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The Role of Meridional Circulation in the Formation of Classical Be Stars

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Abstract—At the stage of mass exchange in a binary system, the meridional circulation brings to the surface of the star up to two-thirds of the angular momentum that entered the star along with the accreted matter. As a result, the mass and angular momentum of the star can increase due to accretion. After the end of accretion, the star has a rotation typical of rapidly rotating Be stars. It is assumed that the angular momentum carried by the meridional circulation to the star's surface from the accreted matter is removed from the star by the accretion disk. The article is based on a talk presented at the astrophysical memorial seminar "Novelties in Understanding the Evolution of Binary Stars," dedicated to the 90th anniversary of Professor M.A. Svechnikov.

Keywords: Be stars, binary star systems, structure and evolution of stars

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1. INTRODUCTION

Classic Be type stars include stars of OBA spectral classes, in which emission in hydrogen Balmer lines is observed or was previously observed. These stars are not supergiants and exhibit rapid rotation [1]. A separate group consists of Be stars of the early spectral subclass (B3–O9). These stars have a wide range of rotation velocities. The lower limit of this range is from 40 to 60% of the Keplerian velocity, and the upper limit is from 90 to 100% [2]. The masses of these stars are within (8–20) $M_\odot$.

The question about the origin or causes of the high rotation velocities of Be stars still does not have a definitive answer. Young Be stars of early spectral subtypes, like O stars, are characterized by reduced rotation velocities [3]. At the same time, 70% of these stars are observed in binary and multiple systems [4, 5]. Considering selection effects, one can expect that all such stars are part of multiple systems. In the process of evolution, close binary systems go through the stage of mass exchange. The result of this stage may be an increase not only in the accretor's mass, but in its angular momentum as well. In this case, the rotation velocity of the accretor surface is limited from above by a critical value—the Keplerian velocity. The mass exchange in binary systems, assuming that the accretor reaches a critical rotation velocity, seems to be the preferable scenario for the appearance of Be stars [6–10].

The article examines the role of meridional circulation in changing the state of rotation of the accretor during the process of mass exchange in a binary system in the Hertzsprung gap.

2. PROBLEM STATEMENT

2.1. Increase in Accretor's Angular Momentum

Observations [11–17] and hydrodynamic calculations of the mass exchange in binary systems [18–21] show the presence of a disk around the star accreting mass. At the beginning of accretion, the angular rotation velocity of the matter falling onto the star decreases in a narrow boundary layer from the Keplerian value at the inner edge of the accretion disk to the rotation velocity of the star's surface [22, 23]. The angular velocity decreases due to the transfer of angular momentum from the boundary layer to the outer layers of the accretor by turbulence at a rate

$$\frac{dJ}{dt} = \frac{2}{3}R^2(\Omega_{\rm crit} - \Omega_{\rm seq})\dot{M}, \quad (1)$$

where J and R are the angular momentum and the size of the accretor, $\Omega_{\rm crit}$ and $\Omega_{\rm seq}$ are the critical velocity and the rotation velocity of the accretor surface at the equator, $\dot{M}$ is the accretion rate, and t is time. Thus, angular momentum enters the star through two channels: (1) together with matter, which has the same rotation velocity as at the surface of the star, and (2) in the form of a turbulent flow.

The possibility of increasing the mass and angular momentum of the accretor in a state of critical rotation, when the rotation velocity of the accretor surface at the equator is equal to the critical one, is due to the removal of angular momentum from the star by the accretion disk [22, 24]. At the same time, the rotation velocity of the accretor surface at the equator remains critical,

$$\Omega_{\rm seq} = \Omega_{\rm crit}. \quad (2)$$

2.2. Transfer of Angular Momentum in the Interior of a Rotating Star

The transfer of angular momentum in the radiative layers of a star is considered within the framework of the shellular rotation model [25]. This model considers two mechanisms of angular momentum transfer: meridional circulation and shear turbulence. The transport properties of turbulence in the horizontal direction (i.e., along a constant-pressure surface) are much more pronounced than in the vertical direction. Therefore, an arbitrary constant-pressure surface rotates almost rigidly. The angular velocity can change in the vertical direction. The transfer of angular momentum is described by the law of conservation of angular momentum [26]:

$$\frac{\partial(\rho\varpi^2\Omega)}{\partial t} + {\rm div}(\rho\varpi^2\Omega\mathbf{u}) = {\rm div}(\rho\nu_v\varpi^2\,{\rm grad}\,\Omega). \quad (3)$$

