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Formation of Be stars in binary systems with conservative mass exchange

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Abstract. In the case of conservative mass exchange in a binary system in the Hertzsprung gap, the mass of the accreting star can increase by up to two times. The accreted matter brings Keplerian angular momentum with it. The meridional circulation transfers 80–85% of the incoming angular momentum to the surface of the accretor. The increase in the mass and angular momentum of the accretor occurs due to the loss of this part of the angular momentum. After the mass exchange is completed, most of the angular momentum is concentrated in the accreted layers. The accretor has a large enough angular momentum to maintain its status as a Be star during its subsequent evolution on the main sequence.

Keywords: stars: binaries; emission-line; Be; early-type; rotation

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1 Introduction

Recently, a number of Be stars have been discovered in binary systems with sdO subdwarf (Chojnowski et al. 2018; Wang et al. 2023). The most studied representative of systems of this type is the binary system ϕ Per (Gies et al. 1998). This system could have been formed as a result of conservative mass exchange in the Hertzsprung gap (Schootemeijer et al. 2018). The mass range of Be stars in these systems overlaps with the range of masses of accreting components in long-period Algols. The observed characteristics of long-period Algols can also be reproduced (except for rotation) within the framework of the hypothesis of conservative mass exchange in the case of the shell source burning donor (Van Rensbergen & De Greve 2020). The periods of binary systems with Be stars are longer than those of long-period Algols. The axial rotation of the Be stars is also greater than that of the accreting components in the long-period Algols. We have studied the possibility of spinning-up of Be stars in the process a of conservative mass exchange. The initial parameters of binary systems are chosen to cover the range of masses of Be stars observed in systems with O-subdwarfs. The possibility of the spinning-up of accreting component has also been studied depending on the initial distance between the stars of the pair.

2 Calculation data

We have considered conservative mass exchange in a system with the initial masses of the components $(M_d)_0$ and $(M_a)_0$ of $6\,M_\odot$ and $5\,M_\odot$ and the distance between the components A_0 of $30\,R_\odot$, as well as with the initial masses of the components $3\,M_\odot$ and $2.5\,M_\odot$ and the distances of $30\,R_\odot$ and $15\,R_\odot$. The first and second systems are similar to the progenitors of the Be star systems ϕ Per (Vanbeveren et al. 1998) and BD $-01°$ 1603, the third system is similar to the progenitor of the long-period system of the Algol type RX Gem.

3 Calculation results

After the mass exchange has started, the mass of the accretor begins to increase. The angular velocity of the accretor surface also increases. In the accreted matter, a cell of meridional circulation is formed (Staritsin 2021, 2022, 2023a,b, 2024a). The bottom of the cell goes down into the accretor interior. The circulation transfers part of the angular momentum of the accreted layers into the interior of the accretor. The mass of the layers, into which this part of the angular momentum enters, increases with time in the process of the mass exchange. The mass fraction of these layers changes during the mass exchange in approximately the same way in accretors with different initial masses. However, the fraction of mass that falls on the convective core is smaller, the smaller the initial mass of the accretor. Angular momentum begins to enter the convective core at the very end of the mass exchange if $(M_a)_0 = 2.5\,M_\odot$, but before the end of the mass exchange if $(M_a)_0 = 5\,M_\odot$. After the mass exchange, angular momentum continues to flow into the convective core. The angular velocity of the convective core increases (Fig. 1).

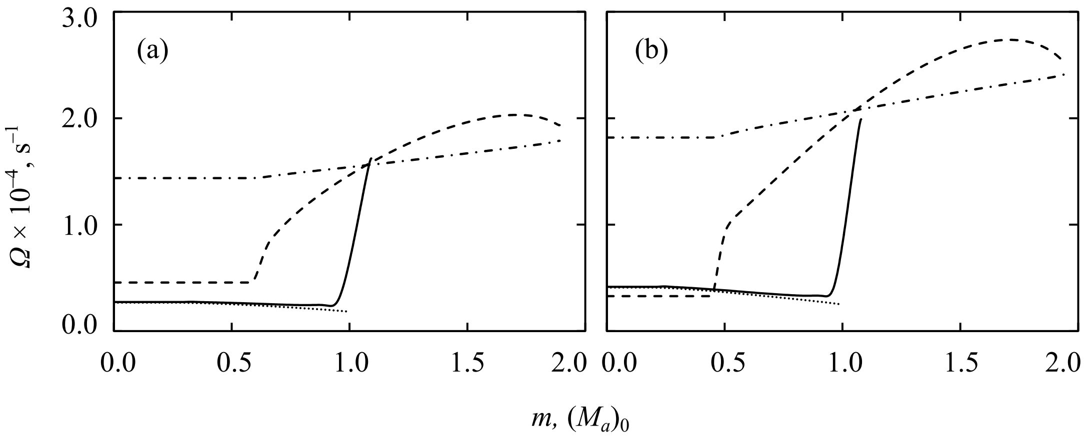

Fig. 1. Angular velocity in the interior of the accretor before the mass exchange (dotted line), when the surface receives Kepler rotation (solid line), at the end of the mass exchange (dashed line), and after relaxation towards thermal equilibrium (dot-dashed line) in the cases where the initial mass of the accretor is $(M_a)_0 = 5\,M_\odot$ (a) and $(M_a)_0 = 2.5\,M_\odot$ (b).

