Mass and Angular Momentum Loss of B[e] Stars via Decretion Disks

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Abstract. We study the disks of B[e] stars assuming that the disks stem from the angular momentum loss from the central object. The angular momentum loss may be induced either by evolution of the stellar interior of critically rotating star or by merger event in a binary. In contrast to the usual stellar wind mass loss set by driving from the stellar luminosity, such decretion-disk mass loss is determined by the angular momentum loss needed to keep the central object in equilibrium. The angular momentum loss is given either by the interior evolution and decline in the star’s moment of inertia, or by excess angular momentum present in a merging binary. Because the specific angular momentum in a Keplerian disk increases with the square root of the radius, the decretion mass loss associated with a required level of angular momentum loss depends crucially on the outer radius for viscous coupling of the disk. The magnetorotational instability can be the source of anomalous viscosity in decretion disks. The instability operates close to the star and disappears in the region where the disk orbital velocity is roughly equal to the sound speed. We study the differences between Be and B[e] star disks and discuss the reasons why stars of the stellar type B have disks, while other stars do not.

1. Introduction

The definition of the B[e] phenomenon is based on common spectral characteristics of individual objects, which are the presence of Balmer lines in emission, forbidden emission lines, and infrared excess. Therefore, several evolutionary types of stars may be classified as B[e] stars (Lamers et al. 1998; Miroshnichenko 2007) regardless of the physical origin of the B[e] phenomenon. In our study, we focus on the supergiants and main sequence stars, in which the B[e] phenomenon can be explained by a presence of cool outflowing dusty disk.

The origin of the disk is unclear. The most straightforward explanations include the angular momentum loss connected with the (near) critical rotation of a single star or binary interaction. However, the description of the outflowing disk is the same and does not depend on the mechanism that actually drives the disk.

In this paper we discuss the angular momentum loss that stems from critical rotation and describe the physics of outflowing disks.
2. Disks Resulting from Critical Rotation

We assume a single star that rotates as a rigid body. In this case the magnitude of stellar angular momentum \( J \) is given by the product of the stellar moment of inertia \( I \) and the angular frequency \( \Omega \), \( J = I\Omega \). During stellar evolution, the time rate of change of angular momentum depends on the changes in moment of inertia and rotation frequency (Krtička et al. 2011),

\[
J = I\dot{\Omega} + I\dot{\Omega}.
\]  

(1)

For example, if during some evolutionary period the moment of inertia declines at a rate \( \dot{I} \) and the change of the angular momentum is negligible (\( \dot{J} = 0 \)), then the star has to spin up at a rate given by \( \dot{\Omega}/\Omega = -\dot{I}/I \). However, the spin-up can only proceed to a certain limit. The rotational velocity at the stellar equator cannot exceed the critical rotational velocity, which is equal to the Keplerian velocity \( v_K(r) = \sqrt{GM/r} \) at the equatorial radius \( R_{\text{eq}} \) of a critically rotating star, \( v_K(R_{\text{eq}}) = \Omega_{\text{crit}}R_{\text{eq}} \). Once the star reaches the critical rotation frequency \( \Omega = \Omega_{\text{crit}} \equiv \sqrt{GM/R_{\text{eq}}^3} \), this spin-up has to end (\( \dot{\Omega} = 0 \)), requiring instead a shedding of angular momentum given by

\[
\dot{J} = I\dot{\Omega}_{\text{crit}}.
\]  

(2)

At critical rotation the gravity force is balanced by the centrifugal force on the stellar equator and the material rotates with the critical speed

\[
V_{\text{crit}} = v_K(R_{\text{eq}}) = R_{\text{eq}}\Omega_{\text{crit}} = \sqrt{\frac{GM}{R_{\text{eq}}}}.
\]  

(3)

The critical speed is however lower than the escape velocity from the stellar equator,

\[
V_{\text{crit}} < V_{\text{esc}} = \sqrt{\frac{2GM}{R_{\text{eq}}}}.
\]  

(4)

This means that the material cannot immediately escape to infinity and creates a circumstellar disk.

