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New findings supporting the presence of a thick disc and bipolar jets in the β Lyrae system*

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ABSTRACT

Context. Understanding large-scale mass exchange in binaries also requires studies of complicated objects in the rapid phases of the process. β Lyr is one such object.

Aims. Our goals were to analyse 52 photographic and 651 electronic spectra of β Lyr to obtain additional information about circumstellar matter and to investigate spectrophotometric information for the first time.

Methods. Improved quadratic ephemeris was derived via orbital solution with the FOTEL program. The spectra were disentangled using the KOREL program. Spectrophotometric quantities of 15 stronger absorption lines of the primary were measured and corrected for the orbital continuum variations using the fluxes calculated from a fit of the light curves with the BINSYN program. Central intensities of the V and R peaks of the Hα emission line were measured and corrected for the orbital light changes using the R-band light curve numerically modelled with the program PERIOD04.

Results. Disentangling of photographic and electronic spectra led to the detection of weak absorption lines originating from the pseudophotosphere of the accretion disc. This way, a rich line spectrum of the accretion disc, not limited to only two previously known Si II 6347 and Si II 6371 lines, was obtained. A projected rotational velocity of 180 km s^{-1} was estimated for the disc spectrum. Such a value agrees well with the assumption of the Keplerian rotation of the outer layers of the accretion disc. After the correction, a pronounced increase of the strength of all absorption lines around phases of the primary eclipse was found. We argue that this is due to additional absorption of the light of the primary in one of the jets and/or scattering envelope above the accretion disc of the gainer. The net intensity of the V peak of Hα shows no orbital variation, but a possible 271-d periodicity. The net intensity of the R peak shows mild orbital changes and a slow change over a cycle of about 2780 days. These results seem to support the earlier conclusion that the Hα emission originates in the jet-like structures.

Conclusions. All new findings support the current picture that the circumstellar structures of β Lyr consist of a thick accretion disc, bipolar jets, and a scattering envelope above the disc.

Key words. stars: binaries: eclipsing – stars: individual: β Lyrae – binaries: close – ISM: jets and outflows

1. Introduction

The second brightest star of the Lyra constellation, β Lyr (HD 174638), is one of the first known Be stars and a typical eclipsing binary. According to current views, β Lyr is a binary observed at the end of the rapid initial stage of a large-scale mass exchange between the components. Its orbital period of $12\overset{\mathrm{d}}{.}94$ is increasing at a rate of 19 seconds per year and the now more massive star is completely hidden from view by a thick accretion disc. For a long time, no orbital radial velocity (RV hereafter) curve of the star hidden in the accretion disc was available. Only Skul'skij & Topilskaya (1991) discovered the faint pair of Si II 6347 and 6371 lines varying in antiphase with the lines of the donor[1] and interpreted them as the lines of the "invisible" gainer. This finding was re-interpreted

* Individual radial velocity and photometry measurements are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/463/233

[1] It is customary to denote the components of a binary system as the primary and secondary, respectively, either according to their mass or the relative brightness. For normal binaries, both criteria lead to a unique identification of the primary and secondary. However, this is not so for β Lyrae . To avoid confusion, we shall denote the Roche-lobe filling B6-8II component as *the donor* and the star inside the disc as *the gainer*.

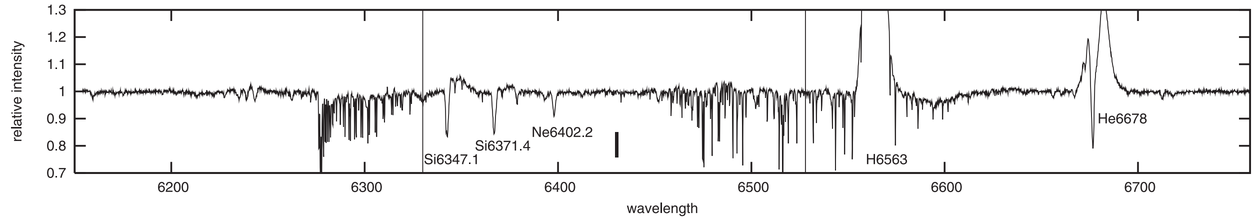

Fig. 1. Electronic spectrum of β Lyr in orbital phase $0^{\mathrm{P}}\!.255$ secured in DAO Observatory. Vertical lines and a roman numeral I mark the region selected for disentangling. All identified lines (except He I 6678) were used for spectrophotometric measurements.

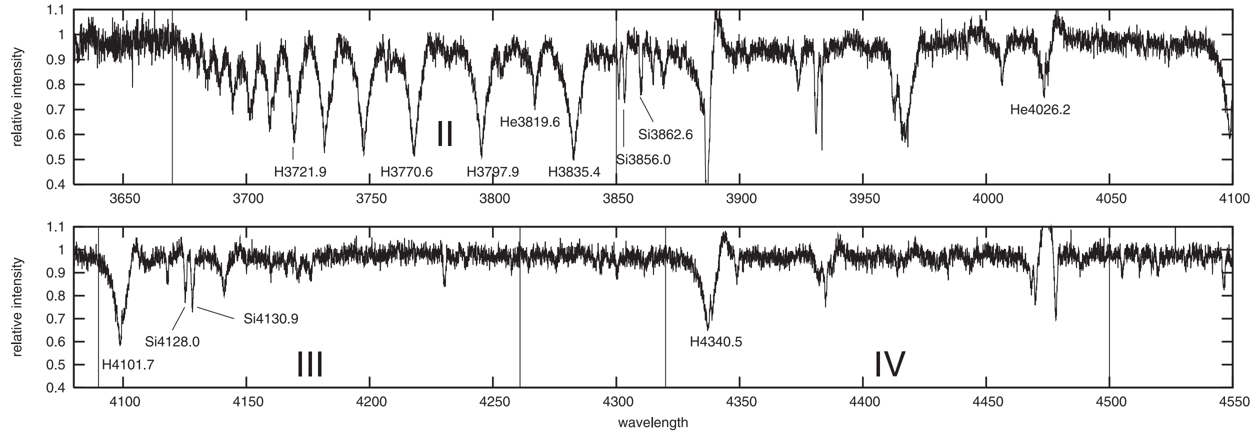

Fig. 2. Photographic spectrum of β Lyr in orbital phase $0^{\mathrm{P}}\!.245$ secured in Ondřejov Observatory. Vertical lines and roman numerals II, III, and IV mark the regions selected for disentangling. All identified lines were used for spectrophotometric measurements.

