Analysis and Evolution of a binary system with PHOEBE AND MESA

Saakshi Wadhwa[1] Jai Mirchandani[1] Tejas Sonawane[1]

Institute Voor Sterrenkunde(IVS), KU Leuven

December 29, 2023

ABSTRACT

An analysis of a semi-detached binary star system using a combination of observational data and modeling techniques was carried out in this project. The light curve and radial velocity datasets were employed to determine the system's fundamental parameters, such as orbital period, eccentricity, and mass ratio. Through the use of sophisticated tools like the Lomb-Scargle periodogram and various estimators in the Phoebe software, we successfully derived values for the masses, radii, temperatures, and other key properties of the binary components. The application of Kepler's Third Law facilitated the estimation of the total mass of the system. Later on, we evolved the star using two simulations: Single star and with a binary companion with Mesa software and found completely different stellar evaluations due to Roche lobe overflow and mass transfer. The main goal of this study was to understand Phoebe and Mesa software to understand different binary systems and study their evolution

Key words. PHOEBE – MESA – Binary stars

1. Introduction

There are several tools in modern astronomy that are used to analyse and estimate the physical and orbital parameters of a binary star. These parameters include the orbital period, masses of both the stars, semi major axis, eccentricity, radius, etc. These parameters can be used to further understand the evolution of binary system.
In this project we will be analysing these parameters and evolving the system for a provided data set of a binary system.

1.1. Light Curve

Light curves are graphical representations of flux versus time. They tell us about the change in brightness of the system we are observing which gives us a deeper knowledge to classify the objects. Light curves are extremely useful for learning about variable stars, including binary stars as it also helps us understand about the period and the type of binary system in question. An even intricate analysis of the curve tells us the reason behind these dips in the brightness. Significant dips are observed in the lightcurves of Eclipsing Binaries due to the transits of both the stars. A larger dip is observed when the brighter star is eclipsed and a shallower dip is observed when the smaller star is being transited by the primary star. In this project we have plotted the light curve of the given binary system to understand its nature and get the orbital period.

1.2. Radial Velocity Curve

Similar to light curves, Radial velocity curves also help us in getting the period of the binary system. Radial velocity curves are basically plots of radial velocity of system against time. Parameters like eccentricity and the argument of periastron can affect the shape of the curves, making it a helpful tool to get the correct estimation of parameters for binary systems. With the RV data provided for the stars, we have plotted the curves to get the same period as given by the lightcurves.

2. Data Analysis

2.1. PHOEBE

PHysics Of Eclipsing BinariEs (PHOEBE) is an eclipsing binary modelling software written by an international team of professional astronomers. It employs advanced algorithms and computational techniques to model various phenomena associated with binary stars. It has the capability to simulate various binary star configurations, incorporate detailed physical parameters of the stars involved, and accurately reproduce observed light and radial velocity variations. We have used Phoebe in this project to get the correct parameters for our binary system by fitting the light curves and radial velocity curves to further evolve the system using MESA.

2.2. Evolution of Binary Stars with MESA

Modules for Experiments in Stellar Astrophysics (MESA) is an open source 1D Stellar Evolution code. It simulates and evolves a star from it's birth to end. MESA provides a detailed framework for the modelling of the star making it possible for us to model a wide range of stellar masses and compositions. Alongside, we also get to know about the parameters at each timestep of the evolution.

2.3. Orbital Period estimation

In this analysis, we employed observational data comprising light curve (LC) and radial velocity (RV) measurements for a binary star system. The LC data is converted from magnitudes to flux values , revealing the lowest flux at a date of

