THE PRELIMINARY RESULTS OF INVESTIGATION OF ENIGMATIC STAR β LYRAE

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The results of preliminary spectral investigations of enigmatic star β Lyr have been presented. Spectral observations of this star were performed at Cassegrain focus of 2-m telescope of Shamakhy Astrophysical Observatory (ShAO) named after N.Tusi of Azerbaijan National Academy of Sciences, by using fiber-echelle spectrograph ShaFES with the CCD camera 4K$\times$4K pixels, cooled by liquid nitrogen. Spectral resolution and wavelengths region are 56 000 and $\lambda\lambda$3700-8500 ÅÅcorrespondingly. Here we presented mainly the results of spectral investigations of spectral lines H_α and HeI 6678. The line H_α is double-peaked emission. This line consists of "broad" and "narrow" emission components and with absorption feature that is always blue shifted. The spectral parameters (radial velocity, equivalent widths etc.) of emission components of lines H_α and HeI 6678 have been determined and character of the variability of these components was investigated. By measuring radial velocities of lines SiII $\lambda\lambda$ 6347 and MgII4481 the radial velocity curve of bright giant component (primary) was derived. The orbital period of β Lyr undergoes change because high mass loss rate of bright giant component. The period increases by $\sim$19 s per year. We determined the period of β Lyr corresponding to our observation season as 12.941428 days.

1. INTRODUCTION

The star β Lyr (HD 174638, HR 7106) is a bright ($V_{max} = 3^m.4, B-V = 0^m.0$) semi-detached interacting eclipsing close binary with the period of $P = 12^d.943296$ days [1]. According to modern views this binary system consists of a B6-8 II bright giant (primary star) with a mass of about $3M_\odot$, undergoing rapid mass transfer to an invisible more massive ($\sim 13M_\odot$) secondary star, surrounding with the thick accretion disk (Fig.1). The massive secondary star occults the blue bright giant

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(B6-8 II) every P =12.943296 days producing primary eclipses. Note that the physical nature of the massive secondary of β Lyr remains a mystery. Because that outer regions completely obscured by the thick accretion disc we could not determine the spectral type and derive radial velocity curve of this star.

As usual, we call the more massive and low-mass components of the binary system the primary and secondary components correspondingly. However, in the case of star β Lyr, the initially more massive component (primary component) losing mass through Roche-lobe overflow became less massive and vice versa. The initially less massive component (secondary) gaining loosing mass became more massive component of this system. Because of this, to avoid confusion, we will call the Roche-lobe filling giant star, B6-8II component as the **loser**, and the more massive star surrounding with the dense disc as the **gainer** (Fig.**??**). Fig.**??**. shows orbital separation ($\sim$ 55 $R_\odot$), radius of accretion disc ($\sim$ 30 $R_\odot$), the masses of loser and gainer ($\sim 3M_\odot$, $\sim 13M_\odot$), radiuses of loser and gainer ($\sim$ 15.2 $R_\odot$, $\sim$13 $R_\odot$). The temperatures **loser** and **gainer** are 13 300 K and 32 000 K correspondingly. The orbital inclination of β Lyrae is slightly smaller than 90° ($\sim$ 81°) and orbit approximately circular.

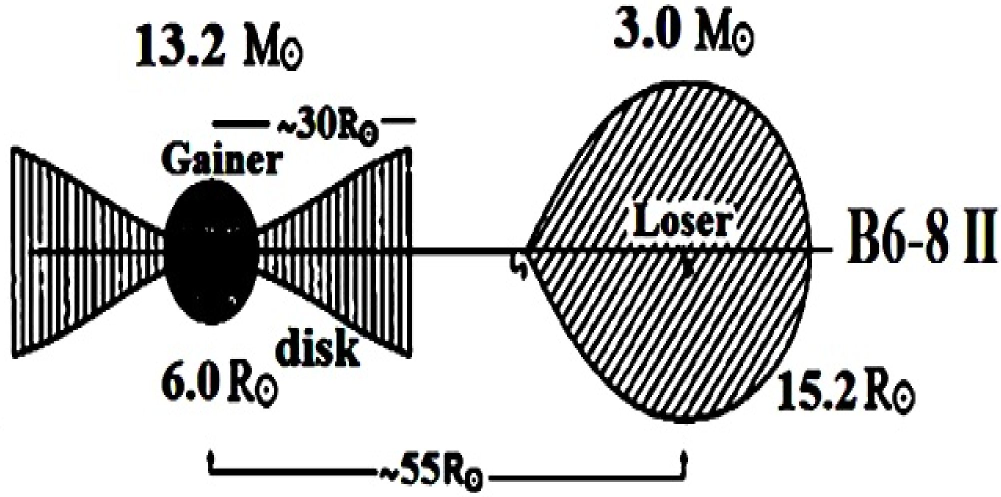


Fig. 1: The components and some parameters of the binary system βLyr.

According the modern view the less massive star (B6-8 II bright giant) initially was more massive member of the binary system β Lyr. Approximately 32 million years ago the masses of primary and secondary stars of this binary system were $\sim$9 $M_\odot$ and $\sim$7 $M_\odot$. It is known that the temp evolution of stars critically depends on mass. More massive component of this system evolves more rapidly and fills its Roche lobe. After filing Roche lobe massive component underwent rapid mass transfer to a secondary (less massive) component through the inner Lagrangian point. Due to this mass transfer the originally secondary star, become more massive star and is surrounded by a dense accretion disk. This accretion disk completely obscured the secondary star, lowering its apparent luminosity and making it difficult to determine stellar type and deriving radial velocity (RV) curve of this star. The massive accretion disk is likely dynamically unstable.

The amount of mass loss of B6-8 II bright giant is about 20×10^{-6} $M_{\odot}$ per year. The B6-8 II type bright giant mass loss to the more massive secondary induces a period change. The orbital period of this binary system is increasing at a rate of ∼19 second per year.

