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Modeling of Beta Lyrae
An Exploration of Conditions Resulting in Stellar Jet Formation

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Abstract

Have you ever looked to the sky and wondered why stars can look brighter on some nights and not on others? Chances are you are observing a binary star system, a system consisting of two stars which rotate around a central point. Beta Lyrae is one such star system in which the less massive star transfers matter to the other, creating an accretion disk that can shroud the star or the entire system. In these closed systems, stellar jets of matter can form under specific conditions. Based off two existing models of Beta Lyrae's accretion disk (one created by Wilson and the other by Hubeny and Plavec) and Nazarenko's two-dimensional mass transfer model, a new model was constructed with the parameters of a primary star mass of 5.967 x 10^{33} g; a secondary star mass of 2.5857 x 10^{34} g; an orbital period of 12.9 days; a mass transfer rate of 5.967 x 10^{28} g/yr between the two; and an accretion disk with a radius of 1.6008 x 10^{12} cm, a thickness of 6.96 x 10^{11} cm, and a number density of approximately 10 x 13 cm^3 to 10 x 14 cm^3. The separation between the two stars in the system is 46.7 arc seconds and their position angle is 149.6 degrees. Seven simulations with values for contrast between atmospheric temperature (outside the torus) and torus temperature (T_con), contrast between atmospheric density and torus density (D_con), and the ratio between gas pressure and magnetic field pressure (BETA) will be run for forty time steps (a time step equates to .57 days): the original parameters (T_con of 10, D_con of 1 x 10^{-4}, and BETA of 350), altered T_con values of 0.1 or 100, altered D_con values of 1 x 10^{-2} or 1 x 10^{-3}, and altered BETA values of 3.5 or 35. Velocity, density, and pressure will be monitored in the models, and each will be observed to determine whether stellar jets form under those conditions. Preliminary results reveal that simulations with altered D_con and BETA values exhibited signs of stellar jet formation while the two simulations with altered T_con values did not; however, the altered T_con value simulations still showed activity in the region. With decreasing D_con, the system seems to form stellar jets faster. At a D_con level of 1 x 10^{-2}, the formation started at time step 15; at D_con level of 1 x 10^{-3}, the formation started at time step 10; and at D_con level 1 x 10^{-4} of the initial simulation, the formation started at time step 9. However, after further analysis, it was determined the simulations were unstable. Rather than forming stellar jets, the systems were expelling torus matter.

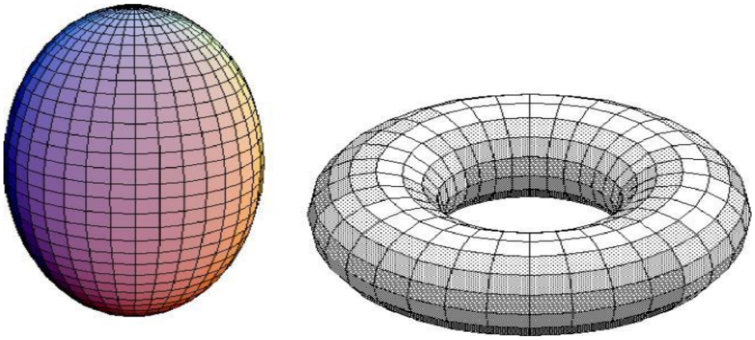
Keywords: stellar jets; binary star systems; Beta Lyrae

1. Introduction

Beta Lyrae was discovered in 1789 by J. Goodricke [4]. Since then, Beta Lyrae has been observed for the last 200 years; within the last 30 years, observational studies have utilized X-ray, UV, optical, radio and IR.