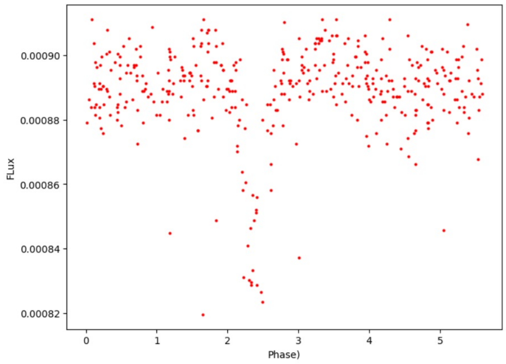

Fig. 1. Phase Folded Light curve of given binary system

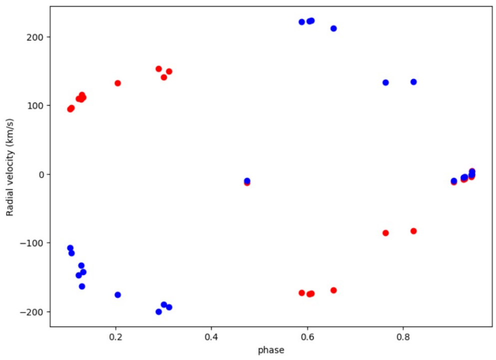

Fig. 2. Phase folded radial velocity curve of given binary system

3913.74114(HJD). The RV curves for both the primary and secondary stars provide insight into the dynamic behavior of the binary system. Fourier transform analyses were then applied to the RV data, yielding dominant frequencies with periods of approximately 5.6047 days for RV1 and 5.5197 days for RV2.

A Lomb-Scargle periodogram was computed for the LC data of the binary star system. The periodogram visually displays the power of different frequencies, with the x-axis presented in a logarithmic scale for clarity. The period corresponding to the highest peak in the periodogram, highlighted in red and denoted as the main period, was found to be approximately 5.6047 days.

In the figures above, the phase folded LC and RV plots showcase repeating patterns in our binary star system. The light curve graph (Fig. 1) reveals a noticeable dip, indicating moments of eclipses or transits in the system. On the other hand, the RV plot (Fig. 2) displays smooth waves for both stars, giving us a clear view of how they move around each other. These folded plots help us see the recurring changes in brightness and radial velocities over time. The period used for folding, around 5.6047 days, was found using a special analysis technique, setting the stage for more detailed modeling with Phoebe.

2.4. Python:Lmfit Modelling

We used first python tools like LMFIT to find the best fit for the period with the help of models. In the Fig.3 we can clearly see Lmfit model for the RV data and how it is fitting. It will give us the best phase values where the fitting of the synthetic model should start.

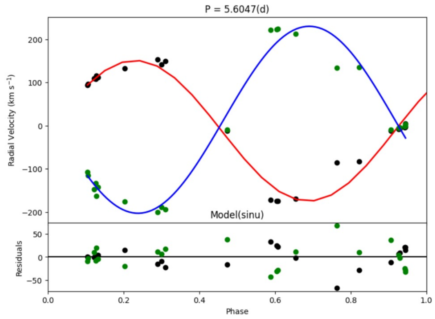

Fig. 3. Lmfit model for the RV data

2.5. Phoebe Phase folded plots and Model fitting

The initial parameters like the efficient temperature for the primary star was provided and orbital period was found. The other paramters were found with the help of Phoebe estimators for RV and LC and manual Lmfit approach. In the end both values were approximately equal. We are not able to find the second dip, it is not clear in the phase folding. Neither it is seen in the phase folded Phoebe plot nor in the normal phase folding. The light curve data is dense and the second dip is difficult to spot on. The estimators though found a dip which was corelated with our synthetic model which is shown in the last part. The code then configures datasets for both LC and RV observations, providing phase-folded data for each. Various settings, such as limb darkening modes, atmosphere type, and scaling for the LC, are established. The script runs a synthetic model using the specified parameters and datasets, generating a phased LC and RV curves. The final visualization (Fig. 4 and Fig. 5) showcases the synthetic results, offering insights into the intricate behavior of a semi-detached binary system.

