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## Formation of a Rapidly Rotating Classical Be-star in a Massive Close Binary System (Post-print)

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### Abstract

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### Full Text

#### Preamble

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#### Formation of a Rapidly Rotating Classical Be-star in a Massive Close Binary System

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## Abstract

This paper investigates the spin-up of a mass-accreting star in a close binary system passing through the first stage of mass exchange in the Hertzsprung gap. Inside an accreting star, angular momentum is carried by meridional circulation and shear turbulence. The circulation carries part of the angular momentum of the accreted layers to the accretor's surface, with this fraction increasing as the rate of angular momentum arrival increases. It is assumed that this portion of angular momentum can be removed by the disk far from the accretor. If the angular momentum in the matter entering the accretor exceeds half the Keplerian value, then the angular momentum obtained by the accretor during the mass exchange stage does not depend on the rate of angular momentum arrival. The accretor may exhibit the characteristics of a Be-star immediately after the end of mass exchange.

**Key words:** (stars:) binaries (including multiple): close -stars: emission-line -Be -stars: early-type -stars: rotation

## 1. Introduction

Classical Be-stars include OBA stars with observed or previously observed emissions in the Balmer lines of hydrogen (Porter & Rivinius 2003). These stars are not supergiants and have large rotational velocities. Among Be-stars, there exists a group of early spectral subclasses (B3-O9). The surface rotational velocities of these stars range widely, with the lower limit being 40%-60% of the Keplerian value and the upper limit reaching 90%-100% (Cranmer 2005). The origin of these large rotational velocities remains unclear.

Young B-stars in the early spectral subclasses and O-stars are characterized by lower rotational velocities (Huang et al. 2010), with 70% of these stars observed in binary and multiple systems (Chini et al. 2012; Sana et al. 2012). Considering selection effects, all these stars are expected to form in binary and multiple systems. Mass exchange in a binary system may be responsible for the rapid rotation of the star receiving mass. Population synthesis of Be-stars in binary systems successfully reproduces the observed number of these stars in the Galaxy (Pols et al. 1991; Portegies Zwart 1995; Van Bever & Vanbeveren 1997; Shao & Li 2014; Hastings et al. 2021).

A simple estimation assuming instantaneous redistribution of angular momentum in the stellar interior to solid-body rotation shows that a 5%-10% increase in the star's mass due to accretion of matter with Keplerian velocity leads to a critical rotation state (Packet 1981). The question of continued accretion into a star near critical rotation has been discussed in Paczyński (1991), Popham & Narayan (1991), Colpi et al. (1991), and Bisnovatyi-Kogan (1993). These au-

thors used various approaches but all agree that accretion does not stop when the star's rotation reaches critical velocity. Paczyński (1991) studied the entire star-boundary layer-accretion disk system for various rotations of the central star.

For models rotating slightly above critical, mass accretion is accompanied by angular momentum loss from the star to the disk, mediated by viscous stresses. However, the solutions obtained in Paczyński (1991), Popham & Narayan (1991), and Colpi et al. (1991) are not self-consistent. The condition for a self-consistent solution for a system consisting of a star in critical rotation and an accretion disk is that “the star absorbs accreted matter with a certain angular momentum, such that the star remains in a state of critical rotation” (Bisnovatyi-Kogan 1993). Let  $J(M)$  be the angular momentum of a star with specific mass  $M$  in critical rotation and let  $j_{\text{Kep}}$  be the Keplerian specific angular momentum at the star's equator. Then  $dJ/dM = j_{\text{Kep}}$ . A mass-accreting star can move along the sequence of stars in critical rotation  $J(M)$  if the excess angular momentum is eliminated. Bisnovatyi-Kogan (1993) constructed models of accretion disks that remove excess angular momentum from the stellar surface while the surface rotation velocity remains critical. Thus, the mass and angular momentum of a star in critical rotation may increase due to removal of excess angular momentum by the accretion disk (Paczyński 1991; Bisnovatyi-Kogan 1993).