The star β Lyr exhibits strong emission lines and unusual spectral variability of these lines [2]. In these emission lines are encoded information concerning to gaseous shell surrounding binary system, the thick accretion disk, and the stellar wind. The star βLyr exhibits also variability in X-ray region [3] and authors of [4] revealed the variable spectral polarization of this star.

The star βLyr shows the light-curve instabilities which is associated with the accretion phenomena. Author of [5] found 275 ± 25 days periodic deviations from the mean light curve. Later by authors of [2, 6, 7] was confirmed 283.4 and 282.4 days periodic light variability. Note that the reason of this variability is not yet understood.

Authors of [8, 9] investigated the evolutionary status of βLyr and concluded that this star is in a Case-B mass transfer stage, with the age $\sim 2.30{\times}10^7$ years and with the mass loss rate $\sim$1.58 $\ldots 10^{-5}$ $M_{\odot} yr^{-1}$. The loser (primary) has exhausted hydrogen in its core and the gainer is slightly evolved with central hydrogen fraction Xch = 0.43 [9]. According results these investigations the mass transfer in β Lyr is quasi-conservative.

Authors of [2, 10, 11] discovered the presence of bipolar jets in star β Lyr from optical interferometric and spectropolarimetric observations. A theoretical justification the presence of bipolar jets was studied in [12].

Despite extensive spectral, photometric, polarimetric etc. investigations for over a century the physical nature of star β Lyr remains a poorly understood. For instance, there are some disagreement between the proposed currently models and observed variations of line spectrum. The aim of this study is investigation of spectral variability of this star by using high resolution observational material.

The modern detailed history of the investigation of β Lyr has been presented in [13].

2. OBSERVATIONAL DATA AND THEIR PROCESSING

The spectral observations of star βLyr were carried out in July-August of 2019 at the Cassegrain focus of 2-meter "Zeiss" telescope of Shamakhy Astrophysical Observatory (ShAO) of Azerbaijan National Academy of Sciences. During 18 nights the forty spectrum of this star have been received. The Shamakhy Fibre Echelle Spectrograph (ShaFES) with the liquid nitrogen cooling CCD matrix (4000×4000 px) was used [14]. The spectral range was $\lambda\lambda$3800–8500 ÅÅ; the spectral resolution was 56000; and the signal to noise ratio was S/N $\sim$ 300. In processing of echelle-spectrograms the software package DECH20T, developed at the Spesial Astrophysical Observatory, Russian Academy of Sciences was used [15]. The exposition time was 20 min. The mean square errors of equivalent widths and radial velocity measurements are 5% and 300 m/s, respectively.

Two echelle-spectrograms were obtained on each night. The two echelle-spectrograms obtained one after the other during each observational night were averaged to remove the traces of cosmic rays. In addition to the spectra of the star being studied, we obtained the spectrum of daylight sky, the dark spectra, and the flat field spectra. For the radial velocity measurements, we build a high accuracy dispersion curve for each order by using the daylight spectrum. The displacements in each order were determined by using the telluric lines in the daylight and star's spectrum. There are a catalog of wavelengths with high accuracy (±0.01 Å) for the solar spectrum in the software package DECH20T. In radial velocity measurements a heliocentric correction connected with the Earth orbital motion, daily rotation and the perturbing effects of the moon and the major planets of the solar system take into account.

3. THE RADIAL VELOCITY CURVE OF PRIMARY (LOSER)

The deriving of radial velocity (RV) curve of βLyr allows us determination the value of orbital period and its secular increase with a high accuracy than derived from photometry. The reason is that due to light curve variations the determination of the times of both minima is difficult. The RV curve of the loser (B6-8II component) nearly sinusoidal and allow us more accurately determination the times of minima. Note that due to mass loss by bright giant (B6-8II) the separation of the centers of components increases and it leads to the secular chance of RV semi amplitude.

For the deriving the RV curves of primary (loser) the lines SiII λ6347 and MgII 4481 were used. Due to the fact that these lines are narrow, radial velocities of these lines can be measured with high accuracy. As seen from Fig.**??** we have achieved good phase coverage.

As noted above, because of mass loss by the loser the period of a binary system β Lyr undergoes a change. The period change has been studied by many astronomers. It was established that the period change rate is approximately constant and the value of the period increases by ~19 sec every year [1]. Because of this, to derive the RV curve, we must at first find the value of period corresponding to our observational season. Our spectral observation performed during July-August of 2016 and at the same season the photometric observations of this star also carried out in [1].

Taking into account that a parabolic O-C diagram for the times of minima very well describes the expected moments of eclipse minima and by using elements of [16] authors of [1] determined the value of period as P = 12.943296 days, for the epoch 3811 corrected for the dP/dt change.

When plotting the RV curve by using our measurements (for lines SiII λ6347 and MgII 4481) with the period of P = 12.943296 days determined by the authors [1] we obtained the shifted RV curve (Fig. 2, blue points) relative to the RV curve derived in [17] (Fig.2, black points). The orbital phases were computed from T=2449559.980, when the primary minimum was occurred. Phase 0 corresponds to the superior conjunction of the loser, i.e. primary minimum. The primary (deeper) minimum occurs when the less massive, more luminous giant star (loser) is eclipsed. By using thumb method we find the value of orbital period