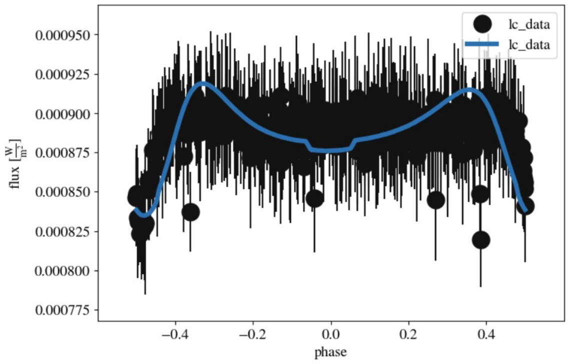

Fig. 4. Fig.4 Phase folded light curve plotted by phoebe. The blue line shows the synthetic LC curve model.

2.6. Phoebe Estimators

2.6.1. RV Estimator

The estimator is a crucial component in refining the model parameters based on observed data. In this case, the 'estimator.rv geometry' solver is employed with RV datasets. After running the solver and adopting the solution, the script prints out the estimated parameters. The refined values include the time of superior conjunction ('t0 supconj'), mass ratio ('q'), projected semi-major axis ('asini'), eccentricity ('ecc'), longitude of periastron

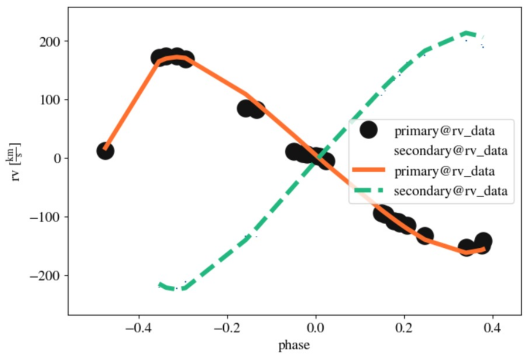

Fig. 5. Phase folded RV plotted by Phoebe. The orange and green lines shows the synthetic RV primary and secondary curve models respectively

('per0'), and systemic velocity ('vgamma'). These values represent an improved fit to the observed RV data, providing a more accurate depiction of the binary system's geometry and dynamics.

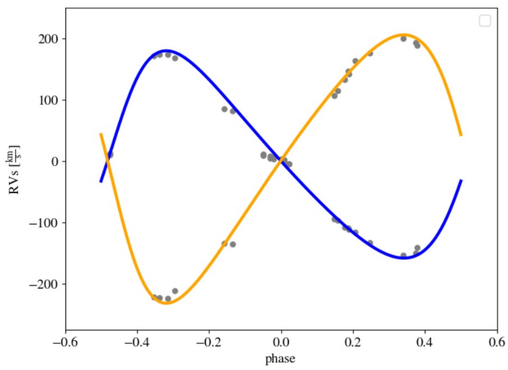

Fig. 6. RV Model using RV Geometry estimator. A smooth RV model is found. The blue line is primary star and the yellow is secondary star. The little difference between the phase and amplitudes is caused due to the small difference in mass.

2.6.2. LC Estimator

The 'estimator.lc geometry' solver is utilized to enhance the model parameters based on the observed light curve data ('lc data'). After executing the solver and adopting the solution, the script prints out the estimated parameters. The refined values include the time of superior conjunction ('t0 supconj'), eccentricity ('ecc'), longitude of periastron ('per0'), sum of fractional radii ('requivsumfrac'), and temperature ratio ('teffratio'). These improved parameters offer a more precise representation of the binary system's geometry, providing a better fit to the observed light curve.

2.7. Cross verification for the Model fitting

2.8. EBai Estimators: Cross verification for the parameters

The EBai modeling process has unraveled key characteristics of the semi-detached eclipsing binary system under scrutiny. Through meticulous comparisons between synthetic and observed light and radial velocity curves, the algorithm converged to a set of parameters illuminating the intricacies of both stars

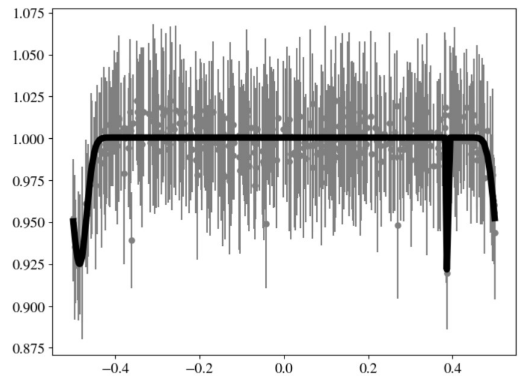

Fig. 7. LC model curve using LC Geometry estimator. The sudden dip which is seen here is due to one single flux value where the estimator founds a dip. It can be neglected. The smooth main light dip is found in a divided phase. It is a however a single dip.