The meridional circulation velocity $\mathbf{u}$ is determined from the law of conservation of energy in stationary form [27–29]:

$$\rho T\mathbf{u}\,{\rm grad}\,s = \rho\varepsilon_n + {\rm div}(\chi\,{\rm grad}\,T) - {\rm div}\,\mathbf{F}_h. \quad (4)$$

The equations are solved considering the first order of smallness in the expansion of the vertical component of the meridional circulation velocity in latitude θ, measured from the rotation axis: $U_r(m,\theta) = U(m)P_2(\theta)$ [25], where $U(m)$ is the amplitude of the vertical component of the meridional circulation velocity (hereinafter, referred to as the meridional circulation velocity), and $P_2(\theta)$ is the associated Legendre function of the second degree. In these equations, ρ and Ω are the average density and angular velocity of a constant-pressure surface; ϖ is the distance to the rotation axis; ν_v is the coefficient of turbulent viscosity in the vertical direction; T is temperature; s is specific entropy; ε_n is nuclear energy release rate; χ is thermal diffusivity coefficient; $\mathbf{F}_h$ is turbulent energy flux, $\mathbf{F}_h = -\nu_h\rho T\partial s/\partial\mathbf{i}_\theta$; and ν_h is coefficient of turbulent viscosity in the horizontal direction. The turbulent viscosity coefficients were determined in [30–32]. It is assumed that the convective core rotates as a rigid body.

The standard equations of stellar structure and evolution [33] were modified to consider the rotation of the star [34], and the mass m of matter inside a constant-pressure surface is used as an independent variable. These equations are solved together with Eqs. (3) and (4) [35–37].

2.3. Parameters of the Variant under Study

The observed number of Be stars in the Galaxy can be reproduced in theoretical calculations of the population of this type of stars if half of the mass lost by the donor falls on another star in the binary system [9]. We considered the mass exchange in a binary system with initial components' masses 13.4 $M_\odot$ and 10.7 $M_\odot$ and a period $P = 35^d$ [38]. By the beginning of the mass exchange, the star with the mass 10.7 $M_\odot$ rotates slowly and synchronously with the orbital rotation. The star with its initial mass 13.4 $M_\odot$ loses 10.5 $M_\odot$ in thermal time scale. Half of this mass (5.3 $M_\odot$) falls on the accretor, and the other is lost by the system. The average accretion rate is $\sim 4.4\times10^{-4}$ $M_\odot$/year.

A special case of mass exchange in a binary system, with the formation of an intermediate convective zone above a layered source of hydrogen nuclear burning in the interior of a more massive star of the pair, was considered in [39]. In this case, part of the mass exchange occurs on the nuclear time scale of helium burning of the more massive star [40, 41]. Meridional circulation turned out to be the main mechanism for transferring angular momentum into the interior of the accretor in this case: the advective flux of angular momentum exceeded the turbulent flux by orders of magnitude. To study the role of meridional circulation in the considered case of mass exchange on a thermal time scale, the turbulent transfer of angular momentum is artificially reduced.

3. TWISTING OF A Be STAR IN A BINARY SYSTEM IN THE HERZSPRUNG GAP

3.1. Accretion at the Stage of Subcritical Rotation of the Accretor

The angular momentum transfer equation (3) is solved with boundary condition (1). At the very beginning of accretion, the rate of angular momentum entering the accretor is $\sim 5\times10^{41}$ g cm^2/s^2. This is five orders of magnitude greater than the typical values of angular momentum flux in single stars [36, 37]. Similar to the case of accretion onto a B star in the envelope of a red supergiant [42], the arrival of angular momentum into the subsurface layer of the accretor leads to the formation of a matter circulation cell in it in the meridional plane. In this cell, circulation transfers angular momentum into the accretor (Fig. 1). The circulation velocity is significantly higher than in models of single stars and amounts to 1–10 cm/s [38]. Accordingly, the characteristic time of the transfer of angular momentum in a cell has the same order of magnitude as the duration of the mass exchange.