Beta Lyrae is considered a closed, eclipsing binary system [4]. An eclipsing binary is "a pair of stars that orbit in the plane of our line of sight [1]." In this system, when neither star is eclipsed, it is brighter because the light from both stars is seen. If one is eclipsing the other however, the system will seem dimmer due to the light from one star being blocked by the other [1]. Beta Lyrae is also considered a closed binary star system [4]. In such a system, the less massive star, otherwise called the donor, is losing mass to the larger star, otherwise known as the accretor, around which it forms an “optically thick envelope.” This envelop is usually taken to be an accretion disk around the primary, but it could enshroud the whole system [4]. The primary star of Beta Lyrae has a mass of 5.967×10^{33} g (3 $M_\odot$); the secondary star a mass of 2.5857×10^{34} g (13 $M_\odot$) [3]; and the stars are separated by 46.7 arc seconds with a position angle of 149.6 degrees [2].

There are two models for the accretion disk of Beta Lyrae: the Wilson model and the Hubeny and Plavec model [4]. The Wilson model “envisioned a massive, dense disk” that took the shape of a prolate ellipsoid, pictured in Figure 1 (a).



(a) Prolate Ellipsoid from http://www.math.cornell.edu

(b) Torus from www.astro.virginia.edu

Figure 1: Accretion Disk Shapes of Wilson and Hubeny and Plavec Models.

On the other hand, in the Hubeny and Plavec model, the envelope forms an accretion disk whose vertical structure is in hydrostatic equilibrium. It has a negligible mass, exhibits Keplerian motion, and has the shape of a torus, pictured above in Figure 1 (b). The disk’s thickness grows with its distance from the star [4].

There has also been numerical modeling of the mass transfer in Beta Lyrae [4]. Nazarenko considered a two-dimensional model. Using varying accretor radii, the mass transfer rate was computed. Various gas-cooling models were considered as well. One of the most important results of the two-dimensional model is the calculation of the number density of the system, which in the disk is $10^{12} - 10^{14}$ cm^{-3} and in the outer envelope is $10^{10} - 10^{12}$ cm^{-3}.

2. Procedure

Using information from the Wilson, Hubeny and Plavec, and Nazarenko models, a new model was constructed which focused on the torus formed around the accretor (secondary star). The torus has been set with a radius of 1.6008×10^{12} cm (23 $R_\odot$) and a thickness of 6.96×10^{11} cm (10 $R_\odot$). The number density of the disk is initially set at $10^{13} - 10^{14}$ cm^{3}. The parameters of a primary star of mass 5.967×10^{33} g, a secondary star of mass 2.5857×10^{34} g, and a separation of 46.7 arc seconds with a position angle of 149.6 degrees between them were also integrated in the model. The accretion disk was not fed with matter from the primary star in our model.

Using PLUTO, seven simulations were run for forty time steps. Each time step is equivalent to .57 days, so each simulation was run for approximately 22.87 days total. In each simulation, values of temperature contrast (the contrast between the atmospheric temperature outside of the torus with the torus temperature) denoted T_con, density contrast (the contrast between atmospheric density and torus density) denoted D_con, and BETA (the ratio between gas pressure and magnetic field pressure) were manipulated. The initial simulation (Simulation 1) was set with the following parameters: T_con = 10, D_con = 1 x $10-^{4}$, and a BETA = 350. The other six simulations are described below:

Simulation 2: T_con = 100, D_con = 1 x $10-^{4}$, and BETA = 350
Simulation 3: T_con = 0.1, D_con = 1 x 10^{-4}, and BETA = 350
Simulation 4: T_con = 10, D_con = 1 x 10^{-2}, and BETA = 350
Simulation 5: T_con = 10, D_con = 1 x $10-^{3}$, and BETA = 350
Simulation 6: T_con = 10, D_con = 1 x $10-^{4}$, and BETA = 3.5
Simulation 7: T_con = 10, D_con = 1 × 10^{-4}, and BETA = 35

The simulations were monitored for stellar jet formation for the duration of the simulation. In order to determine if a stellar jet had formed, the velocity, density, and magnetic fields created in the torus region during the simulation were monitored and analyzed.