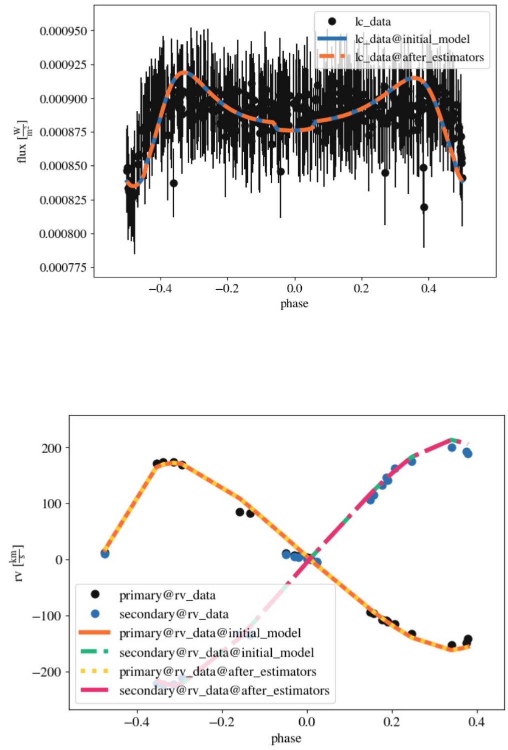

Fig. 8. We plotted the models with initially guessed parameters and after estimators. Above: LC Models, Below: RV models.

and their orbital motion. The primary star boasts a substantial equatorial radius of approximately 13.15 solar radii, coupled with a searing effective temperature of 33,800 K. In contrast, the secondary star, though constrained in radius, exhibits a noteworthy effective temperature of 27,700 K. The orbital dynamics are revealed through parameters such as eccentricity (0.25), mass ratio (0.77), and an inclination angle of 83.36 degrees, indicating an almost edge-on orbit. The semi-major axis of 41.86 solar radii unveils the average separation between these celestial partners. Overall, EBai's iterative approach has unveiled a wealth of information.

```
ParameterSet: 15 parameters
C        requiv@primary@component: 13.14826082502426 solRad
           teff@primary@component: 33800.0 K
C          incl@primary@component: 83.36453 deg
C          mass@primary@component: 17.73590224292108 solMass
       requiv@secondary@component: 1.0 solRad
         teff@secondary@component: 27700.0 K
C        incl@secondary@component: 83.36453 deg
C        mass@secondary@component: 13.601863438485879 solMass
             per0@binary@component: 276.4125250738447 deg
              ecc@binary@component: 0.25
             incl@binary@component: 83.36453 deg
                q@binary@component: 0.7669112770349634
              sma@binary@component: 41.86 solRad
C            sma@primary@component: 18.168940610620325 solRad
C         sma@secondary@component: 23.691059389379674 solRad
```

Fig. 9. Parameters found with Ebai estimators. Values are found almost same as the initial model guessed parameters.

2.9. Mass: Kepler's Law

Then with the kepler 3rd law, we manually found the masses which are almost equal to the ones estimator found.

The total mass of the binary system, calculated using Kepler's Third Law with the given values for the semi-major axis (a) and orbital period (P), is approximately 6.29 x10^{31} kilograms. With the help of mass ratio and simple algebra we found.