by Harmanec (1992), who argued that the lines originate in fact in the pseudophotosphere of the accretion disc. He did not challenge, however, the conclusion of Skul'skij & Topilskaya (1991) that they reflect the orbital motion of the gainer. Later, Harmanec et al. (1996) and Hoffman et al. (1998) independently discovered the presence of bipolar jets in the system from optical interferometry and from spectropolarimetry, respectively. A theoretical justification for the presence of bipolar jets was suggested by Bisikalo et al. (2000). So far, the most successful modelling of the observed light curves, continuum distribution, and line spectra was carried out by Linnell (2000, 2002a,b). These studies also supported the view that there had to be scattering material above the disc. For a detailed history of the investigation of β Lyr, readers are referred to a review by Harmanec (2002). The main purpose of this study is to test the current model of β Lyr, also via spectrophotometry and with the help of spectral disentangling.

2. Observational data and their reduction

In this study of β Lyr, the following four sets of spectra from two observatories are used.

1. 52 photographic spectra secured with the longest camera in the coudé spectrograph of the 2.0-m reflector of the Ondřejov Observatory from July to September 1991. These spectra have a linear dispersion of 4 Å mm^{-1}, a typical *S/N* 45.7, and cover two overlapping spectral regions: 3630−4550 Å (33 of them) and 4060−5000 Å (19 of them). They were digitised and their RVs were already measured by Harmanec & Scholz (1993).
2. 238 spectra obtained with a Reticon 1872 RF/30 detector in the medium camera of the coudé spectrograph of the 2-m reflector in Ondřejov between 1992 and 2003. They have a linear dispersion of 17 Å mm^{-1}, a two-pixel resolution of 12 600, and cover the spectral region from 6280 to 6730 Å. Spectra from 1992−1994 have already been reduced and analysed by Harmanec et al. (1996). The typical *S/N* is 333.5.
3. 37 spectra secured with a SITe-5 800 × 2000 CCD detector and the same setup as set 2.
4. 376 CCD spectra secured with a Loral detector in the coudé focus of the 1.22-m reflector of the Dominion Astrophysical Observatory (hereafter DAO) between 1994 and 2003 (most of them during 9 nights in August 1994). They have a linear dispersion of 10 Å mm^{-1}, a typical *S/N* 135.9, and cover the range 6150−6760 Å. The 1994 spectra have already been used by Harmanec et al. (1996).

Both the digitised photographic and the electronic spectra from Ondřejov were reduced by the reduction program SPEFO, developed by Dr. Jiří Horn (Horn et al. 1996; Škoda 1996). Initial reductions of the DAO CCD spectra (bias subtraction, flatfielding, and creation of 1-D images) were carried out in IRAF. The wavelength calibration and all further reductions were also carried out in SPEFO. The wavelength calibrations were based on Fe comparison spectra for the photographic spectrograms, and on Th-Ar comparison spectra for all electronic spectra (with a few exceptions when an Fe-Ar lamp was used). The zero point of the wavelength scale of electronic spectrograms was corrected individually via selected telluric lines as described in Horn et al. (1996).

One DAO red spectrum is shown in Fig. 1. Besides the strong emission lines of Hα and He I 6678, one can see the Si II doublet, the Ne I 6402 line, and a number of telluric lines. One blue photographic spectrum is displayed in Fig. 2.

We had at our disposal all *UBVRI* photometric observations already used by Harmanec et al. (1996). Additionally, we secured new *UBV* observations relative to γ Lyr at

Hvar, Croatia (62 observations; HJD 2 452 488.5–53 209.5) and at Tubitak National Observatory, Turkey (193 observations; HJD 2 452 759.5–52 770.6). All these observations were reduced and transformed to the standard *UBV* system with the help of non-linear tranformations using the reduction program HEC22 (Harmanec et al. 1994; Harmanec & Horn 1998). Here, we only use the light curves to correct the observed emission-line strengths for the continuum variations and for the comparison with a model light curve. A more detailed analysis of photometry will be the subject of another study.

3. A new ephemeris

The ephemeris of Harmanec & Scholz (1993) was based on 1532 RVs covering a time interval of 36 328 days. Since the data at our disposal represent 682 additional RVs and extend the time span covered for 4335 days, it was deemed useful to derive an improved quadratic ephemeris based on all 2214 RVs. In addition to the new RVs measured in all Ondřejov and DAO electronic spectra, we also included the RVs of the donor from the Crimean CCD spectra (Skul'skij 1992, 1993) and from the Tautenburg CCD spectra (Hildebrandt et al. 1997) and, of course, used all 1532 RVs already used by Harmanec & Scholz (1993). In all cases, we used mean RVs for each spectrogram. Using the program FOTEL (Hadrava 2004a), we derived a solution in which the period change was determined to be one of the elements of the solution. We first derived a solution in which weights of all RVs were set equal to one. Then, we made the weights of individual data sets inversely proportional to the square of the rms errors per 1 observation for the respective dataset which were derived in the preliminary solution with equal weights. The final solution was derived with these weights.

We obtained the following results:

$$\begin{aligned} P &= 12\overset{\mathrm{d}}{.}913779 \pm 0.000016 \\ T_{\mathrm{min.\,I}} &= \mathrm{HJD}\,2\,408\,247.968 \pm 0.015 \\ \dot{P} &= (5.9977 \pm 0.0057) \times 10^{-7}\ \text{days per day} \\ K &= 185.27 \pm 0.20\ \mathrm{km\,s^{-1}}, \end{aligned} \quad (1)$$

which implies the following quadratic ephemeris

$$\begin{aligned} T_{\mathrm{min.\,I}} &= \mathrm{HJD}\,2\,408\,247.968 \\ &\quad + 12\overset{\mathrm{d}}{.}913779 \cdot E + 3.87265 \times 10^{-6} \cdot E^2. \end{aligned} \quad (2)$$

We shall use this ephemeris in the rest of this paper, but note that it does not differ from the ephemeris by Harmanec & Scholz (1993)[2] within the limits of the respective errors of individual elements. This confirms their conclusion about the accuracy and extrapolation power of the quadratic ephemeris based on the RV solution.