Physical processes such as meridional circulation and turbulence require finite time to transfer angular momentum (Staritsin 2019, 2021). At the very beginning of accretion, only the outer layers of the star, including the accreted mass, rotate rapidly. The stellar surface reaches critical rotation shortly after accretion begins. Later, during the accretion stage in a state of critical rotation, circulation carries part of the angular momentum brought with the accreted mass from subsurface layers to the star's surface (Staritsin 2022). Thus, accreted layers can shrink as normally occurs during accretion. The angular momentum transferred by circulation to the stellar surface can be removed through an accretion disk (Paczyński 1991; Bisnovatyi-Kogan 1993). Consequently, the mass and angular momentum of an accretor in critical rotation increase due to removal of excess angular momentum from the accreted layers to the accretor surface and subsequent removal from the star.

In Staritsin (2022), angular momentum transfer in the accretor interior was carried out only by meridional circulation, with turbulence artificially suppressed. This made it possible to elucidate the transport properties of circulation in an accreting star's interior, though the role of turbulence in angular momentum transport within the accretor remained unclear. Regarding angular momentum input, only one option was considered: effective transport of angular momentum from the disk's boundary layer to the accretor's upper layer.

In this paper, we consider two mechanisms of angular momentum transfer in an accreting star: circulation and turbulence. This allows us to determine the role of turbulence in spinning up a star. We also account for possible reduction of input angular momentum, which can be attributed both to transfer of angular

momentum from the boundary layer to the outer parts of the disk and to sub-Keplerian rotation in the disk. The accretor's rotation resulting from mass exchange has been studied as a function of the angular momentum introduced during mass exchange.

## 2.1. The Angular Momentum Input

Matter lost by the donor due to Roche lobe overflow falls into the accretor's gravitational field and swirls around it. The formation of gas structures around the accretor, particularly the formation of a disk and its velocity field, depends on the ratio between three factors: the size of the accretor  $R$ , the minimum distance  $\omega_{\min}$  from the accretor's center to the central line of the stream falling from the donor's L1 point, and the distance from the accretor's center to the edge of the inviscid disk  $\omega_d$  (Lubow & Shu 1975).

Transient disks with sub-Keplerian rotation have been found in direct-impact systems ( $\omega_d < R$ ), such as RW Tau (Kaitchuck & Honeycutt 1982) and  $\beta$  Per (Cugier & Molaro 1984; Richards 1992). Three-dimensional hydrodynamic calculations show disk formation in such systems with rotation velocities of 80% and 60% of the Keplerian value at the inner and outer edges of the disk, respectively (Raymer 2012).

Both transient disks (SW Cyg) and permanent but variable accretion disks (RY Gem, TT Hya, AU Mon) have been discovered in grazing-impact systems. The velocity fields in the transient disk of the SW Cyg system and in the permanent disk of the RY Gem system are sub-Keplerian (Kaitchuck 1988, 1989). Asymmetric structures were found in the disks of the TT Hya and AU Mon systems; the gas in the disk's asymmetric part in the AU Mon system moves at sub-Keplerian velocity (Richards et al. 2014). Hydrodynamic calculations also demonstrate the possibility of disk formation at sub-Keplerian velocities in these systems (Richards & Ratliff 1998). Permanent disks are found in systems with  $\omega_{\min} > R$ . The radial component of matter velocity in the disk is directed toward the accretor and is 10-30 km s<sup>-1</sup>. The tangential component may differ from the Keplerian one with distance from the accretor (Etzel et al. 1995).

The aforementioned observational data and hydrodynamic calculations relate to systems with low-mass accreting components ( $M \lesssim 6M_{\odot}$ ) and donor-to-accretor mass ratios within 0.2-0.3. The formation of Be-stars in early spectral subclasses occurs in systems with large component masses, where the donor-to-accretor mass ratio varies widely. Mass transfer in such systems is non-conservative (Van Rensbergen et al. 2011; Deschamps et al. 2015). The mass-receiving star increases in volume (Benson 1970; Kippenhahn & Meyer-Hofmeister 1977). The distance between the two stars depends on how the system loses mass and angular momentum. Thus, the formation of gas structures in the accretor's Roche lobe depends on mass and angular momentum loss from the system. Since a quantitative theory of mass and angular momentum losses from close binary systems has not yet been developed, the possibility of sub-Keplerian rotation

in an accretion disk due to mass and angular momentum loss from the binary system cannot be ruled out. Therefore, the possibility of mass accretion with sub-Keplerian rotation velocities should be considered.