M1: 3.5586649746261395e+31

M2: 2.7290689957412937e+31

Converting into solar masses

M1: 17.891729384746807

M2: 13.72080943057463

3. Evolution of the Binary system

The presence of a binary companion plays a significant role in evolution of the star. To understand this effect we have evolved our primary donor star of mass 17.73 M⊙ both as a single star as well as with a binary companion with period 5.6 days as obtained in the earlier section. We further added further constraints to our system by including the effect of gravitational wave radiation leading to loss of angular momentum over long timescales. Since, our primary star is more massive, it will evolve faster than the secondary one. This can be seen in figure(10 where the donor star is completely evolved whereas the accreting star is still in its main sequence burning hydrogen. We also plot the HR diagrams of the Donor and Accretor stars for their complete evolution in Figures (11) and (12) respectively . We can clearly see how both the stars evolve differently throughout their lifetime. To understand how the Primary star would have evolved if it was not in the Binary system, We have plotted the HR diagram for the same in Figure (13) assuming it as an individual star. Large differences in the HR diagrams tell us how Mass transfer greatly affects the evolution of a star.

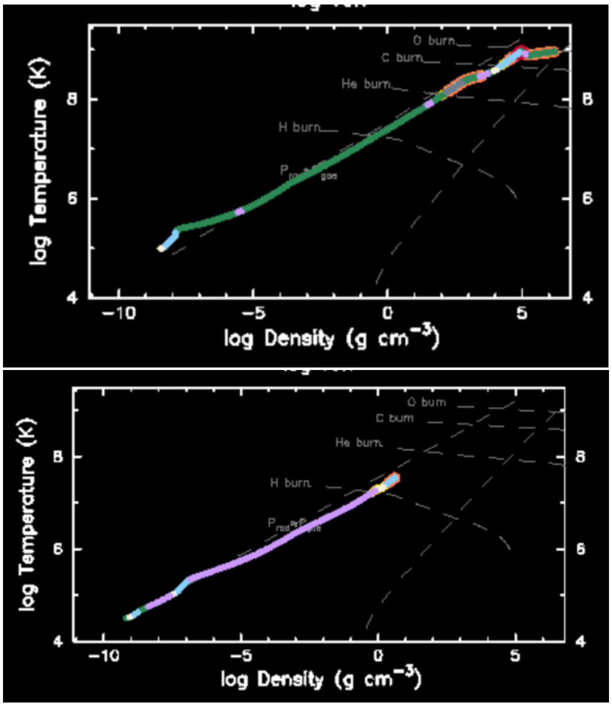

Fig. 10. Evolution of a. Primary star b. secondary star

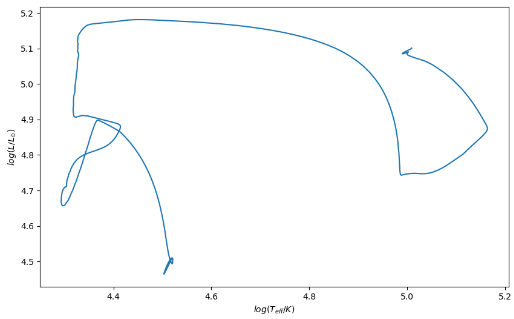

Fig. 11. Hertzsprung - Russel Diagram for the primary star

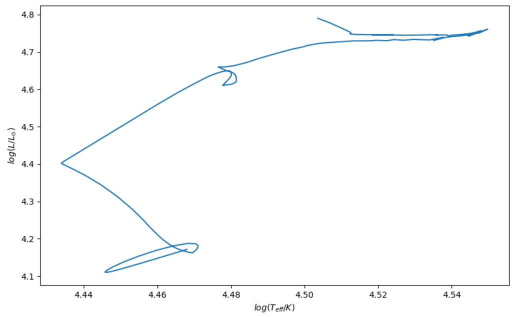

Fig. 12. Hertzsprung - Russel Diagram for the secondary star

The figure(14) represents the total mass of both the systems throughout the evolution. It is visible that the primary star has lost a large amount of mass, being the donor star and the secondary star has a higher mass at the end of the evolution. We can also notice that the proportion of change in the masses is not the same because along with mass transfer due to Roche Lobe overflow, mass loss due to stellar winds also takes place. We can also visualize this from figure (15) where we see the roche lobe overflow and mass transfer from the primary star at different stages of stellar evolution. The roche lobe is filled around the age of 0.98 x10^7 after which the mass transfer takes place. This is in agreement with change in masses of the stars seen in fig(14).The final masses from our evolution for primary and secondary stars are 4.97M⊙ and 18.28M⊙ respectively.After further mass loss. we