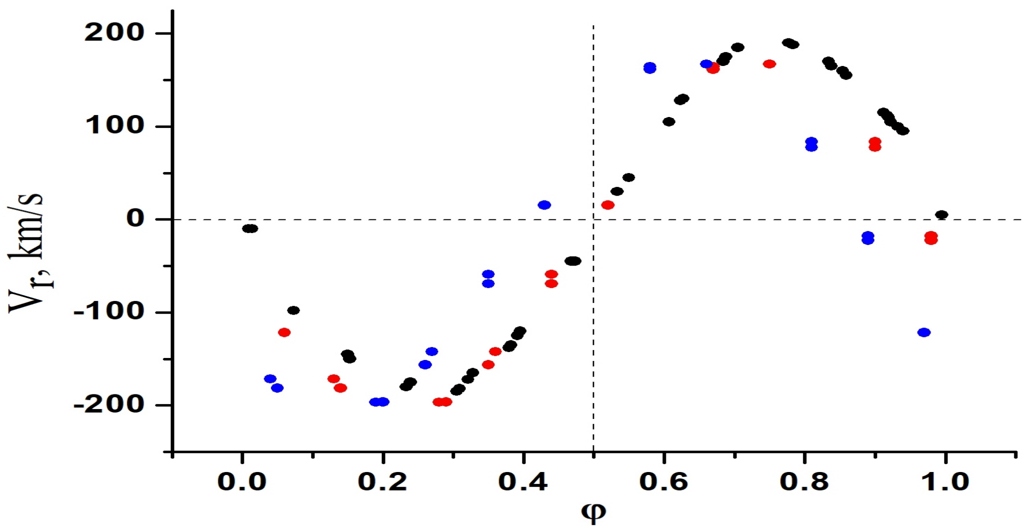


Fig. 2: RV curves of primary (loser): blue - our measurements plotted with the period of P = 12.943296 days; black - Skul'skii [17] RV curve; red - our shifted RV curve coinciding with the Skul'skii [17] RV curve.

of P = 12.941428 days when our (red) and derived in work [17] (black) RV curves are coincide (Fig.2). Thus the value of orbital period corresponding to 2016 year (our observation season) have been determined as 12.941428 days.

Fig.3 and Fig.4 shows the RV curve of primary derived from our measurements of radial velocities of SiII 6347 and MgII 4481 lines correspondingly. As seen from the Fig.5 the RV curves of primary derived from our measurements of radial velocities of lines SiII 6347 and MgII 4481 are coincides.

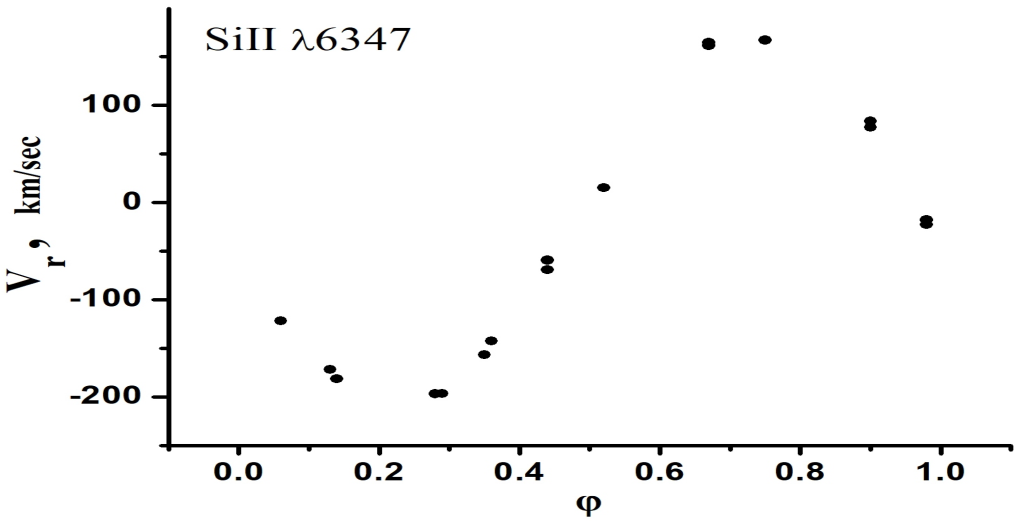


Fig. 3: The RV curve of primary derived from our measurements of radial velocities of line SiII 6347

Note that for a long time, no orbital RV curve of the secondary star hidden in the accretion disc was available. Only authors of [18] discovered the faint pair of Si II 6347 and 6371 lines varying in antiphase with the lines of primary (loser) and interpreted them as the lines of the secondary component. However author of [19], who argued that actually the lines Si II 6347 and 6371 originate in the pseudophotosphere of the accretion disc. But author of [19] agree with the conclusion made in [18] that variation of these lines reflect the orbital motion of the secondary star.

4. VARIATIONS OF THE H_αAND HEI 6678 EMISSION LINES

One of the interesting features in the spectra of β Lyr are strong and variable emission lines of H_α and HeI 6678. These double-peaked emission lines have a complicated behaviour with the orbital phase. These lines were intensively stud-

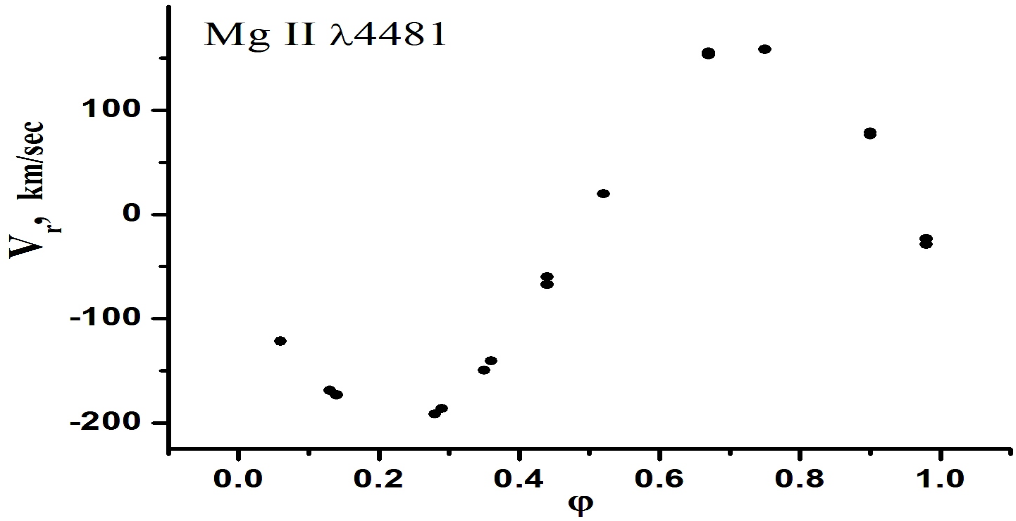


Fig. 4: The RV curve of primary derived from our measurements of radial velocities of line