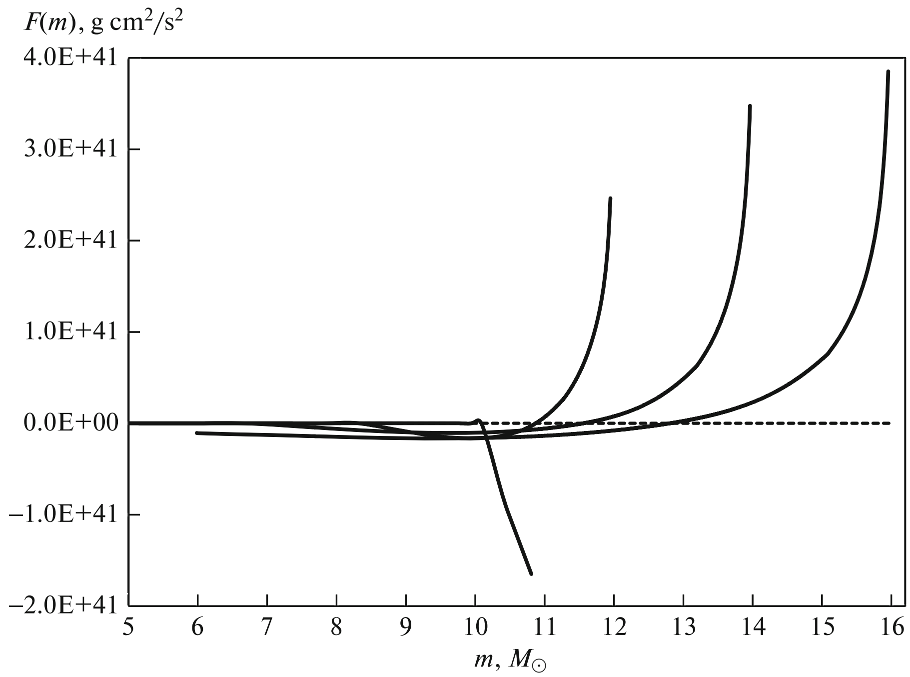

Fig. 1. Angular momentum flux $F(m)$ inside the accretor before the rotation velocity of its surface increases to a critical value, at accretor mass values of 12 $M_\odot$, 14 $M_\odot$, and 16 $M_\odot$.

When the mass of the accretor increases to 11 $M_\odot$, the rotation velocity of its surface reaches a critical value. The mass of the matter in the external circulation cell is 1 $M_\odot$. The angular velocity in the cell decreases from the critical one on the accretor's surface to the initial one at the bottom of the cell.

3.2. Accretion at the Stage of Critical Rotation of the Accretor

The angular momentum transfer equation (3) is solved with boundary condition (2). At this stage, the star accretes 5 $M_\odot$ more. Matter attaches to the star at a critical rotation velocity. In the accreted matter, another circulation cell forms. In this cell, circulation carries part of the angular momentum of the accreted matter to the star surface. It is assumed that this part of the angular momentum is removed from the star by the accretion disk [22, 24]. Angular momentum is removed most quickly from recently accreted layers (Fig. 1). Due to the loss of angular momentum, the accreted layers are contracted, which is usual during accretion. In the process of contraction, the rotation velocity of these layers always remains smaller than the Keplerian value.

In the circulation cell that was formed at the beginning of the mass exchange, the transfer of angular momentum into the star continues. The outer boundary of this cell moves outward through the star's matter, and the bottom of the cell moves inward. When the bottom of the cell reaches the convective core, the angular momentum of the accreted matter begins to flow into the core.

3.3. Characteristics of the Accretor after the End of Mass Exchange

During the mass exchange, the accreted matter brings with it an angular momentum amounting to 1.76×10^{53} g cm^2/s. Meridional circulation transfers 5% of this quantity into the inner layers, which made up the star before the accretion; 30% of the incoming angular momentum remains in the accreted matter. The remaining 65% is transferred by circulation to the star surface. This part of the angular momentum is lost by the star. The mass of the star after the end of accretion is 16 $M_\odot$, and the angular momentum is 6×10^{52} g cm^2/s.

The rotation velocity of the surface near the equator in models of a single star with the same mass and angular momentum as of the accretor exceeds 95% of the Keplerian velocity for the whole time of hydrogen burning in the core [36]. Thus, the exchange of matter in a binary system may be the very process in which stars receive large angular momentum and rotation velocities. A component of a binary system may have the characteristics of a Be star immediately after the end of the stage of mass exchange.

4. CONCLUSIONS

Meridional circulation is a flexible mechanism for transferring angular momentum in stellar interior. The direction and rate of transfer of angular momentum by circulation can vary within wide limits depending on what happens to the star.

Stars can obtain large angular momentum and rotation velocity, typical of Be stars of the early spectral subclass, as a result of mass exchange in binary systems. An increase in the rotation velocity of the star surface to a critical one during accretion is not an obstacle to a further increase in the mass and angular momentum of the star, since the meridional circulation carries part of the incoming angular momentum to the star surface. It is assumed that this part of the angular momentum is removed from the star by the accretion disk.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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