第 15 卷　第 4 期　　天 文 学 进 展　　Vol.15, No.4
1997 年 12 月　　PROGRESS IN ASTRONOMY　　Dec., 1997

Be 星的星周盘模型与 Be/X 射线双星系统

郝　晋　新

（中国科学院北京天文台　北京　100080）

摘　要

介绍了 Be 星的基本特性。评述了近年来对 Be 星星周物质结构研究的成果。重点介绍了最新的关于 Be 星星周盘产生和变化的动力学模型。另外，对 Be/X 射线双星系统的研究也做了简要评述，重点论述了致密星与 Be 星延伸大气的相互作用。

关 键 词　恒星：大气 — 恒星：星周物质 — 恒星：发射线，　Be—X 射线：恒星

Be/X-ray binary system and the disk models of Be stars

Hao Jinxin

(*Beijing Astronomical Observatory, The Chinese Academy of Sciences, Beijing* 100080)

(*Received 1996 April 21, revised 1997 April 22*)

Abstract

The physical properties of Be stars are summarized and recent progress on the study of Be circumstellar materials, especially the new dynamical disk models of Be are reviewed. In addition, the study of Be/X-ray binary system is also reviewed and the focus is taken on the interaction between the compact stars and the Be envelopes.

Key words stars: atmosphere–stars: circumstellar matter–stars: emission line, Be–X-ray: stars

Be stars as a group are important for the study of stellar activities in early-type stars. Be stars are B type stars with hydrogen emission lines in visible wavelength range, usually accompanied by emission lines of singly ionized metals. They are located in the area between main sequence and the giant region in H-R diagram. The study of Be stars began in last century, but at present, it is still an active subject in stellar physics. The motivation of Be star research comes from not only their nature of peculiarity, but also the challenges to our knowledge of Be stars, which arose from more and more observations made in space in far infrared, ultra-violet and X-

---

国家自然科学基金资助项目

1996 年 4 月 21 日收到　1997 年 4 月 22 日收到英文修改稿

ray bands. In this paper, the resent progress in the study of Be stars, especially the envelope of Be star and its new models are reviewed, as well as the work on Be/X-ray binary system.

1 Be Phenomena and the Disk Models of a Be Star's Envelope

As we know, Be stars are characterized by strong emission not only in H_α line, but also in other Balmer lines. The emission lines are believed to be generated in a region outside the classical photosphere which is called envelope. The temperature in the envelope indicated by FeII line is the order of 10^4K, which is lower than the effective temperature of the same spectral type, the density there is the order of $10^{11}-10^{12}$ cm^{-3} and the diameter of the envelope is 5–15 times of the central star. The gas in the envelope is ionized by ultra-violet radiation from the central star and the recombination of these ions can create emission spectra. In fact, a spectrum observed from a Be star is a classical photospherical spectrum overlapped with an emission spectrum from the envelope. When a Be spectrum is compared with a normal B type spectrum of the same sub-spectral-type, we find that they are almost the same except that the Be spectrum has emission lines while the normal B star does not have. Some Be stars can lose their emission features completely and become a normal B type stars. All these seem to indicate that a Be star looks like a geometric combination of a B type star and an envelope surrounding the star. Such a picture of a Be star naturally makes us think that the only difference between a Be star and a normal B type star is the *envelope*. However, when we try to answer the questions, such as, how the envelope forms around a B type star and why only a small part of B type stars have the envelopes while another part never have, we find that almost no answers are satisfied unless we assume some differences between the Be central stars and the normal B type stars. More and more observations as well as theoretical models support the argument that the activities of the central star lead to the formation of the envelope. Some Be stars have the history of phase changes between Be and normal B type star and the time scale is several years to decades. Although the mechanism of Be phenomena is still unknown, we believe that it dominated by the central star itself rather than something outside of the the star. What is the real difference between the central star of a Be system and a normal B type star? This is the basic question that a Be star researcher needs to answer. It is well known that the rotation speed of a Be star is much higher than that of a normal B type star statistically. Basing on this fact, Struve (1931)[1] proposed a model for Be stars. He believed that a Be star is the fast rotator of a B type star. When the rotation velocity reaches its critical value, matter will be ejected at the equator by rotational instability and the equatorial disk or ring will be formed. Thus, the presence of emission lines in the visible spectra of Be stars is the evidence for the existence of an extended atmosphere, whose origin is attributed to the ejection of matter from these stars. This model is still regarded as the fundamental framework of the modern modeling work for Be stars, though the model seems very simple. However, a large amount of the observations in different wavebands show that the structure of the envelope of a Be star is so complicated that we have to take more mechanisms into consideration when we try to model a Be star. What have we seen in the Be stars through the observations?

1.1 The behaviors of a Be star envelope in different wavelength regions

In optical band, wide and double peaked H_α emission line profile with central reverse is usually seen in Be stars. This typical profile is believed to be generated by the circumstellar gas disk with high rotation velocity. This fact is also demonstrated by the recent high resolution, high S/N ratio observations of Balmer and FeII emission lines[2,3,4,5]. These observations indicated that the broadening of the emission lines mainly comes from the rotation of the envelope, and the geometry of the envelope is far from spherical shape. The shape of the H_α emission lines shows very strong evidence of radial movement, which indicated the existence of the outflows in Be stars. But the observed radial velocity of H_α emission region is less than the rotational velocity $150-400\text{km}\cdot\text{s}^{-1}$.

