Spectroscopic Study of Be Star β Lyrae

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Abstract. We present the spectroscopic observation of β Lyrae, an interacting eclipsing binary, with orbital rotation period of 12.9 days, with one component known as the B-emission (Be) star. The primary star is a B6-B8II of 3 Mʘ and the secondary is a 13 Mʘ B0.5V star. The secondary star is embedded in the accretion disk produced by the infalling matter from the primary star, and this disk is estimated as the source of the emission lines. The observations were conducted at Bosscha Observatory, Lembang, Indonesia from May to August 2018, using 10” Meade LX-200R Telescope (D = 254 f/D = 9.84), equipped with a Littrow High Resolution Spectrograph (LHIRES) III, grating of 1200 grooves/mm yielding in the resolution of R~5900, and CCD SBIG ST-402 XME camera with backfocus at 17.5 mm. Seeing during observation was estimated to be 2 arc seconds. During this period, we have obtained 15 spectra in various wavelength coverage, 4 spectra covering around λλ = 5779–6046 Å (typical S/N = 0.02), 1 spectrum covering around λλ = 6430.257–6694.434 Å (typical S/N = 0.06), and 10 spectra covering around λλ = 6487–6752 Å (typical S/N = 0.06). The observed spectra show Hα-emission profiles with V/R variation, He I 6678 Å with P-Cygni profiles, and He I 5876 Å with P-Cygni profiles. These variations are due to the fact that β Lyrae is a binary star system, and also it is suspected that another possible mechanism might be involved.

Keywords: Be Star β Lyrae and Spectroscopic

1. Introduction
The second brightest star of the Lyrae constellation, β Lyr (HD 174638, HIP 92420, HR 7106) is one of the first known Be stars discovered by Angelo Socchi [7] in 1867 who also observed Hβ emission line in the spectrum. It is also an eclipsing binary, was first discovered by John Goodricke in 1785 with orbital period of 12.9 days [8] and inclination 86° [4]. Goodricke and Johann G. Palitsch, a German amateur astronomer, also found that β Lyr is an algol-type star. B Lyr system has an early B-type mass-gaining star embedded in an optically thick disk. This disk is an accreting gas that flows from a less massive companion of B6-B8 II. Harmanec [5] and Harmanec [3] suggested there’s more structures besides disk at β Lyr system. These structures are jet-like structure which is perpendicular to the orbit’s orientation, and a hot-spot (the joint point between gas stream and the disk). It is suggested that these structures are the source where the emission lines of β Lyr come from, which makes this star as a Be-type star. B Lyr shows some emission lines, eg in He I 5876 Å, Hα and He I 6678 Å. According to some papers [1][2][3][5], their emission lines originated from a jet-like structure. The artistic view of these structure of β Lyr had been drawn in figure 1 in Harmanec’s paper [3] and we copy it in this paper as figure 1 with additional information about the position of these structures.
In this paper, we report part of our recent spectroscopic data, focused on He I 5876 Å, Hα and He I 6678 Å lines. The following section 2 describes our research methodology i.e. the observation and data reduction methods. In section 3, we do analysis of our observed spectral lines and we give our conclusion in section 4.

2. Methodology: Observation and Analysis

The spectroscopic observation of β Lyr was conducted at Bosscha Observatory, Lembang, Indonesia from May to August 2018. We used 10” Meade LX-200R Telescope \((D = 254 \text{ f}/D = 9.84)\), equipped with a Littrow High Resolution Spectrograph (LHIRES) III, grating of 1200 grooves/mm yielding in the resolution of \(R\sim5900\), and CCD SBIG ST-402 XME camera with 1x1 on chip binning. We obtained 15 spectra in various wavelength coverage, 4 spectra around \(\lambda = 5779 – 6046 \text{ Å}\), 1 spectrum around \(\lambda = 6430.257 – 6694.434 \text{ Å}\), and 10 spectra around \(\lambda = 6487 – 6752 \text{ Å}\). Table 1 shows observation date and orbital phase of He I 5876 Å, Hα and He I 6678 Å lines. The orbital phase is calculated using quadratic orbital ephemeris [2]. We also fit our spectra images to calculated orbital phase at figure 4 and 5. We use IRAF (http://iraf.noao.edu) for data reduction and to obtain spectral parameters such as FWHM, EW, V/R ratio and E/C ratio of He I 5876 Å, Hα and He I 6678 Å lines. De-blending technique in IRAF was used to estimate the EW and FWHM of He I 5876 Å, Hα and He I 6678 Å lines. De-blending technique with combination of gaussian and Voight functions for Hα and gaussian fitting for He I 5876 Å and He I 6678 Å lines.

