Non-radially Pulsating Hot Stars:
Non-radial Pulsations and Be Phenomenon

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Abstract. We discuss a possible role of non-radial oscillations as a cause of mass-loss in hot stars. In particular, we propose a working model for the episodic mass-loss in Be stars. In this model, equatorial mass loss is thought to be driven by wave-breaking phenomenon of large-amplitude non-radial waves and a circumstellar disk could thus be formed around the equatorial plane of a rapidly rotating star. A kind of relaxation-oscillation cycle could be established between the Be phase and non-Be phase, in which an interplay between non-radial oscillations in stellar atmosphere and the circumstellar disk is essential. We also discuss a viscous decretion-disk model for the circumstellar envelope around Be stars.

1 Introduction

As more precise observations have been made for luminous hot stars both photometrically and spectroscopically, it becomes evident that pulsations and oscillation related phenomena are ubiquitous in these stars. Since the main objective of this colloquium is to discuss non-spherical and variable mass loss from these stars, it is my understanding that my task assigned is to discuss the connection between the non-radial pulsations (abbreviated as "NRP") and mass loss in hot stars. Thus I will discuss in this talk a possible role of NRP for equatorial mass loss in hot stars. In particular, I propose a working model for episodic mass loss in Be stars.

2 NRP and Mass Loss in Be Stars

The Be stars are those rapidly rotating B-type stars that exhibit from time to time emission lines in their spectra, most conspicuously in hydrogen Balmer lines (see, e.g., Slettebak, 1988). Emission lines in these stars are believed to be formed in the circumstellar disks around stars. More than a half century ago, Otto Struve (1931) had already proposed a simple model of Be stars where a rapidly rotating B-type star is surrounded by a rotating equatorial disk which is supported by centrifugal force against stellar gravity. This simple picture for Be stars still seems to be basically correct.

The most fundamental problem of Be stars is the origin of the Be phenomenon. That is, the basic question, why these stars have circumstellar envelopes in the first place, has still remained unanswered. It has been known that the rapid rotation in these stars is not sufficient to produce mass loss and equatorial disks. Some extra mechanism other than rapid rotation of a star seems to be needed. As discussed below, one of possible mechanisms seems to be "NRP" in these stars.

3 Basic Model for Mass Loss in Be Stars by NRP

A very interesting small workshop called "The connection between non-radial pulsations and stellar winds in massive stars" was held in Boulder, Colorado in 1985 and its summary of review talks appeared in PASP in 1986. In this workshop, Penrod (1986) suggested a model for episodic mass loss in Be stars. Since his results were very important and since my working model presented below basically follows his suggestion, here I summarize his conclusions in what follows. Penrod (1986) observed about 1500 spectra of a sample of 25 rapidly rotating Bn and Be stars. He pointed out in his talk that

1. "all but two of the program stars show obvious line-profile variations due to nonradial pulsation".
2. "The non-emission B stars are each pulsating in one or two short period high-degree ($\ell = 4$ to 10) modes while the Be stars are in all cases pulsating in a long period $\ell = 2$ mode, and usually in a short-period high-ℓ mode as well" (see, also Baade, 1987).
3. "There is no evidence of excessive winds or episodic ejection events in the large-amplitude radial pulsating β Cephei stars, or in the slowly rotating 53 Persei stars, which like the Be stars are energetic long-period $\ell = 2$ pulsators."

He suggested from these observational evidences that "both rapid rotation and a long-period nonradial pulsation mode are essential ingredients of a Be star."

Here we propose a working model for episodic mass loss in Be stars along the line suggested by Penrod (1986). It is a scenario of relaxation-oscillation cycle between Be phase and non-Be phase for a star. In fact, this kind of model is not new but it has existed for more than a decade as Penrod (1986), Osaki (1986), and Ando (1986) proposed models similar to the present model.

Our scenario of relaxation-oscillation cycle of Bn and Be phases goes in the following way.