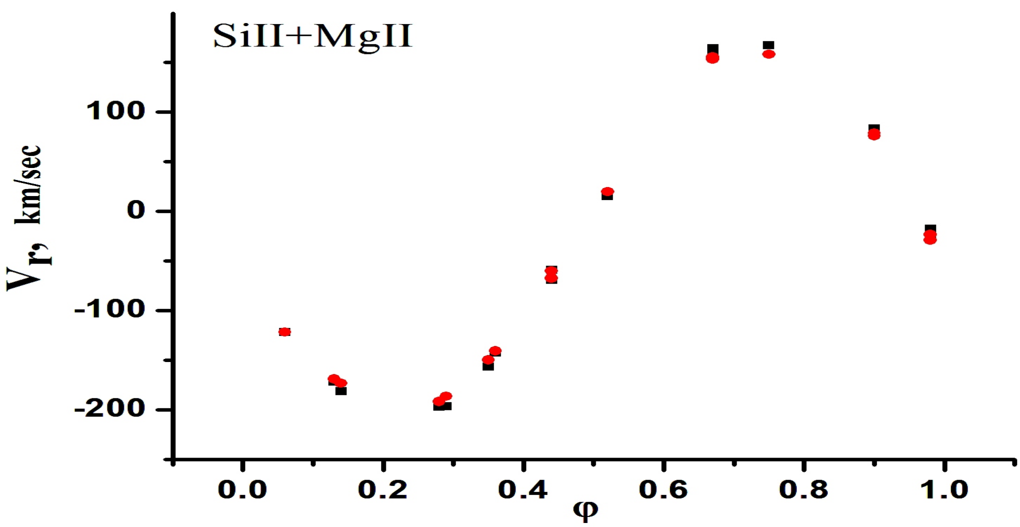


Fig. 5: The RV curves of primary derived from our measurements of radial velocities of lines SiII 6347 and MgII 4481. The RV curve derived for both lines are coincides.

ied in [20–23] and authors of [2, 11] concluded that bulk of emission of these lines originate in jet-like structures perpendicular to the orbital plane.

The variability of emission line H_α. The emission line H_α in the spectrum of β Lyr is double-peaked with the always blue shifted absorption feature (Fig. 6). Therefore the line H_α consists of "narrow" violet and "broad" red emission components (Fig.6). At all phases of orbital period we also observe the so called

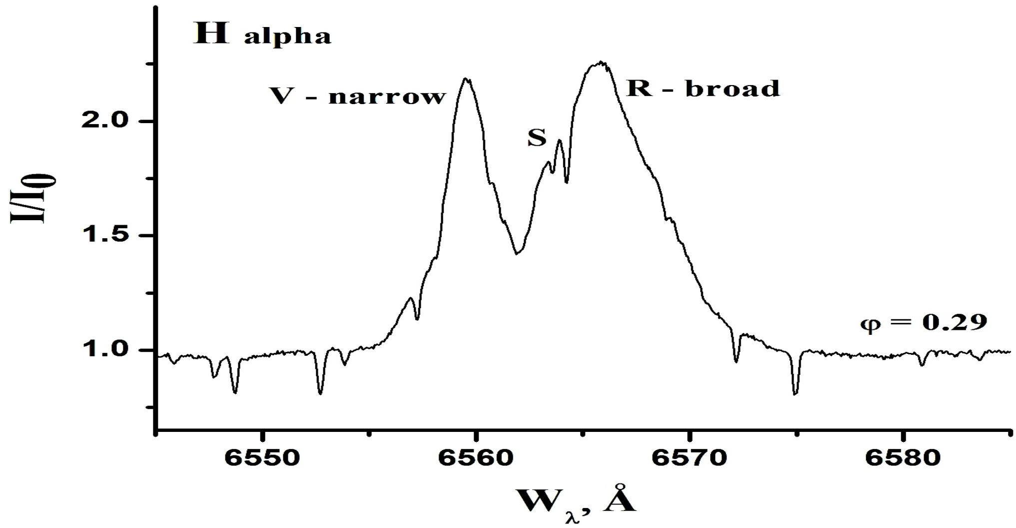
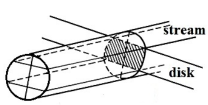


Fig. 6: The profile of line H_α in the spectrum of βLyr at phase 0.29 of the orbital period.

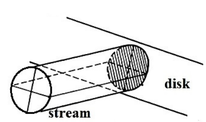
S-wave emission component (Fig.6) in H_α that is characteristic for the cataclysmic variables [24]. Fig.7a and Fig.7b shows mechanism formation of S-wave emission in two cases: 1. S-wave emission originates at the above and below parts of hot spot in the stream if cross section of the stream is larger than vertical dimension of the disk (Fig.7a).

2. It is obvious that stream fully collides with the outer edge of disk, if disk thicker than stream (Fig.7b). In this case S-wave emission originates above and below regions of the hot spot.

Fig.8 and shows the radial velocity vs. phase dependence of red, absorption and violet components of H_α. As seen from this picture the character of variability of violet and absorption components are approximately same. The behavior



(a) The cross section of the stream is larger than vertical dimension of the disk.



(b) he cross section of the stream is lower than vertical dimension of the disk of variation of red component radial velocities is different. The central intensity vs. phase dependence of red and violet components of H_α also is similar (Fig.9). These kinds of variations coincide with the results of earlier investigations [2]. Fig. 10 shows the dependence of the equivalent widths on the phase whole H_α (sum), red and violet components. As seen from Fig.11 the dependence of the FWHI from the phase violet and red components quite different.