![Figure 1. The artistic structure of the β Lyr’s structure at different orbital phases. If we set the observer is at the right side, upper panel is around phase 0.9 and lower panel is at phase 0. This structure shows 5 different parts i.e. gas stream, hot-spot, accretion disk, jet-like structure, and halo/stellar wind above the polar region. [3]](image-url)
Table 1. Observation date and Orbital Phase of He I 5876 Å, Hα and He I 6678 Å lines

| Observation Date | Orbital Phase | Lines          |
|------------------|---------------|----------------|
| May 6 2018       | 0.061         | Hα and He I 6678 Å |
| May 7 2018       | 0.136         | Hα and He I 6678 Å |
| May 10 2018      | 0.369         | Hα and He I 6678 Å |
| June 28 2018     | 0.226         | Hα and He I 6678 Å |
| June 29 2018     | 0.234         | Hα and He I 6678 Å |
| July 10 2018     | 0.161         | Hα and He I 6678 Å |
| July 12 2018     | 0.236         | Hα and He I 6678 Å |
| July 27 2018     | 0.463         | Hα and He I 6678 Å |
| July 27 2018     | 0.469         | He I 5876 Å      |
| July 28 2018     | 0.547         | Hα and He I 6678 Å |
| July 29 2018     | 0.551         | He I 5876 Å      |
| August 2 2018    | 0.924         | He I 5876 Å      |
| August 2 2018    | 0.929         | Hα and He I 6678 Å |
| August 3 2018    | 0.007         | He I 5876 Å      |
| August 3 2018    | 0.008         | Hα and He I 6678 Å |

3. Results

3.1. He I 5876 Å line
All the spectra of He I 5876 Å line show two unique profiles. Those profiles are He I 5876 Å line shows P-Cyg profile, that can be seen at figure 2, and a quite strong wing at R region (5880 Å - 5911 Å). Around R region, we assumed there is mixing of plenty of resonance lines such as of C I, C II, Fe I, Fe II, and F III. We checked the wavelength of each resonance lines at NIST Atomic Spectra Database Lines Form (https://physics.nist.gov/PhysRefData/ASD/lines_form.html). We estimate that there is mixture of those 5 resonance lines at between 5889 Å and 5896 Å and a mixture of only 2 resonance lines of Fe I, and Fe II from 5897 Å to 5900 Å. Because β Lyr is an algol-type star, and it is at the Roche-lobe overflow phase as a semidetached binary system with mass transfer, we presume that the metallic resonance lines detected as the absorption lines at β Lyr spectra are from the evolved primary component. This component transfers mass with heavy materials to secondary component which forms the accretion disk. The secondary component is also in the evolved phase so that some material from this secondary mix with the material from the primary. This is the reason why we detected very strong R-region wing which is closer to He I 5876 Å line.

3.2. Hα and He I 6678 Å lines
As we see at figure 3, Hα and He I 6678 Å lines show different profile. Hα always shows double-peak profile with V/R < 1. We measured the line parameters of He I 5876 Å, Hα and He I 6678 Å, i.e. FWHM, EW, V/R and E/C, shown in the table 2. We plot these parameters to the observation date on figure 6-8 to show their variations.
Figure 2. The β Lyr spectra at 5876 Å line ordered based on observation date (on the right) and orbital phase (on the left) with absorption wing region at the red side.

Figure 3. The β Lyr spectra at Hα and He I 6678 Å lines ordered based on observation date (on the right) and orbital phase (on the left).
Figure 4. The illustration of spectra line of He I 5876 Å fitted with orbital phase.

Figure 5. The illustration of spectra lines of Hα and He I 6678 Å fitted with orbital phase.

