High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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X-ray binary Beta Lyrae and its donor component structure

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Abstract. We show that the structure of magnetized accretion gas flows between the components of the Beta Lyrae system can cause a scattering gas shell that masks completely these components in soft X-ray region. Also we have calculated the inner structure of the donor that is filling a Roche lobe and is preceding a forming of the degenerate dwarf. We show that mass of the degenerate core of the donor is in region $0.3 - 0.5 M_{\odot}$.

Keywords. X-rays: binaries, stars: Beta Lyrae, interiors

First of all, we propose an explanation of the steady state of X-rays of the massive interacting Beta Lyrae system. It was based mainly on our spectral observations that were conducted on the 2.6-m and 6-m telescopes and that led, in particular, to the first determination of the masses of both components ($2.9 M_{\odot}$ for a donor and $13 M_{\odot}$ for an accretor); to the discovery and research of the donor's magnetic field (that varies with the orbital phase within 1kGs); to the study of the dynamics and energetics of developed circumstellar structures of specific configuration, including the accretion disk of a complex structure (Skulskyy 2015). It was necessary to take into account the following factors: the presence of radio nebula surrounding of this system, and soft X-ray radiation, which does not change with the phase of the orbital period, and is associated with the Thomson scattering over the orbital plane. It is also based on an analysis of spectrophotometric studies of the Beta Lyrae system, including the progress in the latest modelings of the light curves from the far ultraviolet to the far infrared region (Mourard *et al.* 2018). The main problem is the harmonization of the results of these simulations with real light curves in the far ultraviolet beyond the Lyman limit, which does not resemble the light curves of the close binary systems (Skulskyy 2015). There is the significant contribution of the accretion disk radiation in the light curve of this system. In particular, two hot regions on the disk rim, that are located in the phases 0.80P and 0.40P with covering respectively 30% and 10% of the disk rim and with the temperatures that are 10% and 20% higher than the average on this disk, are detected (Mennickent *et al.* 2013). The hotter region of the rim disk at the phase 0.40P of the first quadrature is naturally explained by the Coriolis force deflection of the main gas flow that is directed from a donor through the inner Lagrangian point to the accretor's Roche lobe and with further collision of this flow with the accretion disk which is confirmed by own spectrophotometrical observations (Skulskyy 2015). However, this hydrodynamic picture can't explain a wide hot area of the disk, which is observed in the region of 0.80P phases of the second quadrature. This fact as well as a number of other observable facts should have a completely different explanation, connected with our consideration of Beta Lyrae system.

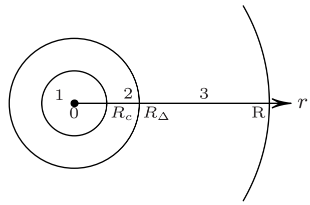

Figure 1. Model of the donor component in Beta Lyrae system.

We show that the structure of gas flows between the components of the Beta Lyrae system is above all due to the presence of the magnetic field of the donor that resembles a dipole with an axis directed along the orbital phases of 0.35 - 0.85P. In the phase range around 0.8-0.9P the magnetic field is maximal and its pole on the donor surface which reaches its Roche lobe is the closest to the accretion disk. This resumes the presence of more effective shock collisions of the magnetized plasma in the phases of the second quadrature 0.6-0.9P. The study of the curves of changes in the magnetic field and the curves of changes in the intensity and radial velocities of the spectral lines with the orbital phase, as well as the data of absolute spectrophotometry, confirm that the spatial structure of mass transfer in the Beta Lyrae system is due to the specific configuration of the donor magnetic field. The energy effect of collision between the disk and magnetized plasma, which is channeled by the donor's magnetic field towards a massive accretor at a speed of 200-700 km/s, is amplified in these phases due to the counter rotation of the disk edge with a speed of 250 km/s in front of the incident gas. This leads to the observation of the hot arc on the accretion disk edge facing to the donor, and this arc includes a wide hot region in the phases near 0.80P (Skulskyy 2015). As a result of high-energy collision of ionized plasma, channeled by donor's magnetic field with the accretion disk, a scattering gas shell is generated. This hot gas shell partially masks the components of this binary system outside the Lyman limit and completely in the soft X-ray region that is associated with Thomson scattering of X-rays in stellar wind and in jet-like structures.