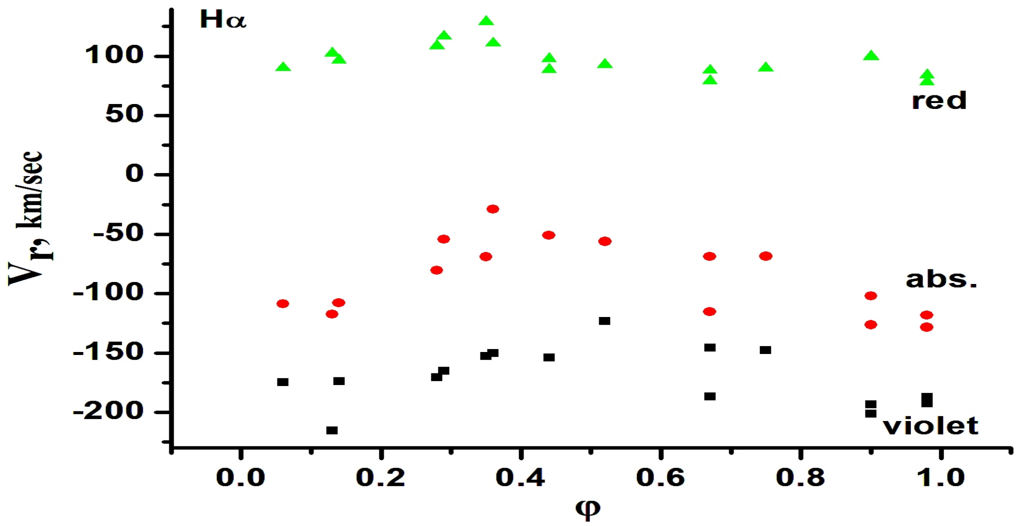


Fig. 8: The dependence of the radial velocities from the phase red absorption and violet components of H_α

One of our quite interesting results is connected with the Fig. 12. As seen from Fig. 12 the ratio of central intensities of violet and red component vs. phase has two maximum at phases approximately 0.36 and 0.86 (Fig.12). These phases are coinciding with the phases when magnetic poles of star β Lyr are directed toward the observer according the model of star βLyr proposed by Skul'skii [17] (Fig.13).

The radial velocities of S-wave emission changes approximately synchronously with the radial velocity variations of the primary, with the small amplitude (Fig. 14). The variability of emission line He I 6678. The profile of this emission line differs from the profile of H_α line. Though the profile of line H_α has two components, the emission line HeI 6678 sometimes has three components (Fig. 15). The second distinctive feature is that the central absorption in case of HeI 6678 deeper in comparison with the line H_α. Fig. 16 shows the dependence of the radial velocities from the orbital phase red absorption and violet components of emission line HeI 6678. As can be seen from this figure the feature of this dependence coincides with the analogous dependence for the emission line H_α(Fig.8).

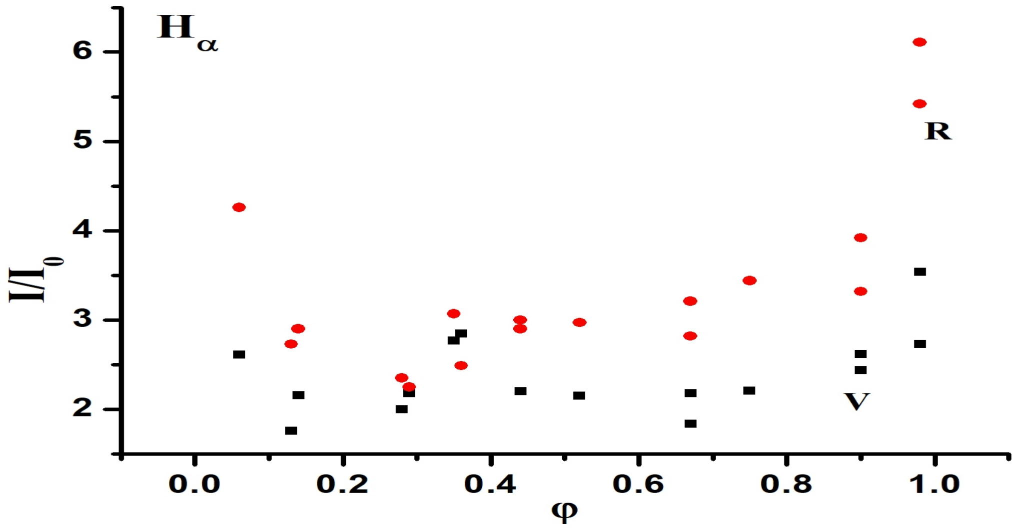


Fig. 9: The dependence of the central intensities red and violet components of H_α from the phase

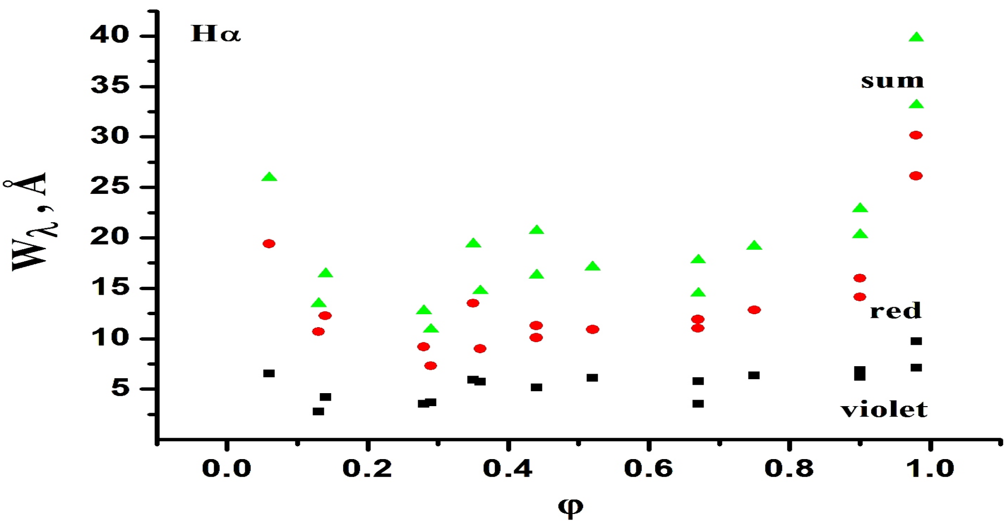


Fig. 10: The dependence of the equivalent widths from the phase whole H_α(sum), red and violet components of H_α