At the very beginning of accretion, when the accretor's rotation velocity is low, the disk matter's rotation velocity decreases in the narrow boundary layer from the maximum value in the disk  $W_{\max}$  to the value on the star's surface  $\Omega_s$  (Paczynski 1991). Turbulence can remove angular momentum from the boundary layer to the accretor's upper layers at a rate of  $\dot{J} = \dot{M}(W_{\max} - \Omega_s)R^2$ , where  $J$  is the angular momentum of the accretor,  $t$  is time, and  $\dot{M}$  is the mass accretion rate.

Supersonic shear flow in the boundary layer is a source of acoustic waves that can carry angular momentum out of the boundary layer both into the accretor's outer part and the disk's outer part (Dittmann 2021; Coleman et al. 2022). In this case, the amount of angular momentum entering the accretor from the boundary layer is less than the Keplerian value.

In an earlier study (Staritsin 2022), we considered a scenario where, during the subcritical rotation stage, angular momentum enters the accretor through two channels: together with matter having the same rotation velocity as the accretor's surface, and due to turbulence within the rate given by equation (1). This represents a case of high efficiency of angular momentum transfer from the boundary layer to the accretor's upper part, where angular momentum transfer in the accretor's interior was carried out by meridional circulation with turbulence artificially suppressed.

In the current calculations, angular momentum transfer in the accretor's interior can be carried out by both meridional circulation and turbulence. We have studied two variants for angular momentum arrival into the accretor.

In the first variant, to clarify the influence of angular momentum transport by turbulence in the accretor's interior on the spinning up of the accretor, we calculated accretion with the same rate of angular momentum arrival as in Staritsin (2022). During the subcritical rotation stage, the parameter  $W_{\max}$  in the angular momentum source (1) equals  $\alpha\Omega_{\text{Kep}}$ , where  $\alpha = 0.8$  and  $\Omega_{\text{Kep}}$  is the Keplerian velocity at the star's equator. After the angular velocity of the accretor's surface increases to the  $\alpha\Omega_{\text{Kep}}$  value, angular momentum arrival from the boundary layer (1) stops. The angular velocity of the added matter is set equal to  $\alpha\Omega_{\text{Kep}}$  for the remainder of the mass exchange.

In the second variant, we consider the case of extremely low efficiency of angular momentum transfer from the boundary layer to the accretor's upper part. The angular momentum source (1) in this case is assumed to be zero. As long as the angular velocity of the star's surface is less than  $\alpha\Omega_{\text{Kep}}$ , the star accretes matter with the same angular velocity as the star's surface. After the surface angular velocity increases to  $\alpha\Omega_{\text{Kep}}$ , the angular velocity of the added matter remains equal to  $\alpha\Omega_{\text{Kep}}$ . To determine the dependence of the accretor's rotation

state after mass exchange on the angular momentum content of the added mass, calculations were carried out at four values of  $\alpha$ : 0.8, 0.6, 0.4, and 0.2.

## 2.2. Angular Momentum Transfer in the Accretor's Interior

Angular momentum transfer in the radiative layers of a star is accounted for within the framework of the shellular rotation model (Zahn 1992). In this model, two mechanisms of angular momentum transfer are considered: meridional circulation and shear turbulence. The angular momentum transfer is described by the law of conservation of angular momentum (Tassoul 1978):

$$\frac{\partial}{\partial t}(\rho r^2 \Omega) + \nabla \cdot (\rho r^2 \Omega \mathbf{u}) = \nabla \cdot (\rho \nu_v r^2 \nabla \Omega)$$

The meridional circulation velocity  $\mathbf{u}$  is determined from the stationary form of the energy conservation law (Maeder & Zahn 1998):

$$\rho T \mathbf{u} \cdot \nabla s = -\nabla \cdot \mathbf{F}_h + \rho \epsilon_n - \nabla \cdot (\chi \nabla T)$$