3. Results

At first glance, the simulations with altered D_con and BETA values, along with the first, initial simulation, seemed to show signs of stellar jet formation. The simulations with altered T_con values of 100 and 0.1 did not exhibit signs of stellar jet formation; however, there was still activity in the region shown in Figure 2 and Figure 3 respectively. The decrease in D_con values seems to allow the stellar jets to form faster. The first simulation showed signs of jet formation at time step 9, what will be referred to as “budding.” By time step 20, a young stellar jet seems to form (shown in Figure 4) and continues to develop through the rest of the simulation shown in Figure 5. Simulation 4 buds at time step 15 and forms a young jet by time step 20. Simulation 5 buds at time step 10 and forms a young jet by time step 16 shown in Figure 6. Both simulations with altered BETA values (Simulation 6 and 7) form young jets by time step 20. Simulation 6 graphs are shown in Figure 7.

However, upon closer inspection of the results, what was thought to be stellar jet formation was actually the displacement of the torus. When the velocity and density graphs are viewed side by side, the areas of highest upward velocity movement coincide with the same area the torus falls in.

Let’s analyze Simulation 4 further and calculate the rate at which the mass of the torus is expelled from the region. If we know that

$$\rho = \frac{\Delta M}{\Delta x * \Delta y * \Delta z} \text{ and } v2 = \frac{\Delta y}{\Delta t}$$

then

$$\rho * v2 = \frac{\Delta M}{\Delta x * \Delta y * \Delta z} * \frac{\Delta y}{\Delta t}$$

$$= \frac{1}{\Delta x * \Delta z} * \frac{\Delta M}{\Delta t}$$

$$= \frac{1}{r * dr * \Delta\theta} * \frac{\Delta M}{\Delta t}$$

Rearrange the formula and change some notation slightly to get

$$\rho * v2 * r * dr * d\theta = \frac{dM}{dt}$$

If we graph ρ x v2 from Simulation 4, the material falls roughly between 6 and 12 with a value of 0.13. Therefore, we'll integrate the above formula from 6 to 12.

$$\int \frac{dM}{dt} = \int_{6}^{12} 0.13 * r * dr \int_{0}^{2\pi} d\theta$$

$$= \left(0.13\frac{r^2}{2}\right)2\pi \quad \text{(Evaluate from 6 to 12.)}$$

$$\frac{1}{2} * 0.13 * ([12(1.6008\, X\, 10^{12}\text{cm})]^2 - [6(1.6008\, X\, 10^{12}\text{cm})]^2) * 2\pi$$
$$= 2.299\, X\, 10^{25}\text{cm}^2$$

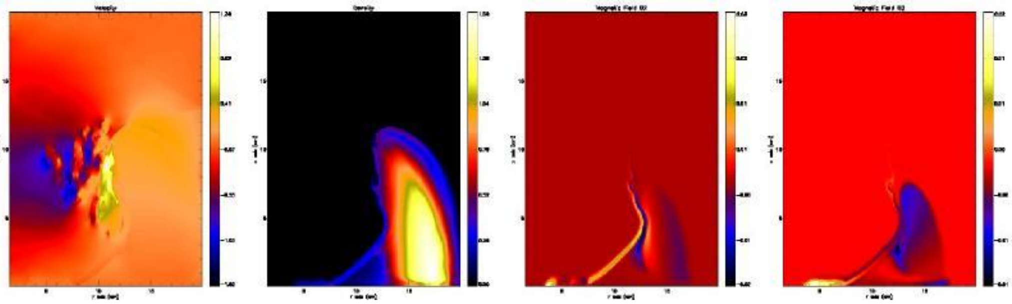
Note: the radius of the torus is taken into account in the third step.
We'll convert this to grams per second with two constants.

$$2.299\text{ X }10^{25}\text{cm}^2 * \frac{1.67\text{ X }10^{-11}\text{g}}{\text{m}^3} * \frac{2.19\text{ X }10^{6}\text{cm}}{\text{s}} = \frac{8.407\text{ X }10^{20}\text{g}}{\text{s}}$$

Next, this value will be converted to solar masses per year. Since 1 yr 3.15 x 10^7 s and $1M_\Theta = 2 \text{ x } 10^{33}$ g, we get the following:

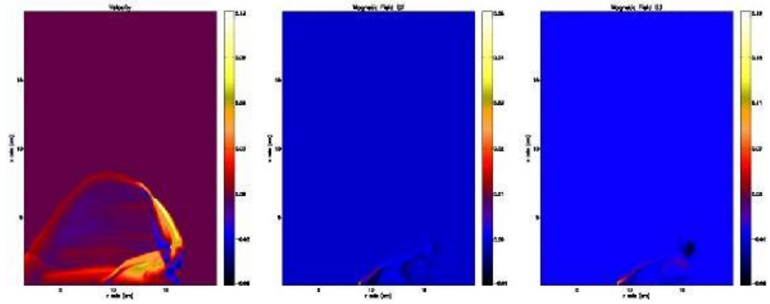
$$\frac{8.407\ \ 10^{20}\text{g}}{\text{s}} * \frac{1\text{M}_\Theta}{2\text{ X }10^{33}\text{g}} * \frac{3.15\text{ X }10^{7}\text{s}}{1\text{yr}} = \frac{1.324\text{ X }10^{-5}\text{M}_\Theta}{\text{yr}}$$

Similarly, the rate at which the mass of the torus is expelled can be calculated for other simulations.



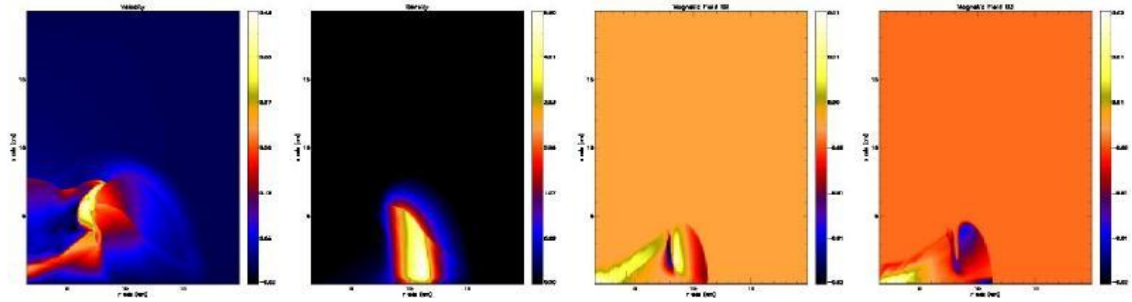
(a) Velocity (b) Density (c) Magnetic Field B2 (d) Magnetic Field B3

Figure 2: Graphs for Simulation Two: T_con = 100



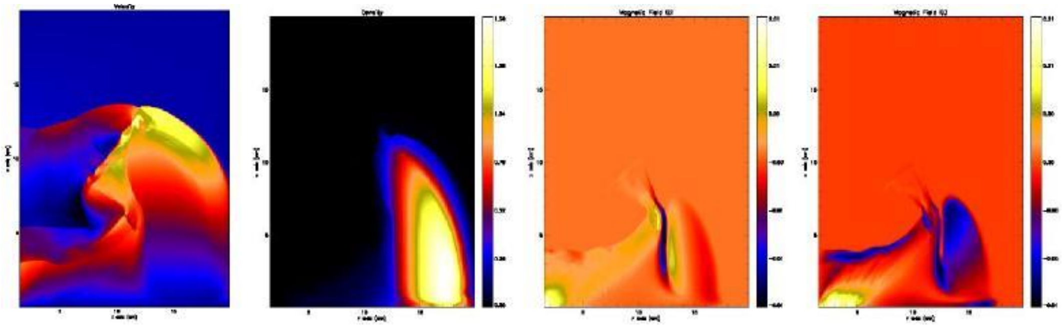
(a) Velocity (b) Magnetic Field B2 (c) Magnetic Field B3