The character of dependence of the central intensities from phase of red and violet components of HeI 6678 (Fig. 17) also similar to the analogous dependence for H_α (Fig. 9). It is interesting that the dependence of ratio of central intensities of violet and red components from the phase for the lines $H_\alpha$and HeI 6678 are

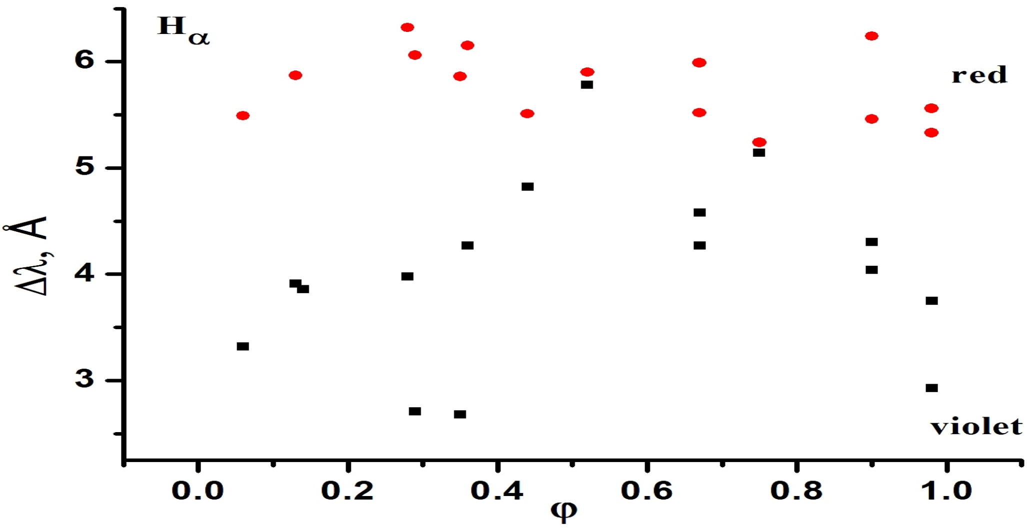


Fig. 11: The dependence of the FWHI of red and violet components of $H_\alpha$from the phase.

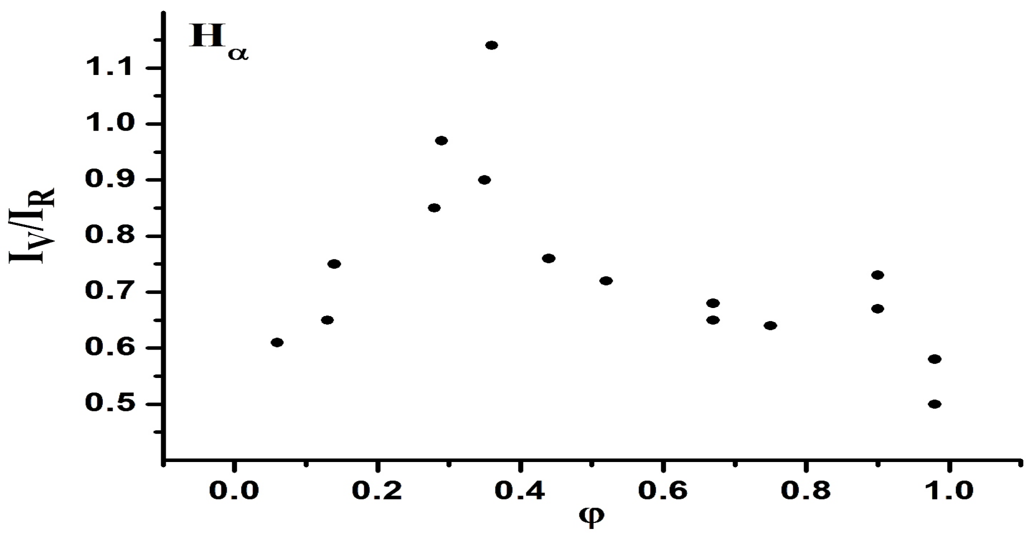


Fig. 12: The dependence the ratio of central intensities of violet and red components of $H_\alpha$from the phase

similar. In both cases there are maximum at phases approximately 0.36 and 0.86 (Fig. 12 and Fig.18).

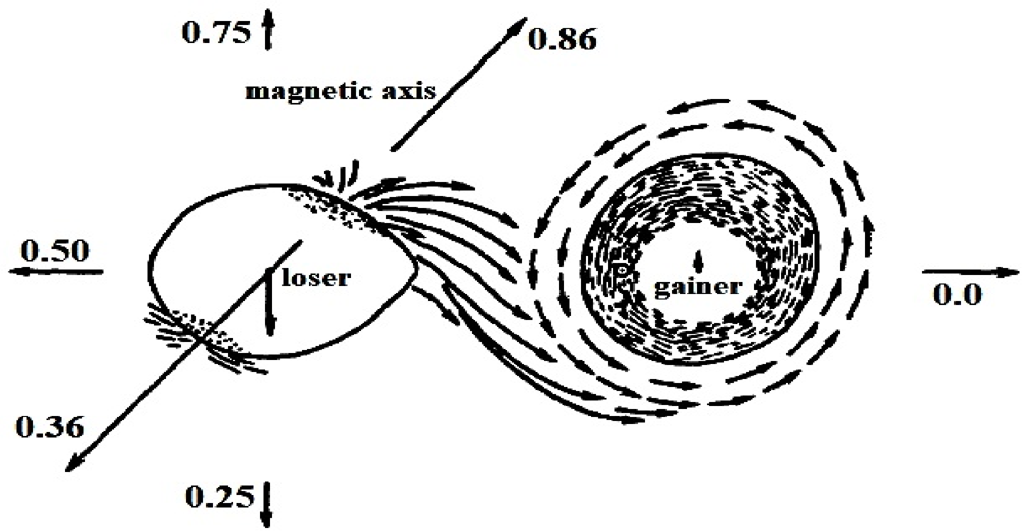


Fig. 13: The model of star βLyr proposed by Skul'skii [17].