Our measurements show that the FWHM of Hα shows no trend with times and orbital phase its EW decreases with times however it increases with orbital phase. We still can not predict the pattern of Hα FWHM at this observational period, however it does not mean there is no periodicity of Hα FWHM, we can say it is monotonically increasing or decreasing trend [9]. Probably, we will see the periodicity of Hα FWHM at long-term observation. For the He I 6678 Å line, on the other hand, the FWHM of He I 6678 Å line shows no trend (figure 10A) however the EW of He I 6678 Å line increase with times (figure 10B). The FWHM of He I 6678 Å line shows no trend with orbital phases (figure 11A) but its EW decreases with orbital phases (figure 11B). For He I 5876 Å, its FWHM increases and EW shows no trend with times but its FWHM and EW both increase with orbital phases.
He I 6678 Å emission line region probably be filled with much material which come from more massive star component. It is because Hα line will shrink towards to more massive star in the future. Hα line will be detached from the emission region of β Lyr system, due to V/R ratio and EW with orbital phase of He I 6678 Å show different trend. The V/R and E/C ratio decreases with times (figure 6C) and E/C ratios shows no trend (figure 6D). Its V/R ratio increases with orbital phases but its E/C ratio decreases with orbital phases (figure 7C and 7D). These trends relate with the position of these spectra lines inside the system that is related to the orbital period at the time of observation. We predict that He I 5876 Å emission originates at around jet-like structure, Hα emission originates from inside the disk and He I 6678 Å emission line originates from gas stream or the hotspot. The reason why He I 6678 Å is at those positions is because He I 6678 Å is more far above the ground level to collisionally excite and must arise from helium recombination within hot medium [1].

### Table 2. The parameters of Hα and He I 6678 Å lines

| Observation Date | Lines     | FWHM (Å) | EW (Å) | V/R  | E/C  |
|------------------|-----------|----------|--------|------|------|
| May 6 2018       | Hα        | 5.5±0.2  | -8.67±0.2 | 0.26±0.1 | 1.36±0.2 |
|                  | He I 6678 Å | 5.35±0.03 | -0.72±0.03 | -1.04±0.5 | -0.01±0.03 |
| May 7 2018       | Hα        | 5.04±0.12 | -6.09±0.12 | 0.43±0.19 | 1.06±0.12 |
|                  | He I 6678 Å | 3.57±0.015 | -0.08±0.015 | -1.46±1.14 | -0.08±0.015 |
| May 10 2018      | Hα        | 5.42±0.1 | -5.34±0.1 | 0.53±0.3 | 0.93±0.1 |
|                  | He I 6678 Å | 5.43±0.005 | -1.48±0.005 | 0.50±0.4 | 0.24±0.005 |
| June 28 2018     | Hα        | 4.27±0.06 | -4.31±0.06 | 0.53±0.37 | 0.9±0.06 |
|                  | He I 6678 Å | 3.11±0.004 | -0.24±0.004 | -1.02±0.5 | ±0±0.04 |
| June 29 2018     | Hα        | 4.21±0.08 | -4.37±0.08 | 0.55±0.4 | 0.92±0.08 |
|                  | He I 6678 Å | 3.01±0.005 | -0.46±0.005 | -0.83±0.3 | 0.03±0.005 |
| July 10 2018     | Hα        | 5.92±0.11 | -7.39±0.11 | 0.30±0.13 | 1.2±0.11 |
|                  | He I 6678 Å | 7.35±0.01 | -0.63±0.01 | -1.56±0.85 | -0.17±0.01 |
| July 12 2018     | Hα        | 4.63±0.09 | -5.30±0.09 | 0.55±0.34 | 1.01±0.09 |
|                  | He I 6678 Å | 7.49±0.007 | -1.10±0.007 | -1.19±0.26 | -0.04±0.007 |
| July 27 2018     | Hα        | 4.6±0.17 | -5.14±0.17 | 0.22±0.23 | 1.09±0.17 |
|                  | He I 6678 Å | 7.2±0.02 | -1.74±0.02 | 0.51±0.56 | 0.32±0.02 |
| July 27 2018     | Hα        | 4.78±0.04 | -3.77±0.045 | 0.47±0.42 | 0.65±0.04 |
|                  | He I 5876 Å | 5.2±0.04 | -3.76±0.04 | 0.63±0.52 | 0.67±0.04 |
| July 28 2018     | Hα        | 6.09±0.17 | -7.91±0.17 | 0.55±0.3 | 1.24±0.17 |
|                  | He I 6678 Å | 5.8±0.02 | -2.28±0.02 | 0.56±0.48 | 0.16±0.02 |
| August 2 2018    | Hα        | 5.1±0.22 | -7.78±0.22 | 0.4±0.27 | 1.47±0.22 |
|                  | He I 6678 Å | 2.23±0.008 | 0.09±0.008 | -1.07±2.1 | -0.01±0.008 |
| August 2 2018    | Hα        | 8.83±0.04 | -3.44±0.04 | -0.88±0.12 | 0.07±0.04 |
| August 3 2018    | Hα        | 5±0.4 | -10.94±0.4 | 0.28±0.13 | 1.82±0.4 |
|                  | He I 6678 Å | 5.68±0.02 | 4.5±0.02 | -0.42±0.07 | 0.46±0.02 |
| August 3 2018    | He I 5876 Å | 6.1±0.04 | -5.67±0.04 | -1.17±0.02 | 0.25±0.04 |