Secondly, the massive binary system Beta Lyrae has donor component in the phase of active mass transfer and its core's structure is similar to that of hot white dwarf with helium degenerate core. Therefore simplified description of donor's structure can be obtained with generalization of white dwarf models (Vavrukh *et al.* 2018). We have used spherically symmetric three-phase model, depicted on Fig. 1, without taking into account rotation and orbital motion. Region 1 corresponds to degenerate core; region 2 is the transition layer, where the electron subsystem becomes non-degenerate; region 3 corresponds to surface layer, which fills Roche lobe.

We consider degenerate core with radius which consists of two regions 1 and 2, the former one is isothermal with temperature T_c. Also, we have modeled average molecular weight per electron in order to take into account radial dependence of chemical composition

$$\mu_e(r) = \mu_e\, t(r/R_\Delta), \quad 0 \leqslant r \leqslant R_\Delta,$$
$$t(r/R_\Delta) = \left\{1 + \alpha\,(r/R_\Delta)^2\right\}^{-1}, \tag{0.1}$$

where $\mu_e \equiv \mu_e(0) = 2.0$ and parameter α is close to one. In the transition layer ($R_c < r < R_\Delta$) we have assumed radial temperature distribution as follows

$$T(r) = T_c \left\{1 + \gamma \left(\frac{r - R_c}{R_\Delta}\right)^2\right\}^{-1}, \tag{0.2}$$

where γ is unknown parameter.

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Mechanical equilibrium equation inside regions 1 and 2 can be rewritten as equation for local chemical potential of electrons $\mu(r) = m_0 c^2 \left\{ \left[1 + x^2(r)\right]^{1/2} - 1 \right\}$, where m_0 is electron mass, $x(r) = \hbar\,(m_0 c)^{-1} \left(3\pi^2 n(r)\right)^{1/3}$ - local relativistic parameter, $n(r)$ - electron number density on a sphere with radius r.

Mentioned above equation has the next form:

$$\frac{1}{r^2}\frac{d}{dr}\left(t^{-1}(r/R_\Delta)\, r^2 \frac{d\mu}{dr}\right) = -\frac{32\pi^2 G (m_u^2 \mu_e)^2 t(r/R_\Delta)}{3h^3} \int_0^\infty dp\, p^2 n_p(r),$$

$$n_p(r) = \{1 + \exp\left[\beta(r)(E_p - \mu(r))\right]\}^{-1}, \tag{0.3}$$

where $E_p = ((m_0 c)^2 + c^2 p^2)^{1/2} - m_0 c^2$, m_u - atomic mass unit (inside the core $T(r) \equiv T_c$).

Equation (0.3) satisfies initial conditions

$$\mu(0) = m_0 c^2 \left\{ \left(1 + x_0^2\right)^{1/2} - 1 \right\}, \quad \frac{d\mu}{dr} = 0 \text{ at } r = 0, \tag{0.4}$$

where $x_0 \equiv x(r)$ at $r = 0$. Core radius can be found from condition $\mu(R_c) = 0$ and outer radius of the transition layer R_Δ, in turn, from $\exp\{-\beta(R_\Delta)\ \mu(R_\Delta)\} \gg 1$ i.e. $\mu(R_\Delta) = -Ck_B T(R_\Delta)$, which means that degeneration is negligible (in our calculation we took $C = 2.7183$).

Equation of state in the surface layer ($R_\Delta \leqslant r \leqslant R$) we have taken in the polytropic form

$$P(r) = DT^{1+n_*}(r), \quad \rho(r) = DT^{n_*}(r)\,\frac{\mu_* m_u}{k_B} \tag{0.5}$$

with polytrope index $4.0 < n < 5.0$, where μ - average molecular weight in atomic mass units m_u.