In these equations,  $\rho$  is density,  $s$  is specific entropy,  $T$  is temperature,  $\varpi$  is distance to the rotation axis,  $\Omega$  is angular velocity,  $\nu_v$  is turbulent viscosity in the vertical direction,  $\epsilon_n$  is nuclear energy release rate,  $\chi$  is thermal conductivity, and  $\mathbf{F}_h$  is turbulent enthalpy flux in the horizontal direction:

$$\mathbf{F}_h = -\nu_h \rho T \frac{\partial s}{\partial \theta}$$

with  $\nu_h$  being turbulent viscosity in the horizontal direction. The coefficients of turbulent viscosity were determined by Talon & Zahn (1997), Maeder (2003), and Mathis et al. (2004). The convective core rotates as a solid body. These equations are solved together with equations related to stellar structure and evolution using a set of programs from Paczyński (1970) modified to calculate the evolution of rotating stars (Staritsin 1999, 2005, 2007, 2009, 2014).

## 3.1. Binary System Parameters

We consider mass exchange in a binary system with component masses of 13.4 and 10.7  $M_\odot$  and period  $P = 35$  days, as in Staritsin (2022). By the beginning of mass exchange, the rotation of the 10.7  $M_\odot$  star is synchronized with orbital motion, giving it an angular momentum of  $1.3 \times 10^{51} \text{ g} \cdot \text{cm}^2 \text{ s}^{-1}$ . The 13.4  $M_\odot$  star loses 10.5  $M_\odot$  in 12,000 years, after which it decouples from its Roche lobe and the mass exchange stage ceases. The second star accretes 5.3  $M_\odot$ , reaching a final mass of 16.0  $M_\odot$ . The accretion rate was set constant at the average value of  $\sim 4.4 \times 10^{-4} M_\odot \text{ yr}^{-1}$ . We consider the case where the entropy of the added matter equals that of the surface layers of the second star. The thermal timescale

of the second star is longer than the mass exchange duration, and the star's reaction to mass increase is well understood (Benson 1970; Flannery & Ulrich 1977; Neo et al. 1977). The second star is driven out of thermal equilibrium by mass accretion. Nuclear power output in the star's center increases, with some nuclear energy release being spent on increasing entropy in the central regions. Gravitational energy release in the surface layers adds to nuclear energy release in the center. The typical luminosity distribution in the second star's interior is shown in Staritsin (2022) (see their Figure 4 [Figure 4: see original paper]).

The remaining mass lost by the first star leaves the system. Tidal interaction between the two stars cannot synchronize the accreting star with the orbit due to the system's long period and short accretion timescale. The accretion of matter and angular momentum, as well as transport processes inside the accretor and in the disk, determines the accretor's angular momentum.

### 3.2. The Case of High Efficiency of Angular Momentum Transfer from the Boundary Layer to the Accretor's Upper Part

With the beginning of mass exchange, a circulation cell forms in the accretor's subsurface layer, carrying incoming angular momentum downward. The cell consists of accreted layers and the underlying swirled layers of the accretor. In the cell's upper part, angular velocity has an almost constant value, but near the bottom it sharply reduces to the initial value (Figure 1 [Figure 1: see original paper]). Therefore, turbulence contributes more significantly to angular momentum transfer than meridional circulation (Figure 2 [Figure 2: see original paper]). The cell bottom descends into the star faster than when turbulence is artificially suppressed. The angular momentum entering the accretor is distributed over a larger mass than in the suppressed turbulence case. The accretor's surface reaches critical rotation when its mass increases to  $11.3 M_{\odot}$  (compared to  $11.0 M_{\odot}$  with suppressed turbulence (Staritsin 2022)). The angular velocity distribution in the accretor's interior at this moment is shown in Figure 3 [Figure 3: see original paper].