The V/R ratios of Hα decrease with times but increase with orbital phase. Its E/C ratio increases with times and orbital phase. The V/R and E/C ratio of He I 6678 Å show no trend with orbital phases (figure 11C and 11D). The V/R and E/C ratio of He I 6678 Å line show no trend with times (figure 10C and 10D). For the He I 5876 Å line, on the other hand, the V/R ratio decreases with times (figure 6C) and E/C ratios shows no trend (figure 6D). Its V/R ratio increases with orbital phases but its E/C ratio decreases with orbital phases (figure 7C and 7D). These trends relate with the position of these spectra lines inside the system that is related to the orbital period at the time of observation. We predict that He I 5876 Å emission originates at around jet-like structure, Hα emission originates from inside the disk and He I 6678 Å emission line originates from gas stream or the hotspot. The reason why He I 6678 Å is at those positions is because He I 6678 Å is more far above the ground level to collisionally excite and must arise from helium recombination within hot medium [1]. Because of the rotation of the system, the position of these emission lines periodically changes. If those lines moved towards us, EW and V/R ratio will show increasing trend and vice versa. Because EW and V/R ratio of He I 5876 Å and Hα lines increase with orbital phases, we surely suggest that He I 5876 Å Hα and lines are moving towards observer. For He I 6678 Å line we cannot predict where it moves against observer due to V/R ratio and EW with orbital phase of He I 6678 Å show different trend. Due to the increases of E/C ratio and the decreases of the EW and V/R and value of Hα line with times, we confidently predict that Hα line region will be filled with much material which come from more massive star component. It is because Hα line will shrink towards to more massive star in the future. He I 6678 Å emission line region probably will be detached from the emission region of β Lyr system, and might be back to the less massive companion since its position is around the hot-spot area or at the...
gas stream due to its EW increase with times. He I 5876 Å region shrinks towards more massive star it is because the trends of E/C and V/R ratios with times of He I 5876 Å indicate so.

Figure 6. He I 5876 Å line plotted to observation date (x-axis) based on the data at table 3. (A) FWHM, (B) EW, (C) V/R ratio, and (D) E/C ratio.

Figure 7. He I 5876 Å line plotted to orbital phase (x-axis) based on the data at table 1 and 3. (A) FWHM, (B) EW, (C) V/R ratio, and (D) E/C ratio.
Figure 8. Hα line plotted to observation date (x-axis) based on the data at table 3. (A) FWHM, (B) EW, (C) V/R ratio, and (D) E/C ratio.

Figure 9. Hα line plotted to orbital phase (x-axis) based on the data at table 1 and 3. (A) FWHM, (B) EW, (C) V/R ratio, and (D) E/C ratio.
Figure 10. He I 6678 Å line plotted to observation date (x-axis) based on the data at table 3. (A) FWHM, (B) EW, (C) V/R ratio, and (D) E/C ratio.

Figure 11. He I 6678 Å line plotted to orbital phase (x-axis) based on the data at table 1 and 3. (A) FWHM, (B) EW, (C) V/R ratio, and (D) E/C ratio
4. Conclusion
From this study, we conclude several points such as First He I 5876 Å emission originates at around jet-like structure, Hα emission originates from inside the disk and He I 6678 Å emission line originates from gas stream or the hotspot. Second, The FWHM of Hα line the E/C ratio of He I 5876 Å line and the V/R and E/C ratio of He I 6678 Å line do not show any trend with times. Third, The FWHM of He I 6678 Å line, and the V/R and E/C ratio of He I 6678 Å do not show any trend with orbital phases. Forth, Hα and He I 5876 Å lines are moving toward the observer due to the increases of EW Hα line. Fifth, He I 6678 Å emission line region probably will be detached from the system and might be back to the less massive companion since its position is around the hot-spot area or at the gas stream. Sixth, Hα and He I 5876 Å emission lines region is shrinking toward more massive star in the future due to the decreases of the E/C and V/R ratios of He I 5876 Å and due to the decreases of EW and V/R ratio of Hα and the increases of E/C ratio of Hα.

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