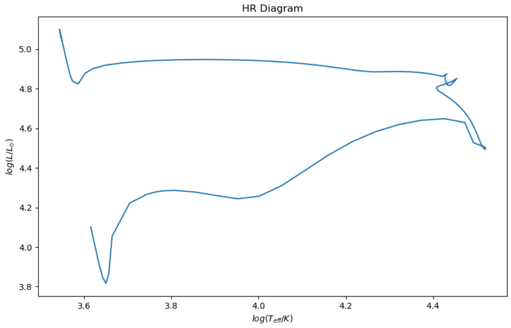

Fig. 13. Hertzsprung - Russel Diagram for the single star evolution of the primary star

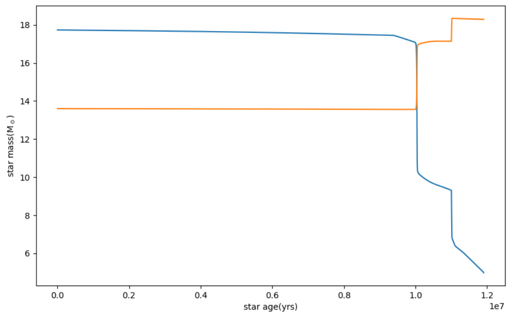

Fig. 14. Mass of both the stars as a function of age of the star

can also see from fig(15e) that the star undergoes core collapse ,probably resulting in a supernova explosion. Figure (16) shows that 2 mass transfer episodes occurred throughout the evolution as we can see 2 sharp peaks marking the change in the mass transfer activity of the primary star.

Figure (17) shows the change in radii of both the stars throughout their evolution as a binary system. At the beginning of the evolution, both the stars had a similar radius in the neighborhood of 5R⊙. The peaks in the curve of the Primary star shows the increase in the size of the star occurring as it starts to fill its and Roche lobe and during the Roche lobe overflow respectively. After it's final mass transfer episode, our primary star which is in the supergiant branch goes into core collapse and thus we see a sharp dip in the radius at the end of the evolution. The radius of the star after the collapse indicates formation of a possible neutron star. The secondary star's radius doesn't change much throughout and changes in its value can mainly be seen during the mass transfer episodes. During the evolution of the donor as a single star, in Figure (18) the simulation reaches upto core collapse but a very large radius of the star is seen as it is in its supergiant phase.

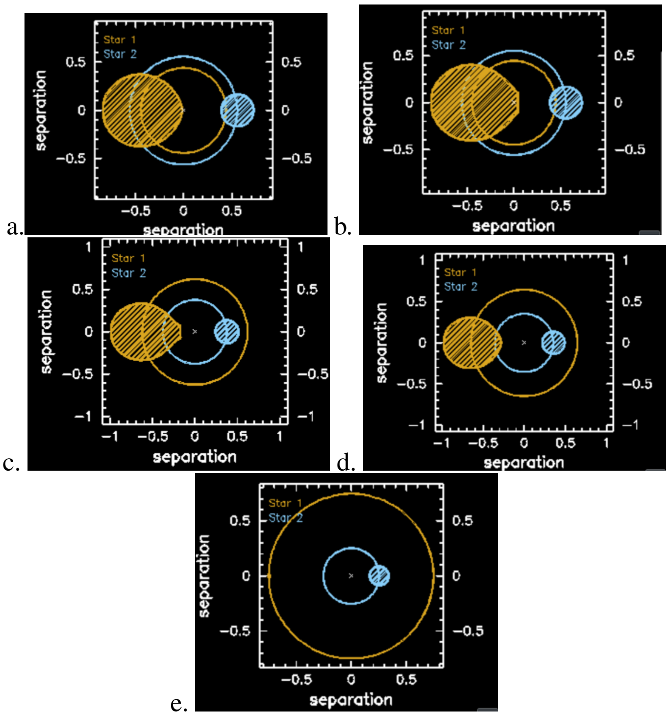

Fig. 15. Binary system at the age of a. 0.98 x10^7 yrs b. 1.001 x10^7 yrs c. 1.006 x10^7 yrs d. 1.10x10^7 yrs e. 1.12 x10^7 yrs