It was the observations in ultra-violet region, which began in 1970s, that greatly changed our knowledge about Be stars. What did we see from the ultra-violet spectra? First, the high ionized resonance lines, such as OVI and NV were observed. The temperature of these lines is 10^5-10^6K, much higher than the effective temperature of B type stars. This phenomenon is called superionization, which evidently indicates the existence of non-radiative energy in the envelope of a Be star. Second, the asymmetry of SiIV, CIV and NV profiles showed that there is an outflow in the envelope and the typical mass loss rate and wind speed are 10^{-10}–$10^{-8}M_\odot\cdot\text{yr}^{-1}$ and 1000–2000 $\text{km}\cdot\text{s}^{-1}$, respectively, which can be obtained by measuring the asymmetry of the line profiles. Third, the observations showed that the strength, shape and displacement of superionized lines from the B type star and Be star of the same sub-spectral-type and luminosity class are different. This means the physical properties of the superionized region in a star cannot be described only with the two parameters, T_{eff} and $\log g$, which are used to classify the stellar photosphere. The last, persistent monitoring of one target showed that strength, shape and displacement of the ultra-violet superionized lines varied with time.

The observations in X-ray band, especially hard X-ray band, provided us with a very efficient way to probe the envelope of Be stars. We have already found many transient X-ray sources which were believed to be binary systems with Be stars as optical primaries and compact stars, such as neutron stars, as the companion stars moving in elliptical orbits. When the compact star is moving close to the peri-astron point, where the distance to the Be primary is the shortest, the materials of the envelope are strongly accreted by the compact stars and X-ray radiation erupts. Obviously, to study the X-ray behavior of binary systems is a way to know the physical condition of the envelope, such as the density and velocity. The study of Be/X-ray system will be reviewed in detail in the late part of this paper. In soft X-ray band, the observations provide us with much information about the temperature structure of the superionized regions in the envelope because some of the high energy resonance lines can be observed in the wavelength shorter than far ultra-violet.

In infrared (IR) wavelength, the most notable feature is the IR excess, which can be detected in the wavelength longer than Balmer jump. The IR excess is usually believed to be formed by free-

free and free-bound radiation in the envelope. Since the opacity of such radiation is proportional to the wavelength with power 2, $\kappa_\nu \propto \lambda^2$, the optical depth increases redward, so does the IR excess[6]. The wavelength dependence of the IR excess allows the determination of the radial structure of the high-density material: the steeper the density gradient, the smaller the increase of the IR excess with wavelength. This method was applied to 7 Be/X-ray binaries by Waters *et al.* (1988)[7], who determined the gas density near the surface, ρ_0 as 10^{-11} g·cm^{-3} and the power index, n as $3-3.25$ for the power-law density distribution $\rho(r)=\rho_0(r/R_*)^{-n}$, where, r is the distance from the center of the star and R_* is the radius of the central star. But this result is only valid in the area close to the equator within $r<2-8R_*$ due to the limited length of IR band we can cover in the ground base observations. It should be known that some Be stars with forbidden emission lines have such a large IR excess that we cannot use only the free-free radiation to interpret it. For this kind of stars, we have to introduce a cold dust shell far away from the central star. The dust particles absorb the optical radiation from the central star and re-emit in longer wavelength. The temperature there is the order of 10^3K. The development of the infrared detector techniques makes it possible for us to use high resolution, high S/N ratio near and medium infrared spectrograph to observe the combination lines of HI and HeI of Be stars. These lines are distributed in a very wide spectral range and the differences of the strength among them are quite large. Since these lines probably come from different layers of the envelope, the observation of these lines is an important way to study the global envelope. Furthermore, we can use these lines to study the property of the envelope emission very well because the contributions of photospherical absorption to these lines are very small. However, the observation of Br γ lines from ψ Per and 59 Cyg showed that the profiles of these lines do not agree with the optical thin Keplerian disk model of Be envelope.[8]

In 1970s, only those Be stars with forbidden emission lines were detected to have radio radiation. We can derive that the diameter of their dust shell must be very huge, otherwise the radio radiation cannot be detected. The radius of the dust shell is estimated to be several hundreds to thousand times of the radius of the central star. In recent years, some of the IRAS-bright Be sources were detected to have radio radiation with the improvement of sensitivity of sub-millimeter and radio telescopes. The observations showed that, in almost all cases the spectral index found from the radio measurements was larger than 1, which was significantly steeper than that from IRAS 12 to 60 μm data, which is normally between 0.6 and 1. We realized that the steep radio spectra of Be stars do not agree with the behaviors of the stellar wind which blows from the stellar surface and finally reaches its terminal speed under the force of the radiation. Wright & Barlow (1975)[6] pointed out that the spectral index of a spherically symmetry or disk-like outflow should be 0.6 which is much smaller than that of the observed values. The mechanism of the steep radio spectral index is still unknown. Taylor *et al* (1990)[9] gave some possible explanations, such as the recombination, re-acceleration or the geometric changes of the circumstellar matter at large distance from the star.