For completeness, we also mention that the quadratic term of ephemeris (2) is slightly larger than the one obtained from a parabolic fit of the O–C deviations from a linear ephemeris, based on the observed times of photometric minima only, 3.859×10^{-6} (Kreiner et al. 2001). Note that Harmanec & Scholz (1993) already showed that β Lyr is unique in that the local epochs are more accurately derived from RV curves than from photometry.

4. Disentangling the spectra

It is virtually impossible to separate the individual line spectra of binaries and to derive accurate RV curves in a classical way for objects with a large brightness difference between the components and/or with the presence of circumstellar matter. One has to resort to some more sophisticated approach like spectral disentangling. While this technique is gradually becoming a standard tool in the spectroscopic studies of binaries, its application to such a complicated object as β Lyr is all but straightforward. As pointed out, for instance, by Bisikalo et al. (2000), the observed line spectrum of β Lyr consists of at least six different systems of spectral lines, and one has to exercise special care to select suitable spectral regions.

In practice, we used the program KOREL, developed by Hadrava (1995, 1997, 2004b) and made publicly available by the author, which uses the spectral disentangling technique in the Fourier domain. This program uses the digitised spectra in the logarithmic wavelength scale from different orbital phases as input data and returns the spectra of individual components. The component spectra are a priori unknown and can have any shape; the only condition inherent to the method is that they can only vary in intensity not in shape. If desired, KOREL can also derive or improve the orbital elements used to obtain the solution. A simplex method is used for the minimalisation of the respectrive sum of squares.

Our main criteria for the particular choice of suitable spectral regions were that they must contain many stellar absorption lines, avoid interstellar and circumstellar lines, and that their boundaries are at continuum at all orbital phases. The four regions finally selected are denoted by vertical lines in Figs. 1 and 2. Spectra secured in phases around the primary eclipse[3] (phase range from 0.9 to 0.1) were removed from decomposition. These spectra are inconvienient for decomposition since they contain satellite lines and the newly discovered absorption-line spectrum (see next section).

We started the disentangling in the blue spectral region, i.e., for the photographic spectra. They span a large range of wavelengths and are essential for the detection of some weak absorption lines from the accretion-disc rim, especially since they also contain a number of blue Balmer lines of hydrogen, less affected by circumstellar emission than the first three Balmer lines. On the other hand, the danger of using the Balmer lines lies in the fact that they undoubtedly *do* contain some emission components originating from the jet-like structures. These follow their own RV curve with a different amplitude and a phase shift with respect to the binary RV curves (Harmanec et al. 1996).

To cope with this problem, we first disentangled a short spectral region from 4115 to 4157 Å, not containing any hydrogen line, but two pronounced lines of Si II. Then we fixed the resulting parameters to disentangle all selected regions in one run of KOREL. On the practical side, we let KOREL carry out concatenated tasks, gradually allowing convergency of various orbital elements and then also line strengths. The quality of the solution was evaluated via two criteria: the resulting disentangled spectra had to have straight (not wavy) continuum, and the variance of the solution could no longer be decreasing during the next iteration step. The best solution found was used to disentangle all selected spectral regions.

The resulting disentangled spectra are presented in Fig. 3. One can see that KOREL indeed disentangled a number of lines originating in the "pseudophotosphere" of the accretion disc. This is the first detection of such lines other than the two previously known red Si II lines. It seems appropriate from now on to call this set of spectral lines the *line spectrum of the disc*.

[2] The ephemeris by Harmanec & Scholz (1993) reads as follows: $T_{\mathrm{min.\,I}} = \mathrm{HJD}\,2\,408\,247.966 + 12\overset{\mathrm{d}}{.}913780 \cdot E + 3.87196 \times 10^{-6} \cdot E^2$.

[3] Primary (i.e. deeper) eclipse of β Lyr is the eclipse of the donor by the gainer.