In this region equilibrium equation in approximation (0.5) transforms to equation for temperature and is similar to Lane-Emden equation

$$(1 + n_*)\frac{1}{r^2}\frac{d}{dr}\left(r^2 \frac{dT}{dr}\right) = -4\pi G D \left(\frac{\mu_* m_u}{k_B}\right)^2 T^{n_*}(r). \tag{0.6}$$

Condition $T(r) = 0$ determines stellar radius and initial conditions at $r = R_\Delta$ can be found assuming equilibrium between matter in regions 2 and 3:

$$\begin{aligned} P_e(R_\Delta) &= DT^{1+n_*}(R_\Delta), \\ \left.\frac{dP_e}{dr}\right|_{r=R_\Delta-\delta} &= (1+n)DT^n(R_\Delta)\left.\frac{dT}{dr}\right|_{r=R_\Delta+\delta}, \quad \Delta \to +0, \end{aligned} \tag{0.7}$$

where $P_e(r)$ - pressure of electron gas at r.

Model we described here has seven parameters: core parameters ($x_0, T_c, \mu_e(0), \alpha$), transition layer parameters (α, γ) and ones of surface layer (μ_*, n). In our work we have assumed $\mu_e(0) = 2.0$, $\mu_* = 0.6$ (similar to solar chemical composition).

Grid of models was calculated for values of parameters $x_0, T_c, \alpha, \gamma, n$ ranging:

$$\begin{aligned} &4.1 \leqslant n \leqslant 4.9, && \Delta n = 0.1; \\ &0.1 \leqslant \alpha \leqslant 0.7, && \Delta\alpha = 0.3; \\ &0.1 \leqslant \gamma \leqslant 0.7, && \Delta\gamma = 0.3; \\ &0.3 \leqslant x_0 \leqslant 3.0, && \Delta x_0 = 0.1; \\ &5\cdot 10^6 K \leqslant T_c \leqslant 10^8 K, && \Delta T_c = 5\cdot 10^6 K. \end{aligned} \tag{0.8}$$

Table 1. Calculated characteristics of the donor component with polytrope index $n=4.5$: model parameters α and γ; degenerate core parameters (x_0, T_c, R_c); total mass M and radius R of the donor; mass M_Δ and radius R_Δ of the core and transition layer.

α	γ	x_0	T_c, K	R_c/R_0	M/M_0	R/R_0	M_Δ/M_0	R_Δ/R_0
0.4	0.4	0.5	10^7	2.076	1.0091	1389.4	0.086	2.246
0.4	0.4	0.6	10^7	1.896	1.0254	1344.9	0.109	2.016
0.1	0.4	0.6	10^7	1.715	1.0138	1318.5	0.101	1.805
0.1	0.7	0.7	10^7	1.586	1.0467	1389.7	0.122	1.654

Basing on solutions of equations (0.3) and (0.6) we have chosen from the grid models with

$$0.95 \leqslant \frac{M}{M_0} \leqslant 1.05; \qquad 1300 \leqslant \frac{R}{R_0} \leqslant 1400, \tag{0.9}$$

which are in agreement with values of the donor in Beta Lyrae binary system obtained from observations. Here $M_0 \approx 2.887 M_\odot$, $R_0 \approx 1.116 \cdot 10^{-2} R_\odot$ are mass and radius scales, respectively (Vavrukh *et al.* 2018).

There were four models satisfying (0.9) with parameters given in Tab. 1.

As can be seen from our modeling results, within donor's mass and radius errors for mass of its core we have yielded values in range $0.25 - 0.35 M_\odot$. These ones are typical for hot low-mass field white dwarfs and agree with the assumption about white dwarfs as the endpoint of evolution of stars with masses below $8M_\odot$. Our model doesn't account for two substantial factors - donor's axial rotation and magnetic field. The former one can increase of white dwarf mass up to 5% (Vavrukh *et al.* 2018) and the last one can cause partial spin polarization of the core electron subsystem resulting also in mass increase of the white dwarf (Vavrukh *et al.* 2018). In the case of full polarization mass increases in $\sqrt{2}$ times comparing with core's mass with paramagnetic electron subsystem (Vavrukh *et al.* 2018). Thus, the influence of axial rotation and magnetic field can lead to mass increase up to $0.5M_\odot$. This is the upper limit for the core mass of the donor in Beta Lyrae interacting system.

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