Overall, the observations from different wavelengths presented a very complicated global picture of Be star envelope. In the envelope, there are not only radiatively heated but also nonradiatively heated regions, and not only outflows with high velocity and low density, but also those of low velocity and high density. It is a challenge to construct a general dynamical model for Be stars, in which all these phenomena are well considered.

1.2 The variability of Be stars

Generally speaking, all Be stars are variables. In early years, the observations of Be stars were only confined to optical wavelength and they showed that the line profiles of Be stars varied with time. The variation of Balmer lines in visible range is the most notable feature of Be stars. The spectra of some Be stars underwent so called *phase change* among Be, shell and normal B type phases during years to decades. Besides such severe variations, the usually observed features are the variabilities of the emission intensity, the shape of the line profiles, V/R ratio and the radial velocity. There have been a large number of papers published concerning such variability of Be stars. Since 1970s, it has been discovered from high precision photo-electric photometry that most of Be stars are also light variables. There were not only long time scales, such as years to decades, but also short term variations, like hours to days, found with amplitudes smaller than 0.1mag in Be stars. When our research wavelength was extended to ultra-violet band, we found that the variability is such a universal feature in this type of stars that any general model of Be stars must include the mechanism of variability. Of course, the popularity of variability does not belong to Be stars only, but almost all the emission line stars are variables. The study of variability of Be stars began in last century. Since then, a large amount of data concerning the variations of Be stars have been accumulated, based on which our knowledge of the variability of Be stars increases enormously , even though we have not yet drawn out any general law about this property of Be stars. It is difficult to give any prediction for the future variability of some Be stars even we know the details of their variation histories due to the irregularity of the whole group and the peculiarity of the individuals. Since most of the observations were carried out in optical wavelength, it is difficult to obtain a global picture of the variability of Be stars unless a star was observed in various wavebands simultaneously, from X-ray to radio, so that the behaviors of the photosphere and every layer above were well studied. Anyway, the behavior of a star in optical range is usually a criterion which is used to judge if the star is normal or abnormal. There have been a large amount of published materials concerning the variability of Be stars, especially in optical range. We do not intend to dwell on this subject in this paper. The reader can refer to references [10,11,12,13] and other relevant publications.

1.3 The models of Be envelope

As we know, the study of Be stars has a long history. What is the status of the theory of Be phenomenon and modeling of Be stars? The answer can be found in the book, B STAR WITH AND WITHOUT EMISSION LINES (Underhill & Doazan 1982)[14]: There is no Be theory at present time since the mechanism of Be phenomenon is still unknown. During the following decade, much progress has been made. But it is still a long way to go to establish a general model of Be stars. Anyway, we have obtained a series of observations in different periods and different wavebands for different objects, based on which some theoretical and empirical models have been established. The picture of Be stars becomes more and more clear. To know the details of the progress, the reader is suggested to refer to two IAU Symposia, Slettebak and Snow (1987)[12] and Balona *et al* (1994)[10].

Struve was the first person who tried to model Be stars. He proposed the fast B type rotator model to interpret Be phenomenon. In his model, Struve tried to answer the following two questions:

(1) in what region are the emission lines in visible wavelength created, and

(2) how does this region form?

We know that a general model of a Be star has to answer many other questions besides these two. But they are so crucial that any modeling work for Be stars cannot avoid them. According to the classical theory of stellar atmosphere, the emission lines seen in visible range must be generated somewhere outside of the photosphere. In fact, the first question was well answered under the framework of the theory of stellar photosphere. It was on the second question that several models were proposed. By the end of 1980s, all the models were thought to be ad hoc because the physical condition adopted in these models is ad hoc or the dynamics of the envelope is not well considered. We do not plan to review these models here. In this section, we dwell on the structure of the Be stars directly derived from observations and review the new dynamical models of Be stars which appeared in recent years.

1.3.1 Morphology of Be star envelope

Basing on Struve's model and the observations by the end of 1970s, Underhill & Doazan (1982)[14] proposed a gross empirical model of the structure of Be envelope. In fact, this model is a restriction of the modeling work on Be stars rather than a model itself, because each possible component proposed in the envelope is completely derived from the observational facts without any dynamics in it. According to this model, the atmosphere of a Be star should include the following layers from inner to outer,

1. A PHOTOSPHERE, characterized by hydrostatic equilibrium and radiative equilibrium. T_{eff} ranges from 3.5×10^4K to 1×10^4K.

2. A CHROMOSPHERE, defined by a rise in electron temperature, T_{e} coming from non-radiative heating. In this region, the density distribution is in quasi-static, hence in hydrostatic equilibrium.

3. A CORONA, characterized by T_{e} increasing outward, but in this region, the density distribution is in dynamic equilibrium instead of quasi-static one.

4. A POST-CORONAL TRANSITION REGION between the hot, rapidly moving corona and the cool, slowly moving region demanded by the Balmer and FeII observations.