1. Start of relaxation-oscillation cycle. We begin with non-emission phase in which no disk exists around the star. It is assumed in this model that the B stars in our interest are pulsationally unstable to nonradial g-modes. In fact, it is now well established that hot stars in a wide range of B spectral type are pulsationally unstable to NRP g-modes due to the opacity bump of Fe-peaked elements (Pamyatnykh, 1998).
   In particular, some of NRP g-modes with $\ell = 2$ are assumed to be unstable and grow in amplitude.

2. As (prograde-type) travelling waves of NRP g-modes with $\ell = 2$ and $m = -2$ grow in amplitude reaching some large amplitudes, angular momentum is transported within the star by these NRP modes. As discussed by Osaki (1986), this angular momentum transport occurs usually in a sense that angular momentum is transported from the deep interior to the stellar surface and thus the atmospheric layer is accelerated, if waves are prograde.
3. Ultimately, mass loss will occur from the equatorial region and the rotating disk will then be formed around the equatorial region above the star. As discussed below, mass loss may be driven by *breaking* NRP waves. This corresponds to the Be phase.
4. Once the circumstellar disk is formed around the stellar equator, the outer boundary condition for NRP waves has changed in a sense that NRP waves can leak from the stellar surface into the circumstellar envelope. Leakage of wave energy into the circumstellar envelope leads to damping of NRP waves. Thus the wave amplitudes decrease greatly.
5. Once the NRP waves are damped, the supply of mass and angular momentum to the circumstellar envelope stops, which results in the dissipation of the circumstellar disk. Most of mass and angular momentum of the disk is then accreted back onto the star once more while some small amount of mass will leave the system by carrying away extra angular momentum.

   This corresponds to the end of Be phase and the star returns to the Bn phase. This is the end of the relaxation-oscillation cycle and a new cycle starts by going back to the phase 1.

4 Critical Examination of the Model

Let us now scrutinize this scenario for the Be phenomenon. In particular, following three points must be cleared, in order for this scenario to work.

4.1 Angular Momentum Transport by NRP Waves

Problems of angular momentum transport by travelling-type NRP waves within stars have been discussed by Osaki (1986) and Ando (1986) and it need not be repeated here. In short, if progradely travelling NRP waves are excited in some finite amplitudes in stars, NRP waves can carry both energy and angular momentum from the exciting region to the dissipation region within the star. Since the stellar atmospheric regions usually act as dissipation zone in stellar NRP, angular momentum will be deposited in the stellar atmosphere by progradely travelling NRP waves, which may accelerate the stellar atmosphere toward the break-up velocity.

It may be noted here that Kambe et al. (1993) have found observationally that the stellar rotational velocity in a Be star, λ Eri, increased from $V_{\rm rot} =$

380 km/s in the non-emission Bn phase to $V_{\rm rot} = 480$ km/s during Be active phase.

4.2 Mass Loss from the Equatorial Region

Even if the stellar rotational velocity approaches close to the break-up velocity, we need some extra mechanisms for mass ejection to occur from the stellar surface and to form a circumstellar disk. Here we propose a wave "breaking" phenomenon as one of possible causes for mass ejection. In this picture it is assumed that progradely travelling NRP waves in the stellar equatorial region may attain large amplitudes so that non-linear phenomena become important. The wave breaking phenomenon is one of such non-linear effects.

It is well known in ocean waves that wave breaking occurs when amplitudes of waves become sufficiently large (see, e.g., Kinsman 1965). Figure 1 illustrates schematically the wave breaking phenomenon. It is known that when the wave breaking occurs, matter of the wave crest is detached from the main part of fluid. The condition for wave breaking to occur is known as Stokes criterion in that matter at the wave crest moves with the same speed as that of wave profile (i.e., the phase speed of waves). If the star rotates very rapidly, the additional velocity produced by the wave breaking phenomenon may be large enough for the matter to attain above the Keplerian velocity at the stellar surface and to leave the stellar surface by joining the circumstellar disk. In this picture mass is thrown out not vertically but instead horizontally in the direction of wave propagation (in our case in the direction of rotation) near the stellar equatorial region.

