky 1995) suggested the presence of hot plasma in the interbinary medium. We think, that both stars of this close binary system are embedded in a hot, extended and very active plasma (similar to the solar cromosphere-corona), moreover, these active envelopes are physically connected to each other.

2.2. The data

The 51 IUE LWP spectra (1800 – 3200 Å, $\Delta\lambda = 0.2$ Å) of the present analysis were collected in Oct 1994, covering about 2.2 consecutive rotation periods. For the data reductions we used the improved NEWSIPS (New Spectral Image Processing System) instead of the former standard IUESIPS (IUE Spectral Image Processing System) that has been affected by some systematic calibration errors (see, e.g., Busà et al. 1999). The new calibration procedure provided also a better S/N. The ephemerid constants were HJD 244795.6369 at $\phi = 0$ primary minimum and $P_{orb} = 1.983164$ days after Lanza et al. (1998). The observational log can be seen in Table 2. The physical parameters of the system is summarized in Table 3 (Marino et al. 1998).

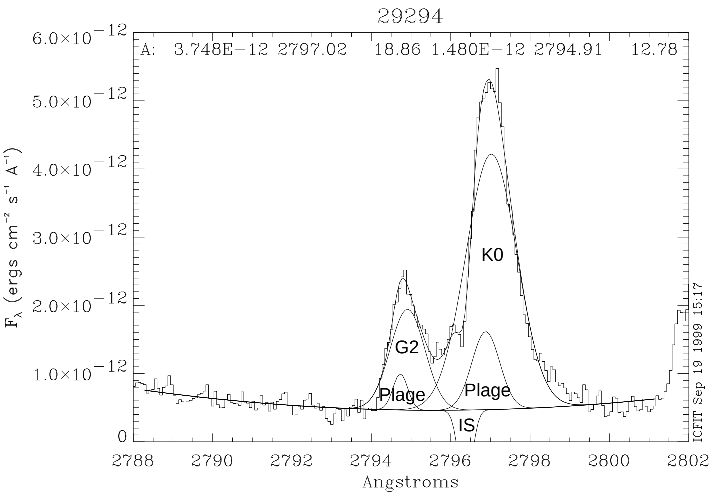

Figure 1: A sample 5-Gaussian-component fit to the Mg II k spectrum (see as frame #4 in Table 2).

For our analysis the Mg II k line ($\approx$ 2796 Å) was used. For the decomposition of the spectra we used the "ICUR Spectral Analysis Package" developed by F. Walter and J. Neff (1992). The code is able to fit one dimensional datasets (spectra) with a maximum of five Gaussian curves. In Figure 1 a sample fit for the Mg II k line is seen using 5 Gaussian components.

2.3. Results

Decomposing the spectra requires an iterative, step-by-step analysis which can result in a series of multi-component fits using a minimum of two and a maximum of five Gaussians

#	LWP	HJD*	ϕ	remark	#	LWP	HJD*	ϕ	remark
1	29290	9627.7340	0.0987		27	29321	9629.9738	1.2282	
2	29291	9627.8225	0.1434		28	29322	9630.0430	1.2630	
3	29293	9627.9611	0.2133		29	29323	9630.1260	1.3049	
4	29294	9628.0328	0.2494		30	29324	9630.1977	1.3410	
5	29295	9628.1057	0.2861		31	29325	9630.2692	1.3771	
6	29296	9628.1766	0.3219		32	29326	9630.3437	1.4147	
7	29297	9628.2590	0.3635		33	29327	9630.4452	1.4658	sec. min.
8	29298	9628.3314	0.4000		34	29328	9630.5183	1.5027	sec. min.
9	29299	9628.4016	0.4354	sec. min.	35	29329	9630.5906	1.5392	sec. min.
10	29300	9628.4720	0.4709	sec. min.	36	29330	9630.6649	1.5766	sec. min.
11	29301	9628.5424	0.5064	sec. min.	37	29331	9630.7347	1.6118	
12	29302	9628.6130	0.5419	sec. min.	38	29332	9630.8039	1.6467	
13	29303	9628.6851	0.5783		39	29334	9630.9310	1.7108	
14	29304	9628.7614	0.6168		40	29335	9631.0030	1.7471	
15	29305	9628.8302	0.6515		41	29336	9631.0818	1.7868	
16	29306	9628.9015	0.6875		42	29337	9631.1545	1.8235	
17	29308	9629.0443	0.7594		43	29338	9631.2262	1.8596	
18	29309	9629.1198	0.7975		44	29339	9631.3041	1.8990	
19	29310	9629.1956	0.8358		45	29340	9631.3908	1.9427	pri. min.
20	29311	9629.2671	0.8718		46	29341	9631.4922	1.9938	pri. min.**
21	29312	9629.3454	0.9113		47	29342	9631.5747	2.0354	pri. min.
22	29313	9629.4176	0.9477	pri. min.	48	29343	9631.6459	2.0713	pri. min.
23	29314	9629.4895	0.9840	pri. min.**	49	29344	9631.7180	2.1076	
24	29315	9629.5623	1.0206	pri. min.**	50	29345	9631.7893	2.1436	
25	29316	9629.6343	1.0569	pri. min.	51	29348	9631.9625	2.2309	
26	29318	9629.7759	1.1284						

* 2440000+, mid-exposure time ** totality

Table 2: The observational log of the data.