5. The COOL EXTENDED ENVELOPE where most of the contributions to the Balmer emission lines arise. Flow velocity is less than some 100 km·s^{-1}. T_{e} lies in the range of 0.5 to 2.0×10^{4}K.

6. A COOL SHELL above the cool Balmer emission envelope, where are formed the narrow,

deep absorption cores of hydrogen and FeII lines. In its outer regions, the low excitation, forbidden lines may arise. These stars are called forbiden line Be stars, denoted as B[e]. So concentrations have dropped to some $10^5\mathrm{cm}^{-3}$. Velocities and T_e are lower than those in region (5).

7. For Be, symbiotic, nova, and possibly other similar stars, but not the conventional Be stars, we have possibly a dust shell, T_e would be of the order of 1 to 2×10^3K.

It should be noted that the model proposed by Underhill & Doazan (1982)[14] is only a morphological description of the atmospherical structure in Be stars. It is by no means a dynamic model. All the layers of the atmosphere are neither spherical nor co-existing all the time. In fact, more and more observations indicated that the envelope is disk-like instead of spherically shaped, while, there are not only the radial but also lateral gradients in some physical quantities within or between layers. Although the size of the lateral gradients are relatively small to the radial ones, the physical mechanism of these gradients is also important to our understanding of Be phenomenon. We should also be aware that some layers proposed in Underhill & Doazan's model actually appear and disappear alternatively in real Be stars. That is why Be stars are characterized with variabilities. Based on the recent observations and studies in optical and infrared ranges as well as a new dynamical model for Be stars, so called Wind-Compressed Disk model (WCD), a geometric model of Be stars shown in Fig.1 was proposed by Waters & Marlborough (1994)[8]. We find that this model is still within the frame given by Underhill & Doazan even though the cool extended atmosphere is disk-concentrated. In this model, the layer that generates H_α emission lines is a thin equatorial disk. The cool shell which is needed by shell stars is a ring outside the disk, but with a larger open angle than that of the disk. It seems that the geometry of a Be star model is so far best described by the model shown in Fig.1. The problem is how to establish the dynamics for such model.

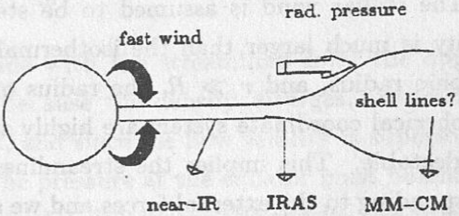


Fig.1 A possible geometry of Be star discs. Near the star the disk is thin and confined because of the collimating effect of the polar wind. At some distance the disc flares (not necessarily to the same thickness as the stellar radius) and the gas is accelerated radially by the strongly forward peaked radiation field.[8]

1.3.2 Wind-Compressed Disk model of Be stars

The most important step to find out the mystery of Be phenomenon is to discover the mechanism of the formation of the envelope. More and more people believe that the envelope forms due to the combined effects of rotation, pulsation, stellar wind, and probably magnetic field. The Wind-Compressed Disk model (WCD) proposed by Bjorkman & Cassinelli (1993)[15] is a dynamical model with rotation and stellar wind as the mechanism to explain the formation of the equatorial disk around the Be stars. This is the first dynamical model to interpret the existence of gas disk around Be stars with the well known properties of early type stars.

WCD model predicts: when the rotation velocity is greater than the threshold, a dense and geometric thin gas disk will form around a fast rotating B type star with stellar wind driven by radiation. Obviously, WCD model provided a physical mechanism of the formation and maintenance of the stellar disk which is badly needed by geometric models, while, the mechanism employed by the model is based on the general condition of Be stars instead of some ad hoc assumptions. In this point, WCD model contributed a critical step to the progress of modeling work in Be stars.

The stellar wind is assumed to be steady-state and isothermal. Generally, the rotation velocity is much larger than the isothermal sound speed of the wind. So, as long as $r \gg r_s$, the sonic radius, and $r \gg R$, the radius of the central star, all three velocity components in the spherical coordinate system are highly supersonic. Then, the pressure gradients of the wind is neglectable. This implies the streamlines of the wind are actually free particle trajectories corresponding to the external forces and we simply integrate Newton's equations of motion using gravity and radiation for the forces to determine the location of the streamlines. Two-dimension model calculation shows that the streamlines of a non-rotating star are entirely radial because both the radiative pressure and the gravity are of central forces. For a rotating star, we have to introduce centrifugal force in the hydrostatic equilibrium on the stellar force. When the centrifugal support is large enough, there is a region, at low latitudes near the surface of the star, where the acceleration of gravity is larger than the radiative acceleration. Within this region, the fluid streamlines which start from the stellar surface must fall toward the equatorial plane. Near the pole, the rotation velocity is small, the streamlines only go toward the equatorial plane for a very short distance, then, they become radial under the force of the strong radiative pressure. Near the equatorial region, the rotation velocity is very large, thus, the region where the gravity acceleration is greater than the radiative acceleration is large. So, it is a long way for the streamlines to fall down toward the equatorial plane after they become radial eventually.

