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A working hypothesis about the cause of Be stars: Episodic outward leakage of low-frequency waves excited by the iron-peak κ-mechanism

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Abstract. Observations indicate that a circumstellar disk is formed around a Be star while the stellar rotation is below the break-up velocity. I propose a working hypothesis to explain this mystery by taking account of the effect of leaky waves upon angular momentum transfer.

In B-type stars near the main sequence, low-frequency nonradial oscillations are excited by the κ-mechanism in the iron bump. They transport angular momentum from the driving zone to the surface. As a consequence, the angular momentum is gradually deposited near the stellar surface. This results in a gradual increase in the "critical frequency for g-modes", and g-modes eventually start to leak outward, long before the surface rotation reaches the break-up velocity. This leads to a substantial amount of angular momentum loss from the star, and a circumstellar disk is formed. The oscillations themselves will be soon damped owing to kinetic energy loss. Then the envelope of the star spins down and angular momentum loss stops soon. The star returns to being quiet and remains calm until nonradial oscillations are newly built up by the κ-mechanism to sufficient amplitude and a new episode begins.

According to this view, the interval of episodic Be-star activity corresponds to the growth time of the oscillation, and it seems in good agreement with observations.

Keywords. stars: emission-line, Be, stars: oscillations, stars: rotation

1. Motivation

Some B-type stars near the main sequence show Balmer line emissions, and they are classified as "Be stars" (Collins 1987). Sharp absorption lines often appear in what is known as a "shell" spectrum, indicating the presence of a cool thin disk surrounding the star. The line shapes and intensities, or even the presence of emission lines, vary with a timescale of the order of decades. It is widely accepted that this kind of activity is preceded by episodic mass loss, occurring quasi-periodically at intervals ranging from several years to some decades, from the equatorial region of the star, and forming a cool gas disk around the star (see, e.g., the review by Porter & Rivinius (2003) and references therein). In the active mass-eruption phase, Be stars show Balmer line emissions. In the quiescent phase, they show normal B-type spectra.

The mechanism of the episodic mass loss in Be stars is, however, as yet unknown. Previously, Be stars were presumed to rotate at their critical break-up velocity, over which the centrifugal force exceeds the gravity at the equator, and to eject their mass from the equatorial zone (Struve 1931). Indeed, the spectroscopically observed rotation velocities of Be stars are higher than those of normal B-type stars. However, careful analyses indicate that their velocities are not high enough to reach the break-up limit (Porter 1996; Frémat *et al.* 2005), though this conclusion is still controversial (e.g., Townsend *et al.* 2004). Some additional mechanisms for the angular momentum transport have been examined to bring the already rapid stellar rotation to its critical value at the surface, and allows the star to eject material. Such attempts are nevertheless incompatible with the observational fact that the rotational Doppler velocities of Be stars are lower than the break-up limit.

The view that rapid rotation of Be stars is likely to be responsible for episodic mass loss presumes that the rapid rotation is an intrinsic characteristic of these stars. It does not attempt to explain the essential question of why Be stars are more rapidly rotating than normal B-type stars. It sidesteps the issue and is then far from a logical explanation. We should go behind the outward form to grasp the inner meaning of the phenomenon. It is uncertain yet even whether rapid rotation of Be stars is the cause of the Be phenomenon or rather the consequence of them.

2. Mystery of angular momentum transfer

Be stars eject their mass, while their surface rotation is not high enough to reach the break-up limit. The essential problem in Be stars is how to transfer angular momentum from the inside of the star to the outer atmosphere by keeping the stellar rotation below the critical break-up velocity. At first glance, this appears to be a quandary. The problem is then how to overcome this dilemma. Nonradial g-modes have been regarded as a promising mechanism to redistribute the angular momentum in stars in general (Unno *et al.* 1989, see also recent more comprehensive reviews, e.g., Lee 2008, Mathis & Alvan 2013). In fact, non-axisymmetric nonradial oscillation modes work to transfer angular momentum in a star from the region where the oscillations are excited to other regions where dissipation works to damp the oscillations. As for Be stars, some attempts were made to see whether the nonradial g-modes efficiently work to accelerate the stellar surface rotation up to the break-up velocity (Ando 1983, 1986; Osaki 1986, 1999; Lee & Saio 1993; Lee 2008, 2013; Cranmer 2009; Neiner 2013). However, as far as we accept the aforementioned observational fact, we think that it is beside the point to consider the case that the stars rotate at the break-up limit.

3. Angular momentum transfer by leaky gravity waves

3.1. *Outwardly leaky gravity waves*

In this paper, we propose a mechanism of angular momentum transfer to the circumstellar environment without much deposition of angular momentum into the layers below the photosphere. Such a situation becomes possible when the nonradial gravity waves become leaky outward from the photosphere. However, this possibility has not been taken into account, while the presence of g-modes with leakage in B-type stars was discussed in detail by Townsend (2000a,b). Instead, in previous studies concerning the angular momentum transfer, the waves were thought to be reflected near the stellar surface to make the oscillation modes a standing wave. Such a treatment of the reflective surface boundary is justified if the oscillation frequency is higher than the critical frequency for g-modes at the surface. However, the critical frequency for g-modes is dependent on the stellar rotation speed, and the reflective boundary condition is not necessarily applicable.