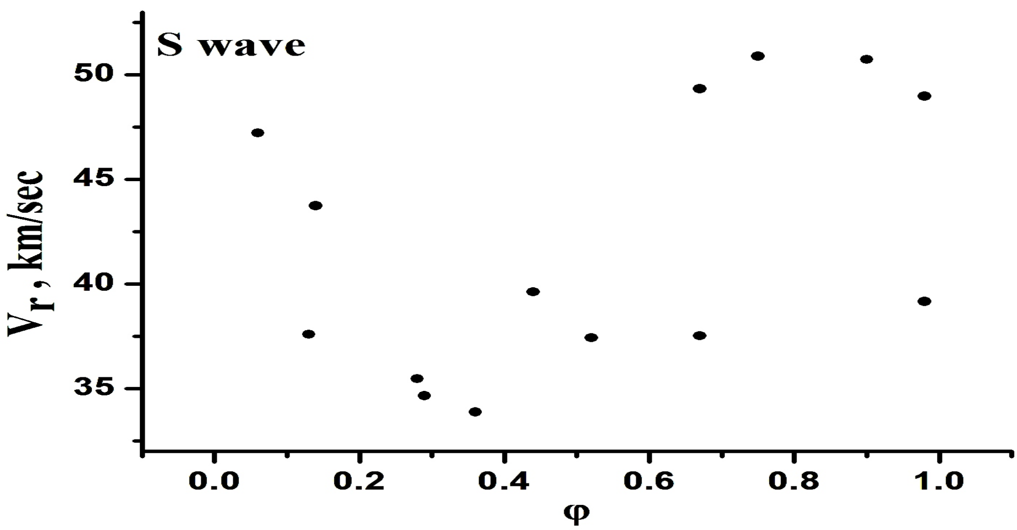


Fig. 14: The dependence of the radial velocity S- wave emission from orbital phase

5. CONCLUSION

Due to high mass loss rate of bright giant B6-8 II (primary) in eclipsing close binary system β Lyr the value of orbital period of this system increases by approximately 19 s per year. Therefore, when we begin to study of this star, we must first determine the value of the orbital period corresponding to our observational season. For this purpose we used the lines SiII 6347, and Mg II 4481. The choice

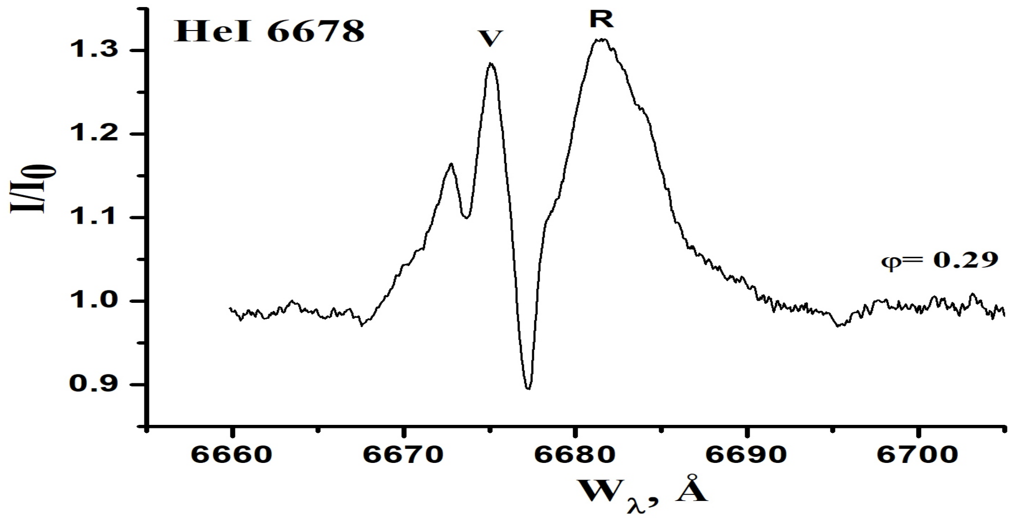


Fig. 15: The profile of line HeI 6678 in spectrum of β Lyr at phase 0.29 of the orbital period.