(for a more detailed description see Rodonò et al. 1989). The main goal is to get such a result that is free of controversion. To achieve this, first one should synchronize the radial velocities of the stars with the respective Doppler shifts of the Gaussian components. To get a consistent model, it is also necessary to filter out the causeless sudden changes in the Gaussian parameters (position, FWMH, maximum) from one spectrum to the next. The results of this step-by-step process is displayed in Figure 1, where we used two Gaussians for fitting the base-profiles of the K0 and the G2 star at their radial velocities, a third Gaussian component with the instrumental width (FWMH = 0.25 Å) to fit the absorption of the IS medium moving by $v_{rad} = -34.54$ km/s, and another two Gaussian components to fit the residuals. Sudden enhancement in the C IV emission, that most probably are flare signatures, helps us to make a decision whether the residuals are the reason of plages or flares. Figure 2 suggests at least three short duration flare events. From those three, finally two were identified in frame #11 at $\phi \approx 0.5$ and in frame #29 at $\phi \approx 1.3$. The third flare at $\phi \approx 0.16$ could not been found in the spectra because of the lack of IUE LWP observations in this phase range.

Figure 3 shows the final solution in the phase-wavelength frame. The two stellar background lines moved with their radial velocities and the IS line has a time-independent position, as expected. However, four other emitting sources were found that were present

parameter	G2 IV	K0 IV
mass $[M_\odot]$	1.23	1.27
radius $[R_\odot]$	1.54	2.82
$v \sin i$ [km/s]	38	72
K [km/s]	119.43	106.73
$a \sin i$ $[10^6$km$]$	3.257	2.911

Table 3: AR Lac system parameters.

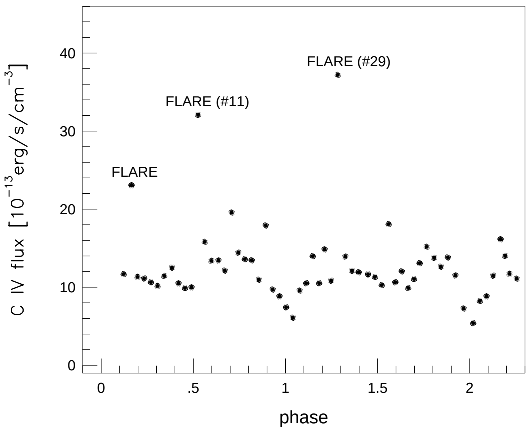

Figure 2: C IV flux variation. Three flare events are clearly seen. The first one at $\phi = 0.16$ could not been found in the Mg II spectra because of the lack of observations, however, the other two were identified easily in the frames #11 and #29.

for different phase ranges. The following equation helps to estimate the positions of these plages if co-rotation is supposed:

$$\Delta\lambda_D = \Delta\lambda_0 + \frac{\lambda}{c}\left[K_{K0}\sin\phi + \frac{2\pi}{P} r_{pl}\sin(\phi - \phi_{pl})\right]. \tag{2}$$

where $\Delta\lambda_D$ is the Doppler shift of the given Gaussian component, $\Delta\lambda_0$ is the radial velocity shift of the system's center of mass, K_{K0} is the orbital velocity of the K0 star, P is the period, ϕ is the phase, while r_{pl} and ϕ_{pl} are the polar coordinates of the plage in a coordinate system tied to the centre of mass of the K0 star.

In Figure 4 the reconstructed pole-on cartoon of the system is displayed with the two stellar disks and the four plages. Plage I and II are probably near, or on the surface of the K0 star, because their velocity shift in the K0 star frame is smaller than the stellar equatorial rotational velocity. Furthermore, these two plages are supposed to be polar features: from Eq. (1) $\beta_{PI} \approx 63^\circ$ and $\beta_{PII} \approx 74^\circ$. These plages are probably on different hemispheres, however, since the inclination is $\approx 90^\circ$ there is no way to make distinction between the northern and the southern side. Plage III is far from the stars, deeply in the interbinary environment. We think, that such interbinary plages are possible, and could be the result of the interacting magnetic fields of the active components (cf. Siarkowski 1995). Such an interaction due to the strong magnetic activity can yield to variations in the orbital period (Applegate 1992), which, in the case of AR Lac, was reviewed recently by Lanza et al. (1998).

The fourth plage (Plage IV) is clearly connected to the G2 star, however, spectral images of the system between 1983-1991 (Pagano et al. 1996) did not show any plage on the hotter component. This considerable difference can be due to the new data reduction

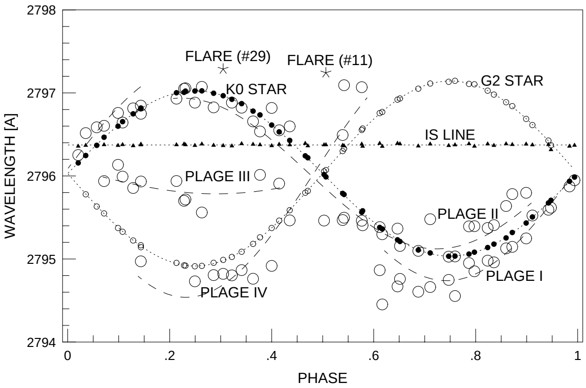

Figure 3: Wavelength changes of the Gaussians. Small marks show the stellar base profile changes and the position of the interstellar component. The two flares identified in LWP frames #11 and #29 are marked by asterisks. The big open circles show the positions of the additional Gaussians which are thought to be plages.