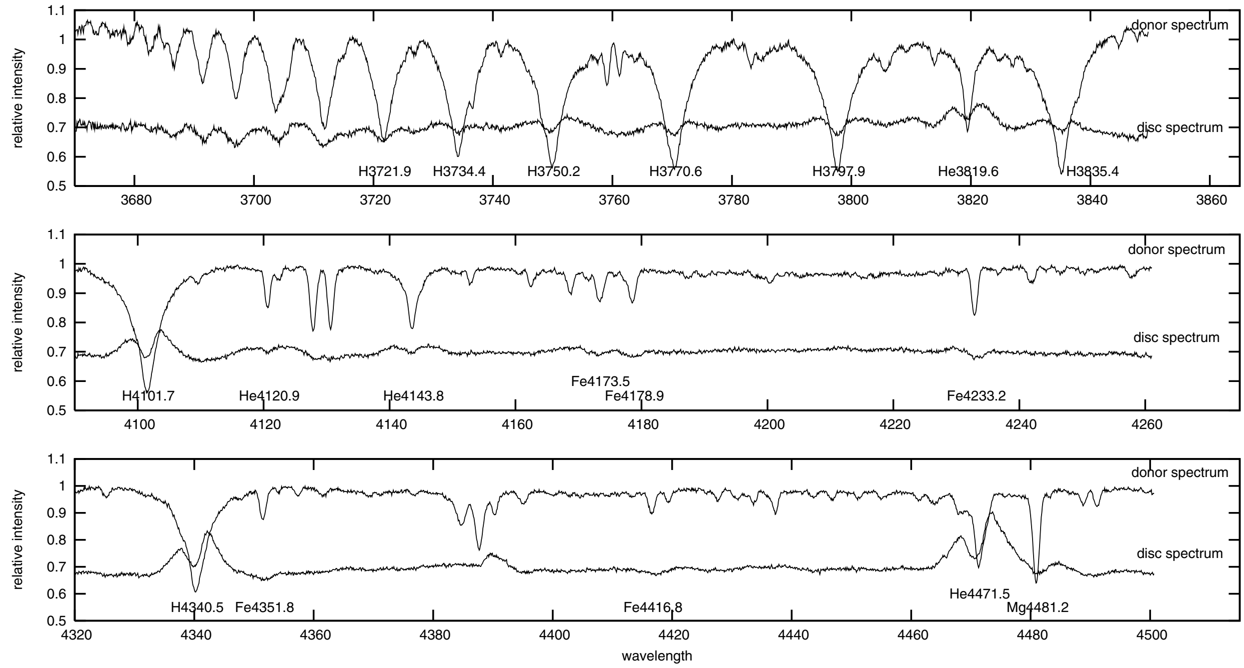

Fig. 3. The disentangled blue *photographic* spectra of the binary components of β Lyr. Note the quite pronounced absorption lines originating in the rim of the accretion disc, which are observed for ions similar to those seen in the spectrum of donor star.

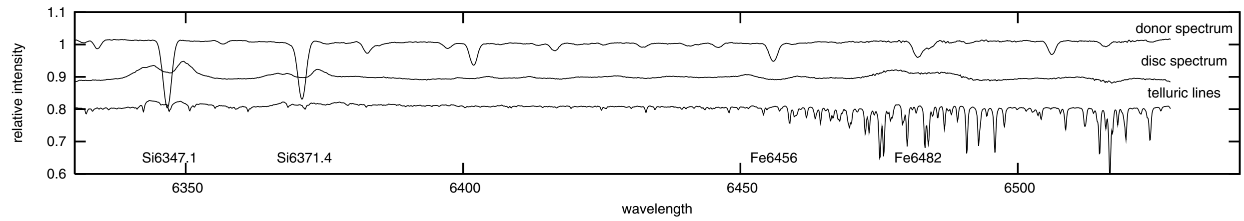

Fig. 4. The disentangled red *electronic* spectra of the binary components of β Lyr. Note several weak absorption lines originating in the rim of the accretion disc (besides the already known Si II doublet), which are observed for ions similar to those seen in the spectrum of donor star.

The disentangling of the blue photographic spectra with KOREL[4] allowed us to obtain some qualitatively new pieces of information not obtained from these spectra earlier. Note, however, that KOREL could not separate emission lines from the jet-like structures and placed them into the disc spectrum. This is not surprising since the jets are close to the disc edge and move *approximately* in antiphase to the donor.

To disentangle the red electronic spectra, we also included the telluric lines in the solution. First we measured the RVs of selected telluric lines and corrected the zero point of the wavelength scale for each spectrum individually for the difference between measured RV and calculated heliocentric correction (Horn et al. 1996). Then we applied KOREL to these wavelength-corrected spectra.

Disentangled electronic spectra are shown in Fig. 4. In addition to the previously known Si II 6347 and Si II 6371 lines, one can also see other weak lines originating from the accretion disc pseudophotosphere. It is also seen that the disentangling of telluric lines worked quite well. The corresponding RV curves are shown in Fig. 5. Disentangling returned RVs for the accretion-disc spectra, which define a sinusoidal RV curve in antiphase to that for the donor well. An increased scatter around the mean curve is not surprising since these RVs arise from a

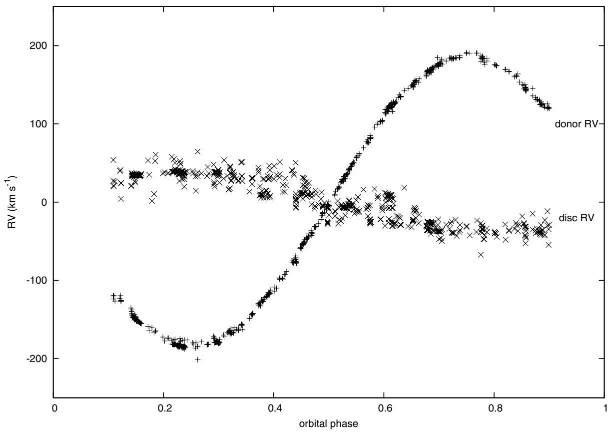

Fig. 5. The RV curves of the donor and the lines from the disc pseudophotosphere based on the disentangling of the red electronic spectra using KOREL.

cross-correlation of individual spectra with KOREL-disentagled ones and may in particular cases be affected by the varying S/N ratio as well as by the presence of additional sets of spectral lines.

A word of caution is appropriate here. As was clearly demonstrated by Harmanec et al. (1996), the RV curve of the emission

[4] To the best of our knowledge, the only other attempt to disentangle digitised *photographic* spectra was carried out by Zverko et al. (1997).

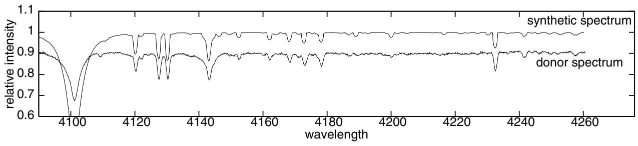

Fig. 6. Comparison of the disentangled spectrum of the donor with a synthetic spectrum for $T = 13\,000$ K, $\log g = 2.5$[cgs], and $v \sin i = 55$ km s^{-1}.

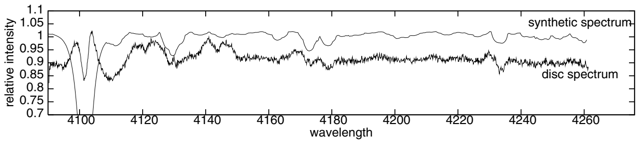

Fig. 7. Comparison of the disentangled spectrum of the accretion-disc pseudophotosphere with a synthetic spectrum for $T = 9000$ K, $\log g = 1.5$[cgs], and $v \sin i = 180$ km s^{-1}.

lines is only approximately in anti-phase to that of the donor star since the bulk of the emission originates in the jet-like structures. The same is also true for the blue-shifted absorption lines. We made several attempts to disentangle these lines independently, simulating another binary system with the same $12\overset{d}{.}94$ period, but these attempts resulted in unstable solutions and did not lead to convincing results. That is why we only present the approximate decomposition on the line spectra of the donor star and pseudophotosphere of the disc.