3. Magneto-Rotational Instability

Specific angular momentum of the material in the disk \( j \sim RV_K(R) \sim R^{1/2} \) increases with radius (here \( R \) denotes radius in cylindrical coordinates). Therefore, some process transfers angular momentum in the disk from inner parts to outer ones. In analogy with accretion disks one can assume that the angular momentum transfer is connected with anomalous viscosity (Shakura & Sunyaev 1973) and that the magnetorotational instability (MRI, Balbus & Hawley 1991) is the likely source of anomalous viscosity.

The MRI exists in weakly magnetized disks. If there is a radial displacement in such disks, the magnetic stresses may win and push the material back toward its original position. These displacements do not cause any instability. The displaced material is forced to corotation with respect to its original position. If the centrifugal force acting on the displaced material is higher than the force due to magnetic stresses, the material
accelerates in the direction of the original displacement, leading to an instability. Such an instability causes radial mixing, which transfers the angular momentum from the inner parts of the disk to the outer parts.

The necessary condition for instability is that the angular frequency should decrease with radius (Balbus & Hawley 1991),

$$\frac{d\Omega^2}{dR} < 0.$$  \hspace{1cm} (5)

This is fulfilled in Keplerian outflowing disks where $\Omega \sim R^{-3/2}$. The instability occurs in weakly magnetized disks,

$$B_c < \frac{\sqrt{6}}{\pi} \left( \frac{2}{\pi} \frac{a v_R \dot{M}}{v_R R^2} \right)^{1/2},$$  \hspace{1cm} (6)

therefore the instability occurs in the disk where the ratio of the gas to magnetic pressure is $\beta > \pi^2/3$. Here $a$ is the sound speed, $v_R$ is the disk radial velocity, and $\dot{M}$ is the disk mass-loss rate. In the outer parts of the disk, where the orbital velocity is lower than the sound speed, the centrifugal acceleration becomes unimportant and MRI disappears (Krtička et al. 2015).

4. Viscous Disk Models

With Shakura & Sunyaev (1973) prescription of the anomalous viscosity, it is possible to calculate the radial dependence of the disk column density, orbital velocity, and radial velocity (Okazaki 2001; Krtička et al. 2011; Kurfürst et al. 2014, see also Fig. 1). The radial disk velocity grows linearly close to the star and is equal to the sound speed at the disk sonic point with radius $R_{\text{sonic}}$. From this approximately linear dependence $v_R \approx aR/R_{\text{sonic}}$ (in isothermal disks) we can get an estimate of the time needed by the disk material to escape the star as $t_{\text{flow}} \approx (R_{\text{sonic}}/a) \ln(R_{\text{sonic}}/R_{\text{eq}})$, that is, the flow time is approximately equal to the sound wave disk crossing time.

The disk rotation is nearly Keplerian up to the sonic (critical) point, where it reaches about half of the Keplerian velocity, $v_\phi(R_{\text{sonic}}) \approx \frac{1}{2} v_K(R_{\text{sonic}})$ (Krtička et al. 2011). In the inner parts of the disk the disk rotational velocity exceeds the sound speed, therefore MRI instability works nearly up to the sonic point (Krtička et al. 2015) and allows the disk material to escape. The angular momentum loss $\dot{J}$ increases up to the critical point, where it is about an order of magnitude larger than the angular momentum loss from the Keplerian stellar equator $\dot{J}_K$. From these considerations the outer disk radius $R_{\text{out}}$ is usually attributed to the sonic point, however we note that the disk expands even further.