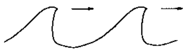

Fig.1. Schematic wave profile when wave breaking occurs. Matter at the very crest moves at the same speed as the wave profile.

We may now understand Penrod's finding why the low-degree modes with $\ell = 2$ is favoured for the occurrence of the Be phenomenon. We note here that the phase velocity of waves is given by $R \times \omega/(-m)$, where R is the radius of the star and ω is the angular frequency of NRP waves and m is the azimuthal order of NRP modes. For a given angular frequency of NRP waves, the largest phase velocity is realized for the lowest order modes. The lowest order modes observed in early-type stars are usually NRP modes with $\ell = -m = 2$.

In this respect, the most interesting observations are those by Rivinius et al. (1998) of μ Cen, a well known Be star. These authors have discovered that emission outburst events occur in μ Cen, whenever the vectorial sum of amplitudes for three NRP modes having closely spaced periods around 0.505 d exceed some critical level by multi-mode beating.

Furthermore these authors (Rivinius et al. 1998) have noted that conspicuous sharp absorption spikes appear close to the line wings, particularly during precursor and early phases of a line emission outburst. This phenomenon could be well understood in term of wave breakings. As seen in figure 1, the NRP wave profiles will then be very steep and almost vertical near the wave crest, that is, they have saw-tooth forms. This means that the wave velocity almost jumps from negative minimum to positive maximum when the wave crest passes. When this wave velocity component is added to stellar rotational velocity, it gives rise to a sharp violet absorption spike near the line wing when the wave crest comes around the stellar limb. As waves propagate over the visible hemisphere, the same feature of absorption spikes will become visible near the red wing after about one-half cycle of oscillation period. Since the wave velocity vector of non-radial g modes is dominantly directed horizontally, these wave fronts are best visible near the line wings. These authors have also noted that "narrow absorption spikes can occur in both the blue and the red wing but are never seen in both wings simultaneously". This indicates that waves of our interest are produced by $\ell = -m = 2$ modes as only one wave crest is seen at any one instance on the visible hemisphere for these modes.

4.3 Damping of NRP Waves in Stars

In order for our scenario of the relaxation oscillation cycle to work, damping of NRP waves must occur before the dissipation of the circumstellar disk. In other words, we need a phase lag between the damping of NRP waves in stars and the dissipation of the circumstellar disk. Otherwise, a kind of steady state could be established in a sense that some low-amplitude NRP waves might be maintained with reduced leakage of wave energy into a remnant circumstellar disk.

The damping of NRP waves is supposed to occur in the dynamical timescale of the star which is on the order of days while if the supply of mass and angular momentum into the circumstellar disk ever stops, the dissipation of the circumstellar disk is supposed to occur in viscous timescale which is on the order of years. Thus we may expect reasonably a time lag between the occurrence of damping of NRP waves and that of dissipation of the circumstellar disk.

5 Circumstellar Disk in Be Stars

As discussed in the previous section, mass is ejected from the equatorial region by wave-breaking to form the circumstellar disk. The disk is basically supported against gravity by the centrifugal force of rotation and therefore its rotational velocity is Keplerian. As mass supply from the star to the disk continues, the matter drifts outwardly in the disk by viscous stresses. Such a disk is called either “decretion disk” or “excretion disk” .

The basic equations describing the decretion disk are basically the same as those of accretion disks which have been studied extensively for cataclysmic variables and X-ray binaries. A question may then naturally arise why a disk behaves sometime as “decretion disk” while sometime as “accretion disk” and what causes this difference. The answer to this question is the difference in boundary conditions !

In order for a decretion disk to be formed, strong torques must act at the inner edge of the disk (which is assumed to extend to the surface of the star). In our case, the NRP waves are supposed to work for this purpose. As travelling-type NRP waves propagate outward into the stellar atmosphere from much denser inner part, wave amplitudes increase and they ultimately begin to break. This wave breaking phenomenon deposit mass and angular momentum in the stellar surface (i.e., at the inner boundary of the decretion disk), which serves for the necessary boundary condition for the decretion disk.