After successful decomposition, we attempted to compare the disentangled spectra with the synthetic spectra having solar composition and based on Kurucz model atmospheres. The main reason was not to improve the knowledge of basic physical properties of binary components, but to judge the quality of the disentangling process. The disentangled spectrum of the donor corresponds quite well to the synthetic spectrum with $T = 13\,000$ K, $\log g = 2.5$[cgs], and $v \sin i = 55$ km s^{-1}, which agrees with the values currently adopted for this star and confirms that it fills the corresponding Roche lobe. The comparison is presented in Fig. 6. There is, however, an obvious problem: the ratio of intensity of the hydrogen lines to that of the iron lines is much higher for the synthetic spectrum than for the spectrum of the donor. This can clearly be seen in Fig. 6, which includes the Hδ 4101 Å line, and is probably related to the fact already discussed by, e.g., Balachandran et al. (1986): the continuing mass transfer brought to the stellar surface some deep layers affected by the nuclear burning with lower hydrogen and higher helium abundance.

A similar comparison of the disentangled spectrum of the accretion-disc pseudophotosphere with a synthetic spectrum is even more problematic since the Balmer lines are partly filled by the emission from the jet-like structures we were unable to disentangle separately. Moreover, it is to be expected that the outer parts of the accretion disc have roughly Keplerian rotation, which implies zero effective gravity. There are currently no synthetic spectra modelling such conditions properly. For a rough comparison, we therefore used a synthetic spectrum with the lowest $\log g = 1.5$[cgs] available. The comparison is shown in Fig. 7 for a synthetic spectrum characterised by $T = 9000$ K, $\log g = 1.5$[cgs], and $v \sin i = 180$ km s^{-1}. One immediately notes the presence of already discussed problems: the disentangled spectrum also contains emission lines and the absorption core of Hδ is much fainter than that in the synthetic spectrum, again relative to the intensity of iron lines. Note, however, that there is a rough agreement between the observed and model line profiles of metallic lines in the longward part of the spectrum. Notably – for the inclination of $i = 86°$ derived by Linnell (2000) – the projected rotational velocity of $v \sin i = 180$ km s^{-1} (which provides the best fit to the disentangled line profiles), corresponds well to the expected Keplerian rotation of the outer parts of accretion disc, see, e.g., the discussion in Harmanec (1992).

5. Phase-locked variations of the strength of the absorption lines

Altogether, 12 absorption lines of the donor from the photographic spectra and 3 absorption lines from the electronic spectra were chosen for the study of line-strength changes (see Figs. 1 and 2). We selected lines that are strong enough to have a good S/N ratio and remain unblended in any orbital phase. We used the program SPEFO to measure the central intensity (CI) and equivalent width (EW) of the selected lines in all spectra. Given the pronounced orbital light variations and the fact that the spectra were rectified to a continuum level containing the contributions from the donor and the disc rim, it is obvious that the observed quantities must be corrected to the continuum of the donor only.

Let us denote the observed quantities with subscript *obs* and those after the correction to the donor continuum level with subscript *c*. Then the appropriate corrections read as

$$CI_{\rm c} = 1 - \frac{F_1(\lambda, f) + F_2(\lambda, f)}{F_1(\lambda, f)}(1 - CI_{\rm obs}) \quad (3)$$

$$EW_{\rm c} = \frac{F_1(\lambda, f) + F_2(\lambda, f)}{F_1(\lambda, f)} EW_{\rm obs}, \quad (4)$$

where $F_1(\lambda, f)$ and $F_2(\lambda, f)$ denote the relative monochromatic fluxes from the donor and from the accretion-disc rim at given wavelength λ and orbital phase f. Note that the corrections depend only on *the ratio* of total flux of the system to the flux of the donor $(F_1 + F_2)/F_1$, which we shall call the *correction factor*.

To obtain the values of the correction factor for different wavelengths and orbital phases, one needs to use some appropriate light-curve solution that takes the non-spherical shape of the donor and the thick accretion disc into account. We used the latest version of the program BINSYN (Linnell & Hubeny 1996), kindly put at our disposal by Dr. A.P. Linnell. BINSYN is one of the very few programs able to model the light curves of binaries with optically thick accretion discs[5]. Input parameters required by BINSYN were adopted from the study of Linnell (2000), who obtained the best fit of the observed light curves of β Lyr over a wide range of wavelengths so far. For details of the modelling we refer readers to Linnell (2000).

In Fig. 8, we compare the final fit with BINSYN to the Johnson U-, B-, and V-band light curves using UBV observations from Harmanec et al. (1996) and more recent Hvar and Tubitak observations. For the V-band light curve, we also show the individual contributions to the overal light variations caused by (a) the light variations of the donor due to eclipses, ellipticity, and reflection, and (b) by the eclipse of the disc rim. Note that the correction factor at each orbital phase is the ratio of the total flux of the binary system to the flux of the donor.

It is seen that the fit by BINSYN shown for the V- and U-band light curves is not optimal. On the observational side, this might be related to the already known secular variations of the light curve in phases around eclipses. However, since an improved solution of the light curve is not the topic of our study, we simply adopt the best light-curve description obtained by

[5] Note that the theory of accretion discs and their geometrical and radiative properties is still in the stage of further development.