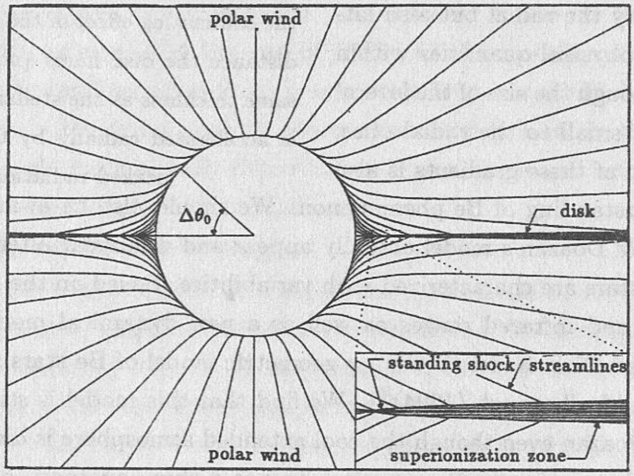


Fig.2 Diagram of the stellar wind and wind-compressed disk. Shown are the wind steamlines, which fall toward the equator. The expanded view shows the standing shocks that form above and below the disk.[15]

When such a region is large enough, the streamlines from the two hemispheres of the star can collide on the equatorial plane as shown in Fig.2. When the rotation velocity V_{rot} is greater than the threshold V_{th}, for latitudes less than $\Delta\theta_0$, the streamlines attempt to cross the equator. The equator crossing latitude, $\Delta\theta_0$, is approximately given by

$$V_{\text{rot}} \cos \Delta\theta_0 \sim V_{\text{th}}$$

When the streamlines cross the equator, they collide with the streamlines from the opposite hemisphere of the star. Streamlines cannot cross because the density diverges. Instead, the increase in density leads to a large pressure gradient, and since the flow velocity is supersonic, a pair of shocks form above and below the equator. The pressure at the equator must balance the ram pressure of the wind, so there is a dense equatorial disk between the shocks. Additionally, the shock temperature is so large (a few 10^5K) that the disk is bounded by a thin superionization zone. Note that this disk forms only when the star is rotating faster than the equator-crossing threshold.

The disk formation threshold depends on the ratio of the terminal speed of the wind to the escape speed of the star, V_∞/V_{esc}. This is because V_∞ is the scale of the wind speed, while V_{esc} depends on gravity. If the gravity is fixed, implying that V_{esc} is a constant, the region where the streamlines fall down to the equatorial plane becomes small with the increasing radiative pressure which leads to the increasing V_∞. To compensate the rotation velocity, V_{rot} of the star should increase so that the streamlines within the latitudes $\Delta\theta_0$ can fall down toward the equator plane.

To assess the validity of the WCD approximations and examine in detail the dynamics of the disk, Owocki, Crammer & Blondin (1993)[16] developed a 2-D time dependent numerical simulation of the wind from a rotating star. This work confirms the results predicted by WCD model. When the rotation velocity is greater than the threshold, an equatorial gas disk forms, which density is about two orders of magnitude higher than that at the pole. This simulation also shows that a weak disk is maintained even at rotation rates below the rotation threshold. In addition, the results show that there is a stagnation point in the disk. Exterior to the stagnation point, the material flows outward. Interior to the stagnation, the material falls back onto the stellar surface. Thus, there is an outflow and inflow in the disk simultaneously.

The shock temperature of WCD model depends on the shock speed, which is approximately the θ component of the wind speed. The simulation showed that the typical value of the shock temperature is a few 10^5K. This temperature is high enough to generate highly ionized spectral lines such as CIV and SiIV by collisional ionization. The faster the stellar rotation, the higher the shock temperature and the higher the ionization state. Besides the shocks which appear with the formation of the disk, there is also an accretion shock in the equator at the surface due to the disk inflow. The typical value of the inflow velocity is a few hundred km·s^{-1} and the temperature of the accretion shock is a few 10^6K, which is high enough to produce soft X-ray radiation. It is just the appearance of such shocks that makes us observe more superionizations in Be stars than in normal B stars.

However, as many other ad hoc models, WCD also has a lot of difficulties on the description of some properties in Be stars. These difficulties are summarized as follows:

(1) The predicted density is two orders of magnitude lower than that of the observation.

(2) The structure of the inflow and outflow in the disk given by WCD is somewhat different from that derived from optical line profile and infrared HI combination line observations.

(3) The open angle of the disk given by WCD is only about 1°, this means the infrared excess produced by the disk highly depends on the angle of the stellar rotation axis. But no observing evidence indicates a relation between the infrared excess and the angle of rotation axis.

(4) WCD model is also difficult to explain the shell stars due to the too small open angle of the disk.

(5) There is no mechanism in the static WCD model to explain the variabilities which is characterized by Be stars.

We may draw conclusion from the limitation of WCD model: The outflow of the material from the stellar surface driven by stellar wind is a possible mechanism, but probably not the unique one. So, we have to consider other mechanisms which cause the outflow of the material or lead to the larger scale disk formation to compensate the weakness of WCD. In addition, we have to construct a non-static model to explain the Be phenomena, such as phase changes and V/R variations.