The radius of the disk sonic point can be estimated as

$$\frac{R_{\text{sonic}}}{R_{\text{eq}}} = \left[ \frac{3}{10 + 4p} \left( \frac{v_K(R_{\text{eq}})}{a(R_{\text{eq}})} \right)^{1-p} \right]^{1/p},$$  \hspace{1cm} (7)

where we assumed that the temperature varies as a power-law in radius, $T \sim R^{-p}$ and $p$ is a free parameter. Assuming that the angular momentum loss at the critical limit
occurs purely through Keplerian decetration disk with mass loss at a rate \( \dot{M} \), the angular momentum loss is set by the sonic point radius \( R_{\text{sonic}} \) of the disk,

\[
\dot{J} = R_{\text{sonic}} \dot{M} \nu_\varphi (R_{\text{sonic}}) \approx \frac{1}{2} \dot{M} R_{\text{eq}} \nu_\varphi (R_{\text{eq}}) \sqrt{\frac{R_{\text{sonic}}}{R_{\text{eq}}}} = \frac{1}{2} J \nu_\varphi (R_{\text{eq}}) \sqrt{\frac{R_{\text{sonic}}}{R_{\text{eq}}}}.
\]

(8)

Setting \( \dot{J} \) equal to the angular momentum loss rate needed to keep the star at critical rotation Eq. (2), we find that the required mass loss rate is given by the stellar moment of inertia change \( \dot{I} \)

\[
\dot{M} = 2 \frac{I}{R_{\text{eq}}^2} \sqrt{\frac{R_{\text{eq}}}{R_{\text{sonic}}}}.
\]

(9)

The angular momentum loss keeps the star at (or close to) the critical rotation in the case of single star or is given by excess angular momentum present in a merging binary. Consequently, the angular momentum loss via Keplerian disks is given purely by the stellar evolution. Together with \( R_{\text{sonic}} \) this also determines the disk mass-loss rate. As \( R_{\text{sonic}} \) gets larger, the required mass-loss rate gets smaller.

The radiative force due to the stellar radiation may ablate the material from the disk and sustain a line-driven disk wind (Gayley et al. 1999, 2001). The resulting disk wind mass-loss rate is comparable to the stellar wind mass-loss rate (Krtička et al. 2011; Kee et al. 2016). Therefore, the radiative ablation decreases the efficiency of the disk angular momentum loss and leads to the increase of the disk mass-loss rate.

5. Comparing B[e] Stars with Other Types of Stars

The inferred disk mass-loss rates are by several orders of magnitude higher in B[e] stars than in Be stars (e.g., Kraus et al. 2007; Klement et al. 2015, Vieira et al., this volume). This could be explained either by a higher moment of inertia change in B[e] stars or
by a larger sonic point radius in Be stars (see Eq. (9)). Because the sonic point radius is typically on the order of hundreds stellar radii in Be star disks (e.g., Okazaki 2001; Krtička et al. 2011), its decrease would not enhance the mass-loss rate by several orders of magnitude (see Eq. (9)), and the former possibility is more likely. This could point out to different disk formation mechanisms in Be and B[e] stars, that is critical rotation in Be stars and binary evolution in B[e] stars (Podsiadlowski 2010).

The disk ablation by the radiative force (Kee et al. 2016) and the angular momentum loss by the stellar wind may be one of the reasons why we do not observe disks around O stars.

6. Discussion and Conclusions

Critically rotating stars and products of binary mergers lose mass via decretion disks. The anomalous viscosity connected with magnetorotational instability may transport angular momentum in such disks. The instability exists in weakly magnetized disk and disappears close to the sonic point. The mass-loss rate is set by the angular momentum loss needed to keep the star at the critical rotation (or by excess angular momentum present in a merging binary), consequently the mass-loss due to the disk is inversely proportional to the sonic radius $R_{\text{sonic}}$ of that disk, $\dot{M} \sim R_{\text{sonic}}^{-1/2}$.

The observational picture of the disks around B[e] supergiants and main-sequence stars in general agrees with the viscous decretion disk scenario. The line profiles originating in the disk are consistent with Keplerian velocities in the disks of B[e] stars (e.g., Kraus et al. 2010, 2013; Aret et al. 2012). However, the ring structure derived from fitting of disk line profiles (Kraus et al. 2010, Maravelias et al., this volume) can be difficult to reconcile with the viscous decretion disk model.

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References

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