3.2. *Pulsations and Be stars*

First of all, we suppose that non-axisymmetric nonradial g-modes are excited in B type stars in a certain effective temperature range due to the iron-peak κ-mechanism.

Pulsations in Be stars were often thought to be a key factor to understand the physical cause of Be stars. Many Be stars show photometric variability which is interpreted as low-degree g-modes, while some others show line-profile variation which is interpreted to be caused by intermediate-degree g-modes. Those g-modes of either low or intermediate degrees are most probably excited by the iron-peak κ-mechanism. It was often claimed, however, that pulsations were not seen in all the Be stars and then pulsations were unlikely to be responsible for the Be phenomena (e.g., Balona 2003).

In our view, any non-axisymmetric, nonradial, low-frequency modes, whether they are detectable or not (in other words, whether or not they are low- or intermediate-degree modes), can transport the angular momentum into the circumstellar environment. The leaky wave conditions are more easily realized in the case of high-degree modes, which are hard to detect. Hence, lack of detected pulsations is off the point.

3.3. *Gravity modes in a rotating star*

These modes transfer the angular momentum to the stellar surface, and the rotation at the surface is gradually accelerated, though still below the break-up speed. In a rotating star, the Coriolis force modifies significantly the oscillation characteristics of the star, particularly those of low-frequency modes. It is known that, with the increase of the rotation frequency, the eigenfunctions are concentrated in low latitudinal zones. This means that the horizontal wavelength becomes gradually shorter with the increase of rotation frequency, that is, the horizontal wavenumber becomes higher near the stellar surface.

Propagation features of nonradial oscillations can be understood with the local dispersion relation, in which the Lamb frequency and the Brunt-Väisälä frequency appear, to a good approximation, as the critical frequencies. A gravity wave does not propagate in radial directions and is evanescent if the frequency is between these two critical frequencies. If waves become evanescent at the stellar surface, they are reflected inward and can become standing waves. The Brunt-Väisälä frequency is high at the stellar surface except within convective zones, while the Lamb frequency being proportional to the sound speed is quite low due to the low temperature near the surface, and then the gravity waves are usually standing waves.

However, this situation is different when the star begins to rotate substantially due to acceleration caused by angular momentum transfer of g-modes. The horizontal wavelength becomes short, and, as a consequence, the Lamb frequency, being proportional to the horizontal wavenumber, becomes high. Then high-order g-modes begin to propagate and leak outward (Shibahashi & Ishimatsu 2012). For more detailed analyses, see Ishimatsu & Shibahashi (2013).

3.4. *On-off mechanism of the valve for the leaky waves*

With the increase of stellar rotation frequency, the critical frequency for g-modes becomes higher, and then high-order g-modes eventually become leaky outward, though the stellar rotation is still below the break-up speed. Once g-modes become leaky, the angular momentum is transferred into the circumstellar environment to form a disk around the star. Since angular momentum is not deposited at the photosphere by leaky waves but transferred through it, the aforementioned apparent dilemma is solved. On the other hand, the wave energy is suddenly lost and then the oscillations are damped soon. The stellar surface rotation slows down, and this shuts the valve for the leaky wave and the reflective boundary is recovered. The star remains quiet until new nonradial oscillations are built up by the κ-mechanism to sufficient amplitude. The circumstellar disk, once formed, gradually loses its angular momentum and the matter will eventually fall back to the star. All the above processes recur, and the timescale of this cycle is governed by the growth rates of g-modes and it is of the order of a decade. In this view, the fairly rapid rotation of Be stars is not a direct cause for the Be phenomena, but an inevitably induced consequence of presence of non-axisymmetric nonradial g-modes excited by the iron-peak κ-mechanism in the process of Be phenomena.

3.5. *Is rapid rotation the main cause of Be phenomena?*

It is certain that Be stars rotate more rapidly than normal B-type stars. It was suspected that mass loss would be a result of the star rotating at critical rotational velocity since Struve (1931). In the view described in this paper, the rapid rotation of Be stars is neither an intrinsic feature nor the cause of Be phenomena, but an inevitable consequence of angular momentum transfer by g-modes excited by the iron bump κ-mechanism.

The amount of angular momentum transferred into the upper atmosphere is highly dependent on the pulsation amplitude. Even if any single mode would not be enough to carry the angular momentum above the photosphere, the total sum of the contributions of many self-excited modes would be substantial. This implies that, during the process of accelerating the stellar rotation by low-frequency g-modes, the angular momentum would be transferred into the upper atmosphere above the photosphere to form a circumstellar disk long before the surface rotation reaches the break-up limit.

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