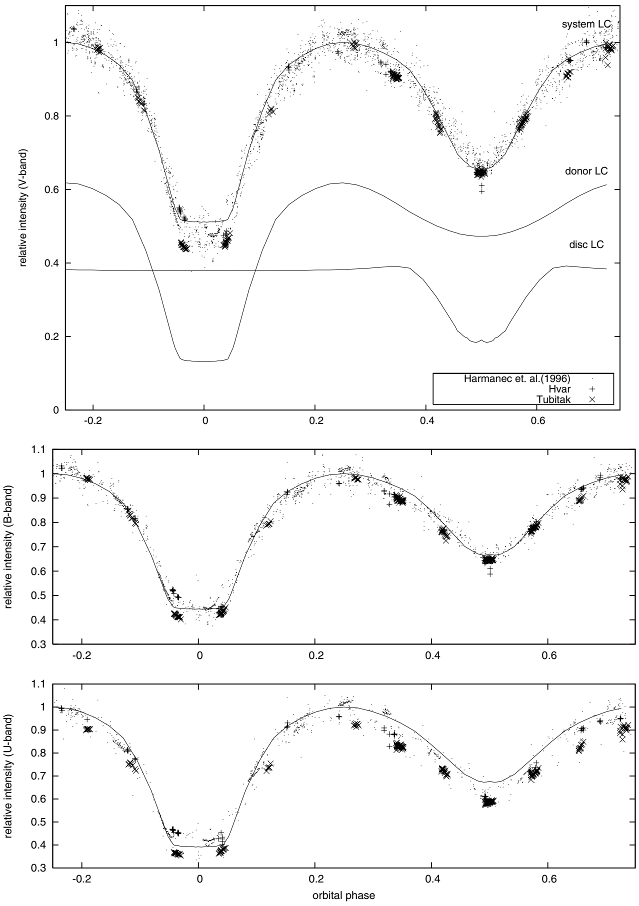

Fig. 8. Comparison of computed light curves of β Lyr with *UBV* observational data. Note the decomposition of the *V*-band light curve to the light curves of the donor star and accretion disc presented in the upper panel.

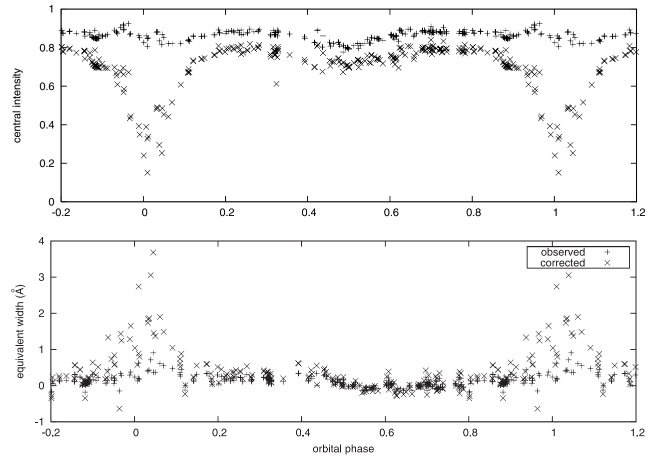

Fig. 9. On-phase dependency of relative central intensity (*top*) and equivalent width (*bottom*) of the Si II 6371 absorption line.

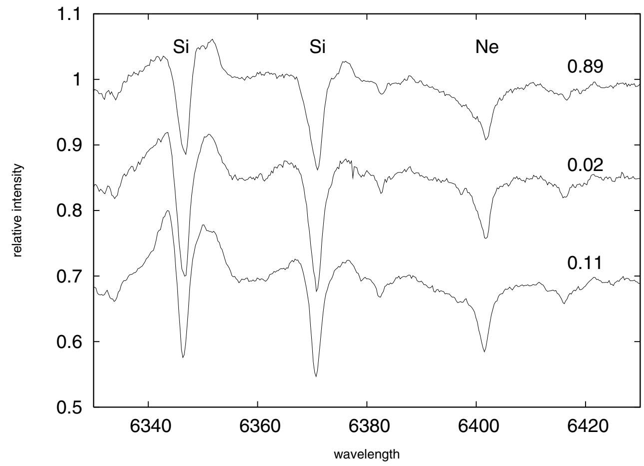

Fig. 10. Samples of 3 electronic spectra around the primary eclipse. The orbital phase is indicated on the right side of each spectra.

Linnell (2000) to correct CIs and EWs of the lines for the phase-dependent flux variations.

Figure 9 is a phase plot of *CI* and *EW* of the Si II 6371 line for both the original and corrected data. There is a very pronounced phase variation in the corrected values of these parameters, with a very clear line strengthening centred on a phase shortly following the primary mid-eclipse. The same phase dependence was also found for all other investigated lines. These changes are too large to be caused by the physical or geometrical properties of the donor. This conclusion is corroborated by the fact that we obtained *negative values* of *CI* near the primary eclipse for the H I and He I lines, which is physically impossible. This effect is also demonstrated in Fig. 10, where samples of 3 spectra around primary eclipse are presented. It is seen that absorption lines in the phase of primary mid-eclipse (second spectrum) are deeper, which is in contradiction with the fact that most of the donor surface is hidden from view in this phase. It is true that a small part of the strengthening of the absorption lines may be accounted for by the fact that the absorption lines of the accretion-disc pseudophotosphere have identical RVs to those of the donor at phases near both eclipses[6]. However, they are too weak to cause such a strong effect.

This situation could drive one to conclude that the effect is a result of inaccuracy of the light-curve modelling (e.g., overestimation of the light from the thick disc) and a consecutive usage of an overestimated correction factor. However, no matter what uncertainity can be introduced by possibly imperfect light-curve modelling, the effect we find must be qualitatively correct. Note that the correction factor is basically given by the orbital light variations, and by its definition, it has a very pronounced maximum at the phase of the mid-primary eclipse. Therefore, the largest correction of the values of CI and EW is expected just in the phases centred on the primary eclipse (compare Fig. 9 also). The result described here would not, therefore, be altered qualitatively by any reasonable change in the correction. To avoid the effect we found, the observed absorption lines would have to be shallower in the phases near the primary eclipse than in the phases out of the eclipse, which is obviously not true (see Fig. 10).

Therefore, we conclude that the strengthening of the spectral lines near the primary mid-eclipse is a real fact and the only way to explain it is to assume that it is caused by *additional absorption from circumstellar matter* in orbital phases near the primary mid-eclipse. It is improbable that it would be due to the so-called satellite lines which appear in the spectrum of β Lyr shortly before and shortly after the primary mid-eclipse since these lines are blue-shifted and then red-shifted for some 150−200 km s^{-1}, so they can hardly be confused with the lines of the donor. Besides, they disappear near the centre of the eclipse.