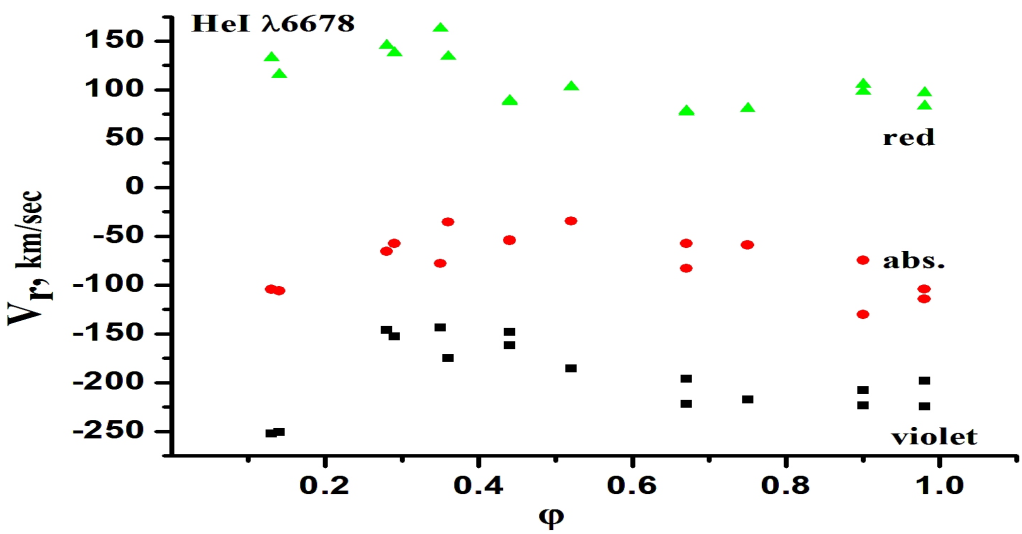


Fig. 16: The dependence of the radial velocities from the phase red absorption and violet components of HeI 6678.

of these lines is connected with the fact that these lines narrow and this allow us to determine the radial velocities of these lines more precisely. By using the RV curves of the lines SiII 6347, and Mg II 4481 lines in the spectrum of star βLyr the value of orbital period for 2016 year (our observation season) determined as

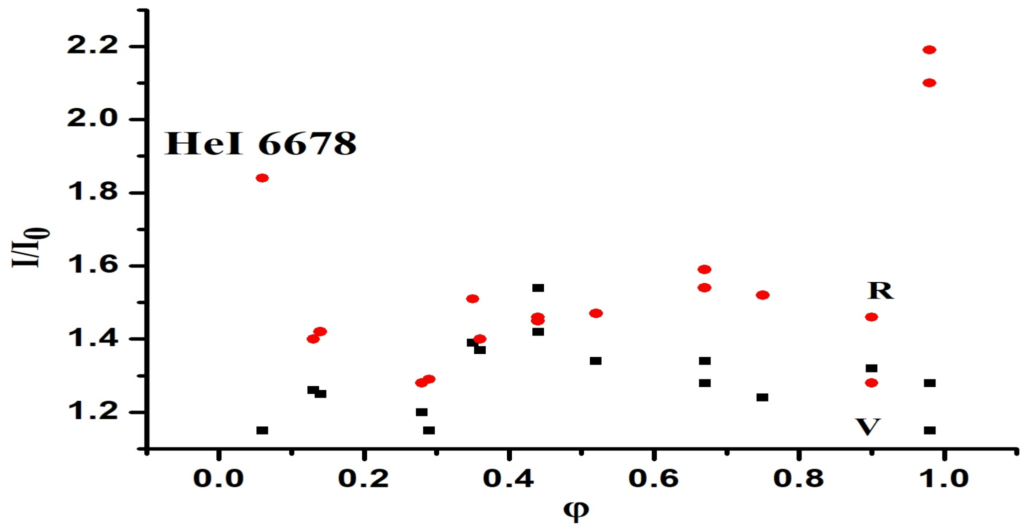


Fig. 17: The dependence of the central intensities from phase of red and violet components of HeI 6678.

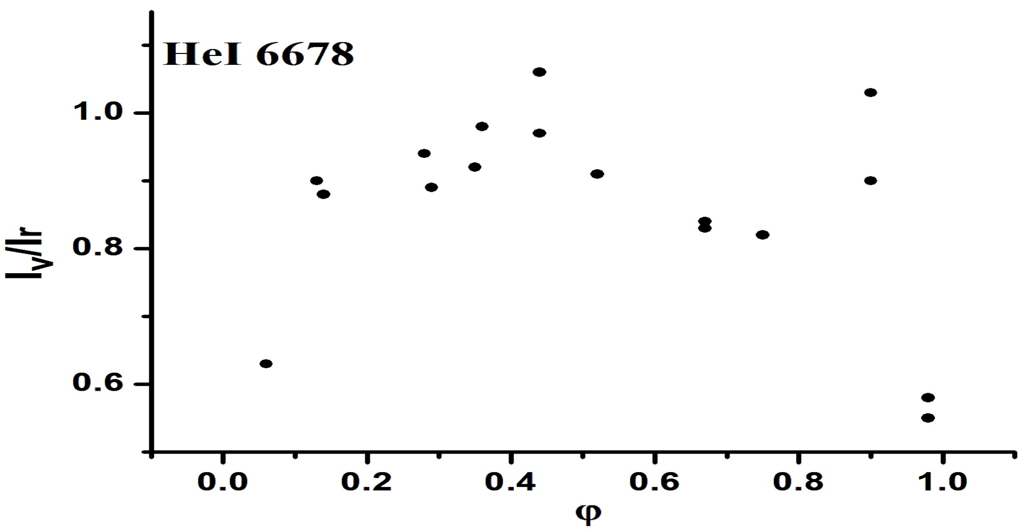


Fig. 18: The dependence of the ratio of the central intensities of the violet and red components from the phase for the line HeI 6678.

12.941428 days. This result is important for the future research.

Different models have been proposed for the star β Lyr until now and one of them is a model proposed by Skul'skii [17] (Fig. 13). According to this model at phases 0.36 and 0.86 the poles of the magnetic field are directed toward the observer. We revealed that the dependence of ratio violet and red components vs. orbital phase of lines $H_\alpha$and HeI 6678 also has maximum at these phases. Therefore we revealed the observational evidence for the reality of the model proposed in [17]. In all orbital phases of the orbital period S-wave emission in the line H_α was observed. It is known that this emission is characteristic for the cataclysmic variables. We revealed that the phase dependence of the radial velocities of the S-wave emission is approximately synchronous with the RV curve of the primary (loser) component, with small amplitude.

Note that the results presented in this study are only preliminary and investigation of star βLyr continues and we hope to reveal more interesting observational facts for the understanding the physical nature of this star.

6. ACKNOWLEDGEMENTS

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