After the increase of the mass of the accretor by 10%, the angular velocity of the surface takes the value of the Kepler velocity (Staritsin 2022, 2023a,b, 2024a). Further, another cell of the meridional circulation is created in the accreted layers. Circulation transfers part of the angular momentum of the accreted layers to the surface of the accretor. This part of the angular momentum can be taken away from the accretor by the disk (Paczynski 1991; Bisnovatyi-Kogan 1993). As a result, the angular momentum coming with the accreted layers is reduced by 80% (Staritsin 2024b). The angular velocity of the accretor surface keeps the Kepler value. The boundary between the two circulation cells moves outward. Therefore, a small part of the angular momentum that came with the accreted layers at this stage of the mass exchange is transferred to the inner layers of the accretor.

The rate of mass exchange in the Hertzsprung gap depends on the initial distance between the components of the binary system. The response of a star to an increase in mass depends on the accretion rate. In the case of $A_0 = 15\,R_\odot$, the accretion rate is less than in the case of $A_0 = 30\,R_\odot$. The increase in the size of the accretor is smaller. The Kepler moment at the boundary of the accretor is also smaller. Therefore, the accreted matter brings less angular momentum in the case of $A_0 = 15\,R_\odot$ than in the case of $A_0 = 30\,R_\odot$. Nevertheless, the angular momentum of the accretor after the mass exchange is the same in both cases. Only the amount of angular momentum transferred by the circulation to the surface is lost by the accretor changes (Fig. 2).

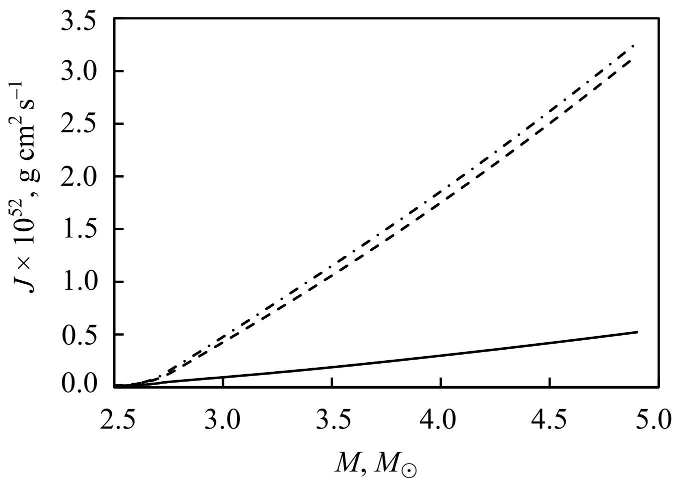

Fig. 2. Angular momentum brought by accreted matter in cases where $A_0 = 30\,R_\odot$ (dot-dashed line) and $A_0 = 15\,R_\odot$ (dashed line), and angular momentum of the accretor (solid line) as functions of its mass.

Due to mass exchange, the mass of the accretor almost doubles. Most of the angular momentum is concentrated in the accreted matter. The distribution of angular momentum in a single star is approximately the same. However, the angular momentum of the convective core and its adjacent layers in the case of an accretor is less than that of a single star of the same mass. After the mass exchange is completed, the circulation continues to transfer angular momentum from the outer layers to the inner layers. The rotation of the accretor becomes subcritical, but remains typical for Be stars of the early spectral subclass. The angular momentum of the accretor is large enough to maintain the status of a Be star during evolution on the main sequence.

4 Summary

In the case of conservative mass exchange in the Hertzsprung gap, the meridional circulation transfers 80–85% of the angular momentum that came with the accreted matter to the surface of the accretor. The loss of this part of the angular momentum allows the accretor to increase the mass and angular momentum during the mass exchange. Meridional circulation and shear turbulence transfer a small portion of the angular momentum that came with the accreted matter to the inner layers of the accretor. After the mass exchange is completed, most of the angular momentum is in the accreted layers. The angular momentum of the accretor does not depend on the initial distance between the components of the binary system. With different initial masses of the progenitors of the Be + sdO binary systems, the accretor obtains an angular momentum large enough to maintain the status of a Be star during the subsequent evolution on the main sequence.

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