[6] Assuming this fact, it is possible to explain weak strengthening of the absorbtion lines around the secondary eclipse, as seen in Fig. 9.

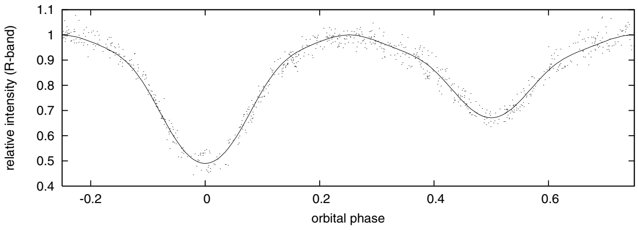

Fig. 11. Fourier fit of the Johnson *R*-band observational data.

Therefore, the only plausible explanation is to associate the additional absorption with the jet-like structures and the scattering envelope above the poles of the accretion disc. Note that the phase of maximum strength of the lines coincides well with the phase when the projection of the jet against the donor should be largest, cf. Harmanec et al. (1996). For any given geometry of the system, there is always a certain part of the donor that remains uneclipsed by the disc during the primary eclipse, and the light from this uneclipsed part goes though both the gas envelope and one of the jet-like structures toward an observer. If correct, this interpretation means that there is yet another absorption-line spectrum observable only in the phases of the primary eclipse. This finding is another independent confirmation of the existence of jet-like structures in the system.

6. Orbital and long-term *V/R* changes of the Hα emission

Very interesting features in the spectra of β Lyr are strong and variable emission lines of Hα and He I 6678 , which were intensively studied by Harmanec et al. (1996), who measured RVs of various parts of them. They concluded that these lines originate in jet-like structures perpendicular to the orbital plane. We measured central intensity of the *V* and *R* peaks of the Hα line on both Ondřejov and DAO electronic spectra in an attempt to find some orbital and/or long-term variations of the strength of this emission line. The measured intensities had to be corrected for the orbital light variations, in a similar fashion to the absorption lines of the donor star discussed in the previous section. However, since the emission is supposed to originate away from the orbital plane, it should not be largely affected by the eclipses. Consequently, we replaced the term F_1 in the correction factor in Eq. (3) by a constant of 1. Note that the correction factor then represents the orbital light change of the whole binary.

In practice, the *R*-band photometry from Harmanec et al. (1996) was used since this passband is centred on the wavelength of the Hα line. We used the program PERIOD04 (Lenz & Breger 2005) to model the *R*-band light curve as a function of the orbital phase for the quadratic ephemeris using the principal orbital frequency and the first six of its harmonics. In other words, the Fourier series in the form $A_0 + \sum A_i \sin(2\pi(it + \phi_i))$, where *t* was orbital phase, up to the sixth order was used. The observational data and the corresponding Fourier fit are presented in Fig. 11. The measured values of the peak intensities of Hα were then corrected using the above analytical expression fitted to the *R*-band light curve.

In Fig. 12, the directly measured and corrected peak intensities of both Hα emission peaks are plotted vs. orbital phase. It is obvious that after the correction, the apparent large phase variations of both quantities almost disappeared. This may indicate that our procedure worked well. Indirectly, this also confirms that the bulk of emission originates in the bipolar jets, i.e., outside the orbital plane. Upon closer inspection, one notes that while the corrected intensity of the *V* peak shows no obvious dependence on the orbital phase, some mild orbital modulation remains in the corrected intensity of the *R* peak.

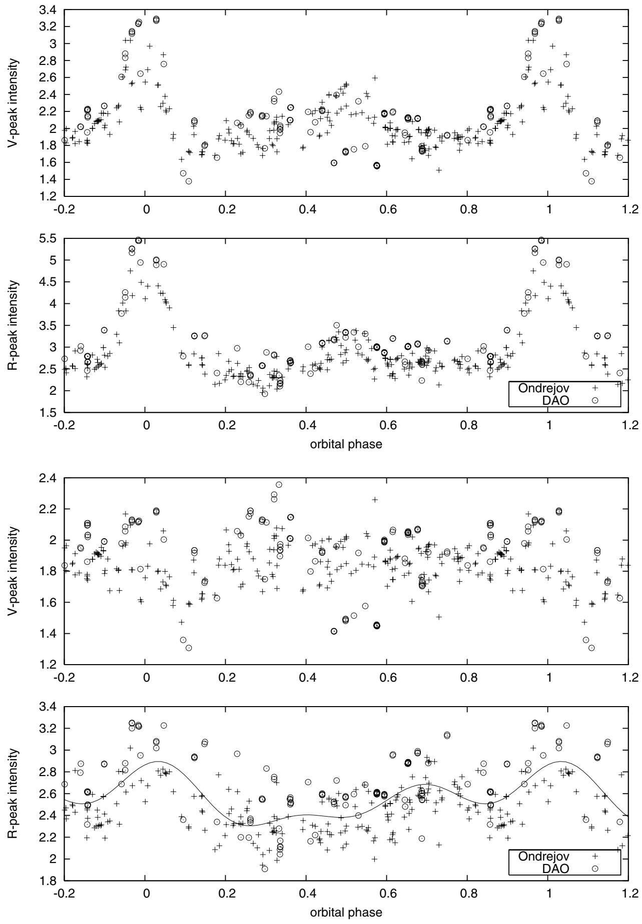

Fig. 12. Relative *V*- and *R*-peak intensities of Hα before the correction (*top*) and after the correction (*bottom*) to the orbital light variations.