At the critical rotation stage, the accretor mass increases by another  $4.7 M_{\odot}$ , forming another circulation cell in the accreted matter. In this cell, circulation transfers part of the angular momentum that arrived with the accreted mass to the accretor's surface (Figure 4 [Figure 4: see original paper]). It is assumed that this angular momentum is removed from the accretor by the accretion disk (Paczynski 1991; Bisnovatyi-Kogan 1993). As a result of angular momentum loss, the accreted layers contract, with their rotation velocity permanently lower than the Keplerian velocity. Throughout mass exchange, angular momentum transfer inside the accretor continues. The mass in this cell increases as the upper boundary moves up along the accretor mass coordinate while the cell bottom moves down. The cell bottom reaches the convective core when the accretor mass increases to  $11.9 M_{\odot}$  (compared to  $15 M_{\odot}$  with suppressed turbulence

(Staritsin 2022)). Turbulence' s role lies in the rapid descent of the circulation cell bottom, which carries angular momentum into the star' s interior.

The amount of angular momentum removed from the accretor during mass exchange depends only slightly on angular momentum transfer processes within the accretor (Figure 5 [Figure 5: see original paper]). When turbulence is present, more angular momentum is transferred to the accretor' s inner layers and less is carried to the surface compared to the suppressed turbulence case (Table 1 ). The angular momentum brought into the accretor during mass exchange is  $1.72 \times 10^{53} \text{ g} \cdot \text{cm}^2 \text{ s}^{-1}$ ; 12% enters the inner layers that originally constituted the accretor, 31% remains in the accreted mass, and 57% is carried to the surface and removed by the disk. In the suppressed turbulence case, the corresponding values are 5%, 30%, and 65% (Staritsin 2022). After mass exchange ends, the accretor' s angular momentum is greater when turbulence is present (Table 1).

### 3.3. The Case of Extremely Low Efficiency of Angular Momentum Transfer from the Boundary Layer to the Accretor' s Upper Part

At the beginning of mass exchange, the rotation velocities of the incoming mass and the accretor' s surface coincide. The rate of angular momentum arrival into the accretor is significantly lower than when turbulence and/or waves transfer angular momentum from the boundary layer to the accretor' s outer part. Due to this low arrival rate, the accretor' s angular momentum increases slowly at the beginning of accretion (Figure 5 [Figure 5: see original paper]).

The general picture of angular momentum transfer in the accretor' s interior at  $\alpha = 0.8$  and  $\alpha = 0.6$  is the same as when angular momentum flows from the boundary layer to the accretor' s upper part. The difference is that the total angular momentum entering the accretor during mass exchange decreases (Table 1 ), due to both the absence of source (1) and the decrease in parameter  $\alpha$ . However, with  $\alpha = 0.8$  and  $\alpha = 0.6$ , the accretor surface' s rotation velocity increases to the critical value when the accretor mass reaches 12.9 and 13.3  $M_{\odot}$ , respectively (Figure 6 [Figure 6: see original paper]). In these cases, a circulation cell forms in the accretor' s outer layer, transferring part of the angular momentum of the accreted layers to the surface. The angular momentum removed from the accreted layers and lost by the accretor is less than in calculations with source (1) (Table 1). The final rotation state is approximately the same as when angular momentum arrival from the boundary layer was considered. A decrease in angular momentum entering the accretor only reduces the angular momentum removed during the critical rotation stage.

At  $\alpha = 0.4$  and  $\alpha = 0.2$ , less angular momentum enters the accretor (Table 1). The accretor' s surface rotation velocity remains subcritical throughout mass exchange; at  $\alpha = 0.4$  it approaches the critical value by the end of this stage. In both cases, a circulation cell forms in the accretor' s subsurface layer at the

beginning of mass exchange, transferring the angular momentum of the accreted matter inside the accretor. The cell bottom reaches the convective core when the accretor mass increases to  $13.1 M_{\odot}$  at  $\alpha = 0.4$  and  $13.9 M_{\odot}$  at  $\alpha = 0.2$ . In both cases, the angular momentum of the accreted mass is transferred inside the star throughout the mass exchange stage. The accretor retains all angular momentum received with the accreted mass (Figure 6 [Figure 6: see original paper]). After mass exchange ends, the accretor's angular momentum at  $\alpha = 0.4$  is slightly less than at  $\alpha = 0.6$  and  $\alpha = 0.8$ , while at  $\alpha = 0.2$  it is significantly less (Table 1).