1.3.3 One-armed oscillation equatorial disk model of Be stars

We noted that WCD model cannot explain the variability which is characterized by Be stars. This drawback was compensated by one-armed disk oscillation model which was proposed by Okazaki (1991)[17] to explain the long term variability in Be stars. According to the theory of oscillation of Keplerian disk, only very low frequency one-armed oscillation (non-radial pulsation with $m = 1$) of the global disk is unstable[18]. Such oscillation is actually the periodical variation of the density distribution caused by density wave. This variation leads to the periodic V/R changes which we usually observed on Be stars. Unlike the WCD model, which tried to discover how the stellar disk forms around Be stars, one-armed oscillation disk model told us why and how the disk varies with time, though the model is still a simple one. Anyway, Okazaki's model gives us some qualitative explanations to the V/R variability in Be stars. This model is successful in the following aspects:

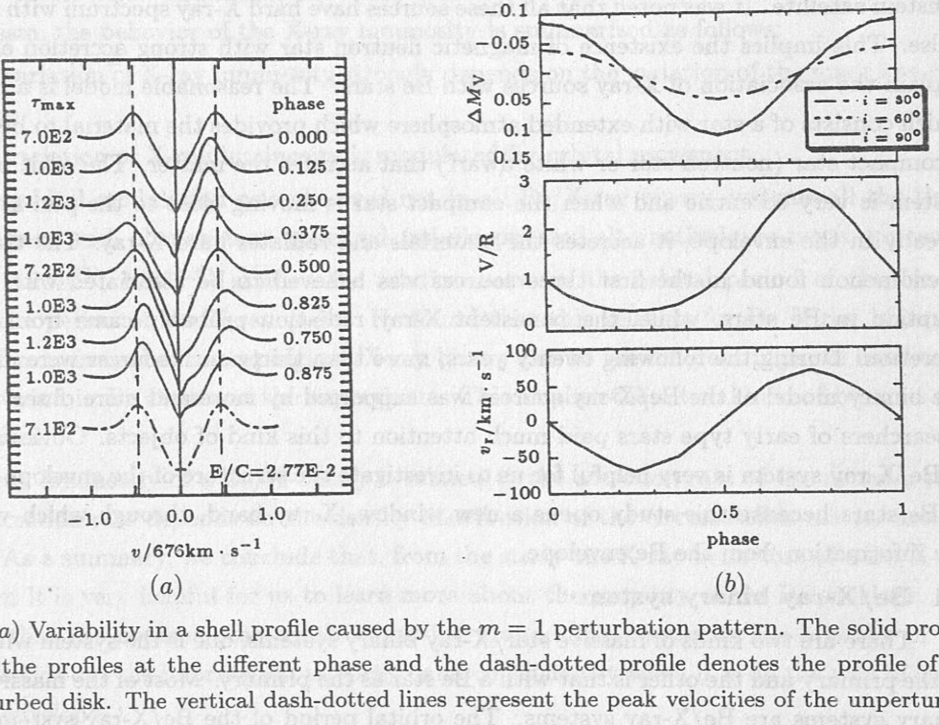
(1) The time scales of the fundamental and the first harmonic oscillations predicted by the model are years or decades. These time scales are the same as the observations.

(2) For the given basic parameters of the disk, the calculated oscillation periods are not sensitive to the spectral type of the central star in Be system. This result agrees with the observations.

(3) The calculated line profile variation based on eigenfunctions also agrees with the observations. This has been confirmed by Hummel & Hanuschik (1994)[19].

The disk is assumed to be isothermal and axis-symmetry. The oscillation is also isothermal. The radial advective motion and viscous effects are neglected. The model calculation shows that the oscillation period of the disk is the function of the radius for a given exponential index of density distribution. This implies if we think the physical condition of the model we used is close enough to that of the real disk we are studying, we can estimate the radius or the density distribution of the disk. Okazaki (1994)[20] calculated the variations of the shell line profiles, the continuum flux, V/R and the radial velocity caused by fundamental one-armed oscillation for a model with B0 type star as the central star, the radius as ten times as that of the central star and the density distribution as $\rho(r) \propto r^{-3}$. These simulated variations are shown in Fig.3. We find that such kind of variations are often seen in Be stars. It seems that not only the long term V/R variability but also long term light variation can be interpreted with one-armed oscillation disk model. These results are very interesting because the long term light variation with amplitude of several tenths of magnitude were commonly observed in Be stars, but the mechanism is still unknown. If one-armed oscillation model works, we can attribute such variation to the oscillation of the disk instead of the central star itself. Of course, only the periodic or quasi-periodic variation can be explained with such mechanism.

In order to test this model further more, Okazaki (1991)[17] gave two predictions of one-armed disk model.



