Evolutionary Study of Binary Star Beta Lyr

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Abstract. We present the evolutionary track of Beta Lyrae (β Lyr), an interacting eclipsing binary star, with orbital rotation period of 12.94 days, with one component known as the B-emission (Be) star. The primary star is a B6-B8II of 3M☉ and the secondary is a 13M☉ B0.5V star. The secondary star is embedded in the accretion disc produced by the infalling matter from the primary star, and this disc is estimated as the source of the emission lines. The evolution of the β Lyr system is simulated by using MESA software with the MESAbinary programming code. We obtain that the age of the binary system is 2.7 x 10^7 years, mass and radius of the primary component are M₁ = 3.54M☉, R₁ = 16.1R☉, and mass and radius of the secondary component are M₂ = 13.1M☉, R₂ = 6.85R☉.

1. Introduction
The β Lyr, the second brightest star in Lyra constellation, is the semi-detached binary, Be-type star system that has inclination of 86° [2] with the current orbital period of 12.993779 ± 0.000016 days [1]. The orbital period of this system increased by 19 seconds / year [5]. The mass of the primary component is 2.88 M☉, with spectrum class B6-B8II, radius of 14.7 R☉ and effective temperature of 13,000 K. The secondary component has a mass of about 12.97 M☉, a B0.5V spectrum class, radius of 6.1 R☉ and effective temperature of 27,989 K [4]. Because the mass of the primary component is smaller than the secondary component, β Lyr is also categorised as the Algol-type star system.

The β Lyr system becomes the Algol-type system is because the secondary component is being transferred an accreting gas from the primary component. This accreting gas made an optically thick disc around the secondary component and embedding it. This mass transfer is the result of evolution of the system which is currently in the Roche lobe overflow (RLOF) phase. De Greve and Linnell [6] simulated the evolution of β Lyr with two different cases, conservative and non-conservative, both cases assuming the β Lyr system underwent an evolution of the AB case (mass transfer occurs when the primary component is in the main sequence phase and in giant phase) for the case of conservatives and evolution of case B (mass transfer occurs when the primary component is in a giant phase) for non-conservative cases. Mennickent and Djurašć [7] simulated the evolution of β Lyr system by assuming the evolution of case B with non-conservative case.

Besides the disc, β Lyr system has several structures that are suggested by Harmanec [8] and Harmanec [9]. These structures are made by Harmanec [8] in an artistic view that we copy as Figure 1 in this paper with additional information of their position which also can be found at Figure 1 in Putra [10]. Figure 1 shows 5 structures at β Lyr system. The Jet-like structure is a material outflow from the system that is perpendicular to the orbit orientation; the gas stream is a flowing material from the primary; hot-spot is the joint point between gas stream and the disc; scattering halo contains material
that outflows from the system. In this paper, we report our simulation result of the evolution of β Lyr system. Section 2 describes our research methodology. In section 3, we present and analyse our result, and we give our conclusion in section 4.

![Figure 1](image_url)

**Figure 1.** The artistic view of the structures of β Lyr system with the position of each structure.

2. **Methodology**

The evolution of β Lyr is modelled by using the Modules for Experiments in Stellar Astrophysics (MESA) software instrument with the MESAbinary evolution code, begin with a metallicity of \( Z = 0.02 \). The simulation starts from Pre-Main Sequence phase to the Zero Age Main Sequence (ZAMS) phase for the primary and secondary components, separately. The result of this initial process is used as the input parameter for the next process. This next process is simulating the two components that have been in the ZAMS phase using the MESAbinary evolution simultaneously. For the binary simulation, MESA will automatically start with a case based on the value of the initial system period. The case used is case B of double star evolution, with the initial period of 1.5 - 87 days [3]. The evolution will stop if a mass flow occurs at the Lagrange point 2 or 3 (L2 or L3) of the system. The evolutionary track of both components, which is plotted in the HR diagram, is shown in Figure 2.

3. **Results**

We separate the evolution of β Lyr system into several steps based on the composition and physical characteristics of each component. We called the first step as stage A-B. At this stage, both components were mostly in main sequence phase. At the end of stage B, the primary is at red-giant phase and the secondary is still at main sequence phase. The next stage is stage B-D. This stage is
known as Roche-Lobe Overflow phase (RLOF). This stage begins with the fulfillment of primary Roche radius by its surface radius (Figure 3 (C)). Mass transfer occurs from primary to secondary component, so that the mass of primary component decreases and the mass of secondary increases. When this happens, it is said that β Lyr is an Algol-type star. The last stage is stage D-E. RLOF phase ends at the beginning of this step (stage D) and every component will evolve individually. At stage E, a mass flow will occur, because the increase of the radius of the primary component makes the star passes its Roche lobe again at the point L3 due to the distance of the secondary is too far away (Figure 3 (A)). The resume of these stages is shown at Table 1.