### 3.4. Accretor Rotation State After Mass Exchange

The distribution of angular velocity in the accretor's interior immediately after mass exchange ends is shown in Figure 7 [Figure 7: see original paper]. In all cases, angular velocity decreases rapidly in a layer of variable chemical composition located between the chemically homogeneous radiative envelope and the convective core. A similar jump forms when angular momentum enters the accretor on a timescale shorter than or comparable to the donor's thermal timescale (Staritsin 2021). The thermal timescale of the accretor is longer than that of the donor in the cases considered in Staritsin (2021, 2022). After mass exchange ends, the jump gradually decreases and disappears during the accretor's thermal timescale (see, for example, Figure 3 in Staritsin 2021).

The angular velocity in the accretor's interior after mass exchange when  $\alpha = 0.8$  and  $\alpha = 0.6$  depends almost entirely on the angular momentum content of the added mass and whether angular momentum is transferred from the boundary layer to the accretor's upper layers. The accretor's angular momentum is  $\sim 7.5 \times 10^{52} \text{ g} \cdot \text{cm}^2 \text{ s}^{-1}$  (Table 1). An isolated  $16 M_{\odot}$  star with this angular momentum value maintains critical rotation throughout core hydrogen burning (Staritsin 2007). Consequently, due to mass exchange, the accretor receives rotation typical for Be-stars.

At  $\alpha = 0.4$ , the accretor receives almost the same angular momentum with the accreted mass as remains in the accretor when  $\alpha = 0.8$  and  $\alpha = 0.6$  (Table 1). Therefore, at  $\alpha = 0.4$  the accretor also has rotation typical for Be-stars. At  $\alpha = 0.2$ , the accreted mass brings much less angular momentum (Table 1). The angular velocity in the accretor's interior is lower than in other cases (Figure 7 [Figure 7: see original paper]). The accretor's surface rotation immediately after mass exchange is lower than that of Be-type stars. In an isolated star with the same mass and angular momentum as this accretor, angular momentum removal from inner layers to the surface occurs intensively during core hydrogen burning (Staritsin 2007, 2009). The star's surface angular velocity, expressed in units of Keplerian angular velocity, increases, and in the final stages the star acquires rotation typical for early-type Be-stars. If tidal interaction is weak, then even in this case the accretor can obtain Be-star characteristics after mass exchange, but only after a long period comparable to a fraction of the core hydrogen burning stage.

## 4. Conclusions

Meridional circulation is a flexible mechanism for angular momentum transfer in the interior of a rotating star. The direction and rate of angular momentum transfer by circulation can vary widely during mass accretion, depending on the star's rotation state and the rate of angular momentum arrival with the accreted mass and waves and/or turbulence. Two main circulation cells form due to mass and angular momentum accretion. In the cell formed during the accretor's subcritical rotation stage, circulation transfers angular momentum into the accretor interior. Only in the lower part of this cell does turbulence make the dominant contribution to angular momentum transfer. Due to turbulence, the cell bottom quickly descends into the accretor's interior. In the cell formed during the critical rotation stage, circulation transfers part of the angular momentum of the accreted mass to the stellar surface; the greater the angular momentum content of the incoming matter, the larger this fraction.

We have considered mass exchange in a binary system where half of the mass lost by the donor falls onto the accretor. If the angular momentum of the mass falling onto the accretor exceeds half the Keplerian value at the accretor's boundary, the accretor's rotation state after mass exchange does not depend on the angular momentum entering the accretor. In other words, processes that could reduce the angular momentum of matter around the accretor to no more than half the Keplerian value do not affect the angular momentum and rotation state the accretor receives by the end of mass exchange. These processes only affect the amount of angular momentum removed by circulation from the accreted mass to the accretor's surface and subsequently removed from the accretor by a disk or other mechanisms.

In the considered system with initial component masses of 13.4 and 10.7  $M_{\odot}$ , the accretor has rotation typical for Be-stars immediately after mass exchange ends if, during mass exchange, the angular momentum of the mass added to the accretor exceeds 40% of the Keplerian value.

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