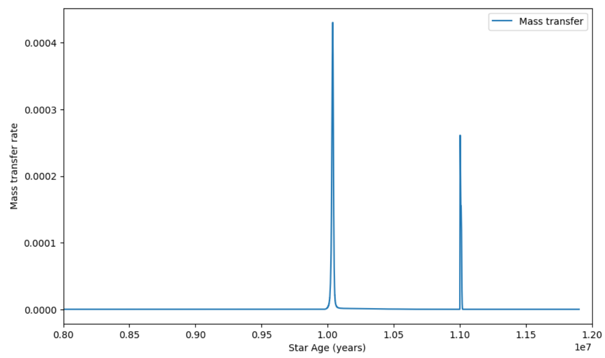

Fig. 16. Mass Transfer Rate of the primary star

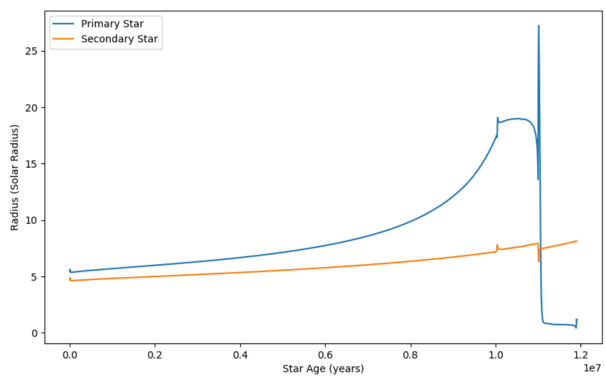

Fig. 17. Radius of both the stars as a function of Star age

4. Conclusion

In this study, we conducted an analysis of a semi-detached binary star system using the given observational data which was the Lightcurve and Radial velocity data and different Modelling

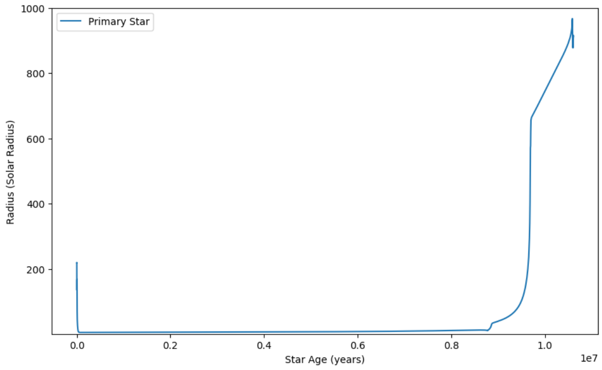

Fig. 18. Radius of Single star as a function of Star age

approaches. The provided light curve and radial velocity datasets were employed to determine the system's fundamental parameters, such as orbital period, eccentricity, and mass ratio. The efficient Temperature of the primary star was provided. Through the use of Fourier analysis, in our case, Lomb-Scargle periodogram we estimated the orbital period which was used to find the phase folded curves. Using various estimators in Phoebe software, we successfully derived values for the masses, radii, temperatures, and other key parameters of the binary components. Estimation of the individual masses of the stars was done using Kepler's Third Law application. The masses were then put into the framework of MESA to evolve them as single and binary systems. Lastly, an analysis of the evolution was done by plotting Mass transfer rates and HR Diagrams. The study contributes to our understanding of the intricacies of binary star systems, shedding light on their physical characteristics and the underlying astrophysical processes.