Figure 3: Graphs for Simulation Three: T_con = 0.1



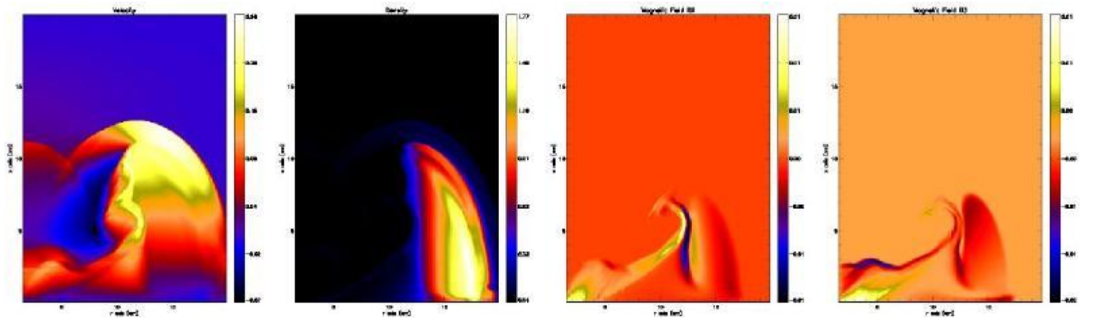
(a) Velocity (b) Density (c) Magnetic Field B2 (d) Magnetic Field B3

Figure 4: Graphs for Simulation One Time Step 20



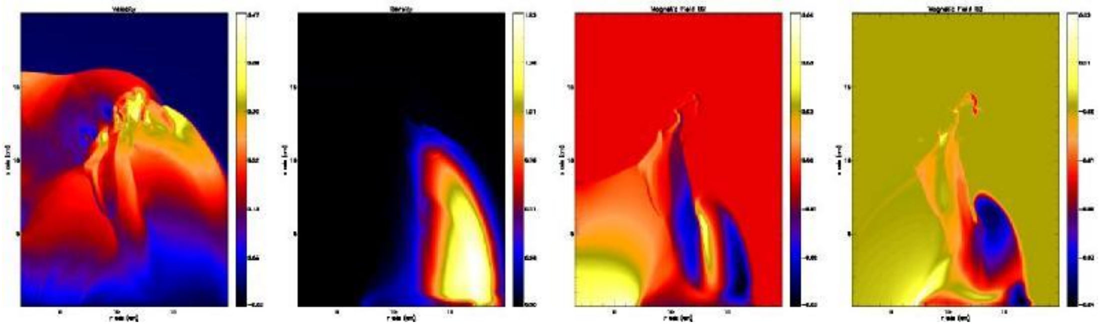
(a) Velocity (b) Density (c) Magnetic Field B2 (d) Magnetic Field B3

Figure 5: Graphs for Simulation One Time Step 40



(a) Velocity (b) Density (c) Magnetic Field B2 (d) Magnetic Field B3

Figure 6: Graphs for Simulation Five



(a) Velocity (b) Density (c) Magnetic Field B2 (d) Magnetic Field B3

Figure 7: Graphs for Simulation Six: BETA = 3.5

4. Conclusions

Unless the torus is fed by a stream of matter, the system will be unstable, and the torus will be expelled from the region. So then the question arises: if the simulation accounted for the incoming mass from the primary star, would the formation of stellar jets be sustainable? We can assume the system would be stable if the amount of mass transferred into the system is equal to or greater than the rate at which matter is lost. Beta Lyrae has an estimated mass transfer rate of 3×10^{-5} $M_\odot$/yr. By calculating the rates at which the matter of the torus is expelled in our simulations, we can compare our results to the mass transfer rate and determine whether or not the systems are supported. For example, in the case of Simulation 4, the rate at which the torus is expelled (1.32×10^{-5} $M_\odot$/yr) is less than that of the incoming mass transfer rate. Thus a stellar jet would be supported. This analysis can be applied to the other simulations to determine stability when accounting for the incoming mass transfer rate as well. However, as shown by seven unstable simulations of which five expelled matter of the torus, unless the torus is fed by a stream of matter, stellar jets cannot be sustained.

5. References

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