The steady-state decretion disks (or the excretion disks) around Be stars have been studied by Lee, Saio, and Osaki (1991). It must, however, be cautioned here that the steady state decretion disk may never be realized in realistic situations because the viscous timescale is very long of the order of years to decades. The viscous timescale, $t_{\rm visc}$, and the radial drift velocity, v_r, in the decretion disk are estimated as

$$t_{\rm visc} \sim \frac{r^2}{\nu} \sim \frac{r}{\alpha c_s}\frac{r}{h}$$

$$v_r \sim \frac{r}{t_{\rm visc}} \sim \alpha c_s \,(h/r)\,,$$

where r and h are the radial coordinate and the half thickness of the disk, respectively, c_s is the sound speed, and ν and α are the kinematic viscosity and the Shakura-Sunyev viscosity parameter which has been used widely in the theory of accretion disks and it is thought to be $\alpha \lesssim 1$.

The viscous timescale of the decretion disk is estimated to be of the order of years to decades and the the drift velocity is of the order of 1 km/s or less. The matter in the decretion disk therefore drifts outward very slowly and thus the decretion disk model is in a good contrast with the wind-compressed disk model proposed by Bjorkmann and Cassinelli (1993) in which the typical expansion velocity is much higher.

The observational evidence for the existence of Keplerian disks in Be stars is provided by the long timescale variation in V/R ratio in emission lines. Some of Be stars exhibit the V/R variation in which the the intensity ratio of the “violet” and “red” components of double emission lines change quasi-periodically with a timescale of several years. Huang (1975) has shown that this curious phenomenon could be explained phenomenologically by the precessing elliptical ring model in which the disk takes an eccentric ring form with its apsidal line slowly precessing. Physical basis for the formation of the eccentric disk in Be stars has been proposed by Okazaki (1991) who has shown that decretion disks in Be stars may be unstable to non-axisymmetric perturbation of degree $m = 1$ (i.e., one-armed spiral mode) and the disk is then deformed into a lopsided shape.

6 Summary and Conclusion

In this talk, we have discussed a working model for episodic mass loss in Be stars in which a kind of relaxation oscillation cycle may be established between NRP waves in the stellar surface and the circumstellar envelope. In particular, I have proposed wave-breaking of non-radial g-modes as a possible mechanism for mass and angular-momentum injection from the stellar surface to the circumstellar envelope. It is concluded that NRPs could be responsible for episodic mass loss in Be stars.

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Discussion

T. Rivinius: From the peak separation variability we have derived a radial drift velocity of the order of a few km/s.

J. Bjorkman: Is the dissipation zone where you deposit angular momentum by NRPs in the photosphere? If so, to obtain a viscous decretion disk, this zone must rotate at Keplerian velocities. Why then do you not observe evidence for such large rotation speeds in the photosphere line profiles?
Y. Osaki: Yes, it is. I suspect that the equator rotates at break-up speed. One possible explanation for why we do not observe such large rotation speeds might be that the rapid rotation is confined to the equator and matter at higher latitude rotates slower. The line profiles are produced by an average over the whole surface area.

K. Bjorkman: Can you comment on the time scale you expect for dissipation of the disk? And is your proposed cycle expected to be strictly periodic?
Y. Osaki: The viscous time scale depends on the size of the disk. I expect that the viscous time scale is on the order of several years for a disk of several stellar radii. The scenario I presented is an idealised model. In reality, many effects will enter. This gives rise to a quasi-periodic phenomenon.

S. Shore: Might you be able to drive (non-linear) breaking Rossby waves, depending on the rotation law, to drive higher latitude mass loss?
Y. Osaki: I am not able to answer your question. In my talk I discussed mass loss by centifugal acceleration. In such a case, we get a circumstellar ring or disk but not a stellar wind. A ring around the star at high latitude seems rather unlikely to me.