(a)　　　　　　(b)

Fig.3 (*a*) Variability in a shell profile caused by the $m = 1$ perturbation pattern. The solid profiles denote the profiles at the different phase and the dash-dotted profile denotes the profile of the unperturbed disk. The vertical dash-dotted lines represent the peak velocities of the unperturbed profile. For each profile, the line optical depth, $\tau_{\max}$, is given. Also given is the ratio of the peak intensity to the continuum level, E/C. (*b*) The correlation between the continuum variability and the V/R variation. The panels exhibit, from top to bottom, the magnitude of the continuum variability, the V/R ratio, and the radial velocity, respectively. In the top panel, the solid, dashed, and dash-dotted curves denote variabilities for $i = 90°, 60°$, and $30°$, respectively.[20]

(1) V/R variation has multiple periodic because the disk oscillates in not only the fundamental but also harmonic frequency.

(2) The line profile variation of low-order Balmer lines lag by about one year behind those of line emitted in an inner portion of the disk, when the oscillations are excited near the star/disk interface and still in a transient stage.

However, it is difficult to test the prediction (1) because the multiple- periodicity can only be derived from the well covered data with high quality.

2 Be/X-ray Binary System and the Circumstellar Materials

Be/X-ray binary system as a group was proposed by Maraschi *et al.* (1976)[21]. There were only four objects at that time. The first three, A0535+26, A1118-61 and 4U1145-61 are strong transient X ray sources with pulse. Within the error boxes of the positions of these objects, there are Be stars as the most luminous optical counterparts. The last one is a weak X-ray persistent source, which is very close to the Be star X Per. Of course, the counterparts of all the four sources need to be confirmed at that time because of the poor accuracy of the pointing of Einstein satellite. It was noted that all these sources have hard X-ray spectrum with regular X-ray pulse. This implies the existence of magnetic neutron star with strong accretion effect. How to explain the association of X-ray sources with Be stars? The reasonable model is a binary system which consists of a star with extended atmosphere which provides the material to be accreted and a compact star (neutron star or white dwarf) that accretes the matter. The orbit of such binary system is very eccentric and when the compact star is moving close to the peri-astron which is already in the envelope, it accretes the materials and radiates hard X-ray. The transient X-ray phenomenon found in the first three sources was believed to be associated with the irregular eruption in Be stars, while, the persistent X-ray radiation probably came from the wind-fed accretion. During the following twenty years, more than thirty such sources were discovered and the binary model of the Be/X-ray sources was supported by more and more observations. Many researchers of early type stars paid much attention to this kind of objects. Obviously, the study of Be/X-ray system is very helpful for us to investigate the structure of the envelope and the wind of Be stars because this study opens a new window, X-ray band, through which we can obtain the information from the Be envelope.

2.1 Be/X-ray binary system

There are two kinds of massive star/X-ray binary systems, one is the system with an OB star as the primary and the other is that with a Be star as the primary. Most of the massive star/X-ray binary systems are Be/X-ray systems. The orbital period of the Be/X-ray system ranges from 16.6d to a few hundred days and the eccentricity is about 0.3 to 0.4. The primary star is a fast rotator of near main sequence Oe/Be star with luminosity class III-V. The companion star is usually a neutron star, which accretes the materials from the Oe/Be star and radiates X-ray. The radius of such system is usually too large to form the Roche stream. This kind of binary systems are believed to be the products of the evolution of the close binary systems. The original massive star in a close binary system evolves and leaves from the main sequence. Then it becomes a helium star after the first stage of mass loss. At the same time, the companion star rotates faster and faster due to the accretion of the matter and angular moment from the massive star. After the second stage of the mass transport, a new binary system, which is called Be/X-ray system, appears when the helium star explodes and eventually becomes a neutron star and another one evolves to early type massive star.

A large amount of the observations show that Be/X-ray binary systems are characterized with many distinctive behaviors. The most notable feature is the very high X-ray luminosity and its variability. The value of the luminosity is almost equal to the Eddington luminosity limit of the neutron star sometimes. We can obtain the mass loss rate from the observations in the ultra-violet band. Then, we can derive the X-ray luminosity from the mass loss rate. The result agrees with the observed X-ray luminosity. According to our understanding of morphology of Be envelope, it is disk concentrated. In the equatorial region, the wind is dense but the velocity is much smaller than that we observed in the pole region of the star, where the wind is much less dense but with high speed. If the neutron star is fed with the equatorial wind, its X-ray luminosity is very large. If the pole wind is fed, the X-ray luminosity should be quite low. Dominated by such mechanism, the behavior of the X-ray luminosity is summarized as follows:

(1) The variation of X-ray luminosity strongly depends on the variation of the mass loss rate from Be stars.

(2) The variation of X-ray luminosity is modulated by orbital movement.

(3) The orbital modulation was observed not in all Be/X-ray binary systems all the time. For some of them, such phenomenon appeared and disappeared alternatively, or never appeared.

Corbet (1984[22], 1986[23]) studied the relation between the orbital period of the binary system and the period of the X-ray pulse. He found that this relation for Be/X-ray binary is evidently different from that for supergiant/X-ray binary due to the different physical conditions of the stellar wind in Be stars and the supergiants. This implies these two kinds of binaries can be distinguished.