If the observed emission originates mainly from the bipolar jets, then the *V* peak of the Hα emission presumably originates in the "upper" jet, i.e., the jet having negative RV with respect to the observer, which (thanks to the orbital inclination slighly smaller than 90°) is seen completely at any orbital phase. In contrast to it, the *R* peak originates in the other jet, which is partly shielded from the view by the accretion disc and by the donor; the amount of this shielding varies with the orbital phase. The puzzling fact is that the corrected *R*-peak intensity has *a maximum* around the phases of the primary mid-eclipse. This disagrees with the expectation that the jet responsible for it should be more occulted by the disc at these phases than in elongations. It is clear, however, that the peak intensities may also be affected by the Hα absorption lines with different RVs, which move across the emission profile as already discussed by Harmanec et al. (1996). For the moment, we leave this piece of information unexplained.

Noting that the scatter of individual emission-peak intensities in both panels of Fig. 12 is quite high, we decided to investigate whether these quantities also vary on timescales different from the orbital motion. For such an analysis, residuals of the *V*- and *R*-peak intensities prewhitened for the orbital variations were used. To obtain these residuals, we simply subtracted the mean value from the *V*-peak intensities (which show no apparent dependence on the orbital period) and fitted the orbital

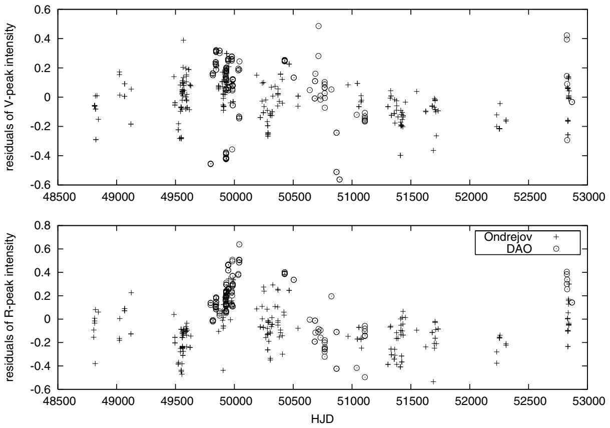

Fig. 13. Residuals of the relative V- and R-peak intensities of Hα (after removal of their orbital modulation) as functions of time.

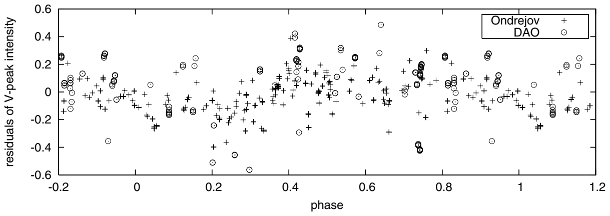

Fig. 14. Residuals of the relative V-peak intensity of Hα vs. phase of a period of $P_V = 271\overset{\mathrm{d}}{.}198$.

period and a few harmonics to the R-peak intensities (see bottom panel of Fig. 12). Then we subjected these peak-intensity residuals, seen in Fig. 13, to a period search from 11 to 5000 d, using the Stellingwerf (1978) PDM period search technique.

The best period found in the residual V-peak intensities was $P_V = 271\overset{\mathrm{d}}{.}198$, but its statistical significance is low. This is also seen in Fig. 14, where the V-peak intensity residuals are plotted vs. the phase of this period. The period of $271\overset{\mathrm{d}}{.}2$ is reminiscent of the period of $282\overset{\mathrm{d}}{.}370$ found in the photometric data prewhitened for the orbital changes by Harmanec et al. (1996). We verified, however, that the V-peak residuals cannot be reconciled with the $282\overset{\mathrm{d}}{.}370$ period, and the significance of our result is not clear.

The best period found in the residual R-peak intensities is $P_R = 2778\overset{\mathrm{d}}{.}7$. It has a higher statistical significance, but as Fig. 13 shows, only slightly more than one such cycle is covered by our data. It may be related to mild variations in the depth of eclipses of the corresponding region (jet below orbital plane) due to, for example, long-term changes in the geometry of the accretion disc. The cycle we find is reminiscent of a cycle of $3646\overset{\mathrm{d}}{.}0$ already reported by Maury (1935).

In passing, we note that we also attempted to disentangle the Hα line into several components with the same (orbital) period using KOREL and initial semi-amplitudes and phases of expected components following Harmanec et al. (1996), but this attempt failed.

7. Conclusion

Analyses of a rich collection of high-dispersion photographic and electronic spectra of β Lyr led to the following findings:

(i) The observed optical spectrum of β Lyr consists not only of a contribution of the donor and other known sets of lines, but also of the line spectrum of the accretion disc. Weak lines from the pseudophotosphere of the disc were disentangled using the program KOREL. A better analysis of the disc spectrum will require further improvement of the disentangling procedure. The possibility of treating several emission and absorption contributions to the spectral lines in the observed spectra during the disentangling process is needed.

(ii) We discovered yet another satellite spectrum of absorption lines which is observable near the primary mid-eclipse. This spectrum is most probably caused by the absorption of light of the donor in the circumstellar structures surrounding the gainer, i.e., in the "upper" jet and the scattering envelope.

(iii) The intensity of the V peak of Hα corrected for the orbital light changes does not show any obvious dependence on the orbital phase. It may vary, however, with a period of $P_V = 271\overset{\mathrm{d}}{.}198$. The intensity of the R peak of Hα corrected for the orbital light changes does show some orbital modulation plus a long-term variation over a 2780-d cycle.

The increasing resolving power of new optical interferometers should soon permit astrometric resolution of the binary orbit and the accretion disc[7]. Note that Harmanec et al. (1996) (using the GI2T spectrointerferometer) only succeeded in partly resolving the bipolar jets in the system. They should also be able to resolve the binary orbit, and their negative result may indicate that the orientation of the binary orbital plane in the sky is more or less perpendicular to the South-North orientation of the only baseline of GI2T. This suggests that future attempts should also use some East-West baseline during interferometric observations. There is little doubt that a succesfull interferometric resolution of β Lyr would help enormously in the understanding of the circumstellar structures and the improvement of the basic physical properties of this enigmatic binary.

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[7] According to the current model of the binary and the Hipparcos parallax $p = 0\overset{\prime\prime}{.}00370$, the projected separation of the centres of both bodies and the projected diameter of the disc should be $0\overset{\prime\prime}{.}00100$ and $0\overset{\prime\prime}{.}00086$, respectively.

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