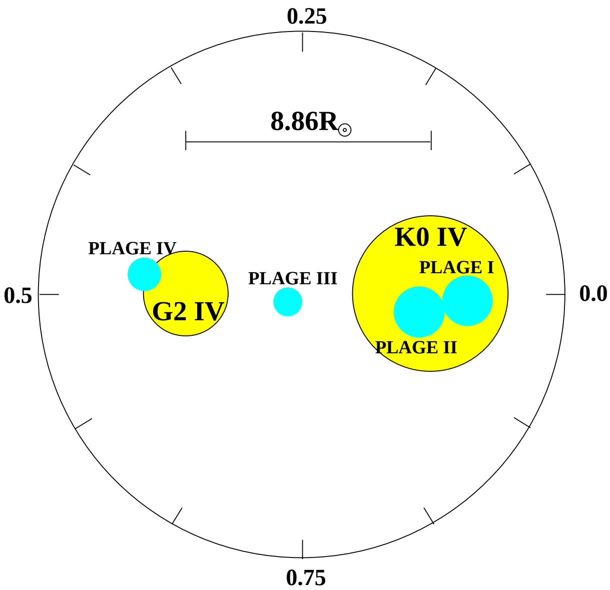

Figure 4: The reconstructed image of AR Lac in Oct 1994 on the real scale. The cartoon shows the system pole-on. The two big gray circles illustrate the two stars, while the darker circles are the extra emitting regions.

procedure (NEWSIPS) applied first for the Oct 1994 dataset. The authors strive to repeat all the UV spectral analysis for the IUE observations of AR Lac re-reduced by NEWSIPS.

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References

Applegate, J.H. 1992, ApJ 385, 621

Busà, I., Pagano, I., Rodono, M., Neff, J.E., Lanzafame, A.C. 1999, A&A 350, 571

Lanza, A.F., Catalano, S., Cutispoto, G., Pagano, I., Rodonò, M. 1998, A&A 332, 541

Marino, G., Catalano, S., Frasca, A., Marilli, E. 1998, IBVS No. 4599

Neff, J.E. 1992, in: *Surface Inhomogeneities on Late-Type Stars*, Proc. Coll. Armagh Obs., eds. P.B. Byrne, D.J. Mullan, Springer-Verlag, Heidelberg, p. 54

Neff, J.E., Walter, F.M., Rodonò, M., Linsky, J.L. 1989, A&A 215, 79

Pagano, I., Rodonò, M., Neff, J.E. 1992, in: *Cool Stars, Stellar Systems and the Sun*, eds. M. Giampapa & J.A. Bookbinder, ASP Conf. Ser., Vol. 26, 362

Pagano, I., Rodonò, M., Walter, F.M., Neff, J.E. 1996, in: *Magnetodynamic Phenomena in the Solar Atmosphere - Prototypes of Stellar Magnetic Activity*, IAU Coll. No. 153, eds. Y. Uchida, T. Kosugi & H.S. Hudson, Kluwer, Dordrecht, p. 631

Rodonò, M., Cutispoto, G., Pazzani, V., et al. 1986, A&A 165, 135

Siarkowski, M. 1995, in: *Stellar Surface Structure, Poster Proceedings*, IAU Symp. No. 176, ed. K.G. Strassmeier, p. 190

Walter, F.M., Neff, J.E., Gibson, D.M., Linsky, J.L., Rodonò, M., Gary, D.E., Butler, C.J. 1987, A&A 186, 241

Discussion

L. van Driel: This is a very exotic binary system for a solar physicist with the chromospheric and coronal emission coming from between the stars. Do you have some data on the density of the emitting plasma?

Zs. Kővári: Yes, I refer to the paper of Byrne et al. (1987, A&A 180, 172) where the authors made attempts to derive the physical parameters of the upper atmosphere of AR Lac. On the basis of some density sensitive lines they estimated a solar-like density value of $\log N_e = 10.5\,\mathrm{cm}^{-3}$.

B. Schmieder: C IV emissions could, may be, correspond to other events than flares. In the Sun "C IV explosive events" have no real signatures in X rays.

Zs. Kővári: It's true. However, while refining the decomposition of the spectra the C IV abrupts were identified even in the Mg II spectra, and we think the flare events to be the most plausible explanation.

S. Antiochos: Is it possible that the emission between the two stars is due to an interaction of the winds of the stars?

Zs. Kővári: I should say that this possibility cannot be excluded. However, I'm not sure that the winds without magnetic field can reach the necessary density between the stars. I'm much more inclined to think that the interaction between the magnetically driven and compressed winds produces the observed interbinary UV emission.