Table 1. Stages of the evolution of β Lyr using case B binary star evolution. M: mass of each component; L: luminosity; R: radius; T_{eff}: effective temperature; X_c: Hydrogen mass fraction in the core; Y_c: Helium mass fraction in the core; Z_c: metal mass fraction in the core. The subscripts 1 and 2 are for primary and secondary components, respectively.

| Stage | Age (Years) | Period (days) | Separation (au) | M_1 (M_☉) | M_2 (M_☉) | L_1 (L_☉) | T_{eff1} (K) | R_1 (R_☉) | X_c1 | Y_c1 | Z_c1 |
|-------|-------------|---------------|----------------|-----------|-----------|-----------|-------------|-----------|------|------|------|
| A     | 0           | 4             | 9              | 4 x 10^3  |           | 23,938    | 3.7         | 0.69      | 0.28 | 0.02 |
| B     | 2.5 x 10^7  | 4             | 9              | 2 x 10^3  | 8 x 10^3  | 19,980    | 5           | 0.38      | 0.6  | 0.02 |
|       |             |               |                |           |           |           |             | 0.98      | 0.02 |
| C     | 2.7 x 10^7  | 10.5          | 3.91           | 215       | 37 x 10^3 | 5,825     | 14.43       | 0         | 0.55 | 0.43 | 0.02 |
|       |             |               |                |           |           |           |             | 0.98      | 0.02 |
|       |             |               |                |           |           |           |             | 0.57      | 0.4  | 0.03 |
| D     | 2.72 x 10^7 | 13.03         | 3.54           | 313       | 14 x 10^3 | 30,917    | 6.85        | 0.7       | 0.9763| 0.02 |
|       |             |               |                |           |           |           |             | 0.57      | 0.4  | 0.03 |
| E     | 3.1 x 10^7  | 59.5          | 13.1           | 38 x 10^3 | 14 x 10^3 | 35,776    | 4.33        | 0.42      | 0.51 | 0.02 |

Figure 3 shows the radius of both components (solid line) to their Roche-lobe radius (dashed line). Mass transfer starts when R_1 > R_{Lp1} and continues until the radii of R_1 and R_{Lp1} decrease. However, R_{Lp1} is still larger than R_{Lp2} so that the mass transfer occurs with lower intensity. Due to the primary component tries to find the new hydrostatics equilibrium, it was re-expanded with R_1 > R_{Lp2} therefore mass transfer still occurs with higher intensity. After some time later, the primary component runs out its energy and matter. This makes the star shrink, and then RLOF ends.

The evolution the primary component with lower intensity occurs at long timescale. We expect it is because the primary is at main sequence phase, so it evolved like a main sequence star. The evolution with higher intensity occurs at short timescale. This is because the primary is at red giant phase. This causes a lot of mass from primary transferred to secondary in a short time. From our simulation, the period of the lower intensity mass transfer is about 1.83 Myr and the higher intensity mass transfer period is about 109 kyr. The diagram for the higher and lower mass transfer rate of the system is shown in Figure 4.
Figure 2. HR diagram of β Lyr for each component. Primary: black solid line; Secondary: black dashed line.
Figure 3. (A) The radius of the primary component. The ellipse mark shows when the primary passes its L3 point; (B) The radius of the secondary component; (C) The radius of the primary when the RLOF occurs.

Figure 4. Mass transfer rate of the system.
4. Conclusion
From this study, we conclude several points:

- The system of β Lyr is still transferring mass and will stop at around 107,000 years from now.
- The age of β Lyr from ZAMS to current state is about 27.05 Myr with red giant phase for primary and main sequence phase for secondary.
- The system of β Lyr has undergone two different mass transfer periods: lower intensity mass transfer with period of 1.83 Myr and higher intensity mass transfer with period of 109 kyr.

References
[1] Ak H, Chadima P, Harmanec P, Demircan O, Yang S, Koubský P, Škoda P, Šlechta M, Wolf M, Božič H, Ruždjak D and Sudar D 2007 New findings supporting the presence of a thick disc and bipolar jets in the β Lyrae system Astronomy & Astrophysics 463 233
[2] Linnell A P 2000 Progress on a model for β Lyrae Monthly Notices of the Royal Astronomical Society 319 1 255-26
[3] Paczyński B 1971 Evolutionary Processes in Close Binary Systems Annual Review of Astronomy and Astrophysics 9 183
[4] Van R W and De G J P 2016 Accretion disks in Algols: Progenitors and evolution Astronomy & Astrophysics 592 A151 1-8
[5] Zhao M, Gies D, Monnier J D, Thureau N, Pedretti E, Baron F, Merand A, ten Brummelaar T, McAlister H, Ridgway S T, Turner N, Sturmann J, Sturmann L, Farrington C and Goldfinger P J 2008 First Resolved Images of The Eclipsing and Interacting Binary β Lyrae The Astrophysical Journal 684 L95-L98
[6] De Greve J P and Linnell A P 1994 Origin and evolution of semi-detached binaries: Beta Lyrae and SV Centauri Astronomy and Astrophysics 291 786-794
[7] Mennickent R E and Đurašević G 2013 On the accretion disc and evolutionary stage of β Lyrae Astronomy & Astrophysics 432 799-809
[8] Harmanec P 2002 The ever challenging emission-line binary β Lyrae Astronomische Nachrichten 323 87-98
[9] Harmanec P, Morand F, Bonneau D, Jiang Y, Yang S, Guinan E F, Hall D S, Mourard D, Hadrava P, Bozic H, Sterken C, Tallon-Bosé I, Walker G A H, McCook G P, Vakili F, Stee P and Le Contel J M 1996 Jet-like Structures in β Lyr Astronomy and Astrophysics 312 879-896
[10] Putra S P, Imaduddin I, Aprilia, Ramadhan D G, Malasan H L and Arifyanto M I 2019 Spectroscopic Study of Be Star β Lyrae Journal of Physics: Conference Series 1231 012011