The X-ray luminosity of a Be/X-binary is related to the accretion rate of the neutron star, while, the accretion rate depends on the density distribution of the circumstellar matter around the Be star. As a summary, we conclude that, from the study the X-ray behaviors of a Be/X-ray binary system it is very helpful for us to learn more about the property of the Be envelope. We can imagine that the neutron star which is moving around the Be star is like a probe of the envelope. It sends out the information in X-ray band continuously when it is on the way of going through the envelope.

2.2 The interaction between the compact star and the circumstellar matter around Be stars

Through the study of the relation between the optical and X-ray behaviors of the Be/X-ray binary systems, van den Heuvel & Rappaport (1987)[24] found that, when the Be star is in an active phase, the X-ray source is ignited. During the whole active period of the Be star, the X-ray burst can be observed in case the compact star is moving toward the peri-astron point in the orbit. So, the transient X-ray phenomenon is actually caused by the orbital modulation. The Be/X-ray binary system V0332+53=HDE 245770 is typically characterized with such modulation. In the phase of the X-ray burst, its X-ray luminosity can reach $10^{37}-10^{38}\mathrm{erg{\cdot}s^{-1}}$. The strong X-ray radiation heats the extend atmosphere of the Be star and the additional optical emission is generated. This phenomenon was evidently observed in another source A0538-66, which optical luminosity increased 2.5mag during its X-ray burst. In addition, the X-ray heating can accelerate the mass loss of the Be star and the strong gravity of the compact star may change the physical condition of the circumstellar matter around the Be star, such as the symmetry, the velocity field etc. The optical activities we have observed during the strong X-ray burst are just the combined effects of these changes. However, it is difficult for us to describe such procedure precisely due to the complicated interaction between the compact star and the circumstellar matter around the Be star. We can estimate some important parameters of the Be envelope using some simple models.

The typical value of the radius of a neutron star is 10km, which is much smaller than the scale of a Be envelope. If the density in the wind at the position of the neutron star is denoted as ρ, and the relative velocity of the gas with respect to the neutron star is v, the accretion rate of the neutron star can be expressed as $M_{\mathrm{acc}} \propto \rho v^{-3}$. Since the X-ray luminosity L_{X} is proportional to the accretion rate M_{acc}, we have $L_{\mathrm{x}} \propto \rho v^{-3}$. This implies the X-ray luminosity is much more sensitive to the relative velocity, v, than to the density of the accreted wind, ρ. The smaller the velocity, the higher the X-ray luminosity. In principle, the velocity of the wind can be derived from the X-ray luminosity in case the density of the wind is known. Such kind of work was done by Waters *et al.* (1989)[25] who estimated the velocity of the circumstellar materials for seven Be stars. He obtained the density of the circumstellar matter from the infrared observations. Then he calculated the X-ray luminosity for the high speed (1000–2000km·s^{-1}) and low speed (200–500km·s^{-1}) wind, respectively, and compared them with the observed values. He argued that the wind accreted by the compact star is the low speed wind. Since the compact star should be very close to the equator plane of the Be star when it is at the peri-astron, we derive that the velocity of the equatorial wind is low. So, this result supports the disk-like envelope model of the Be star.

Waters (1989)[26] carried out the model calculations to study the variation of X-ray luminosity in Be/X-ray binary systems. He found that, if the wind speed of the Be star is low, the X-ray luminosity is high and the effect of the orbital modulation is weak. This conclusion was strongly supported by the observations of the source V0332+53, which showed that there was no orbital modulation detected during the large X-ray burst in 1973, but the orbital modulation appeared during 1983–1984, when the intensity of the X-ray burst decreased 20 times. This means the orbital modulation effect is a measurement of the wind speed of the Be star in the binary system.

The curiosity of astronomers to the early- type emission stars arose more than one hundred years ago, when an Italian person named Angelo Secchi, at the first time, pointed his telescope to the Be stars. With the great development of astrophysics in the twentieth century, we have been learning more and more about the various physical procedures which are taking place in the stars. However, the Be phenomena, as one of the basic activities in early type stars, are still unknown for us even though these phenomena are very important for the study of stellar activity. This is just the reason why the study of Be phenomena lasts so long time and this subject is still active in stellar physics. By our knowledge about the Be phenomena, we believe that it is difficult to use a simple physical procedure to describe these phenomena very well. The Be phenomena are probably the products of the combined effects of several physical procedures, such as the stellar wind, rotation, pulsation, magnetic field etc. This view point is not only supported by the observations, but also indicated by the new theoretical model, WCD, which shows that the disk around the Be star formed by the co-effect of the stellar wind and the rotation is not large and dense enough to fit the observations. New models with more mechanisms being considered are expected.

As the summary, we want to stress that the difficulties of the Be star study are in two aspects. For the observations, we have no enough data to study the relations between the Be phenomena and some physical procedures which is taking place in the Be star, for example, we do not know how the low l number g mode non-radial pulsations found in the Be star are related to the Be phenomena and how large the contribution of the stellar magnetic field is to the mass loss of the Be star. In the aspect of modeling work, there is no theoretical basis for us to take stellar wind, rotation, pulsation and magnetic field into consideration simultaneously. We even have no nonlinear nonradial pulsation theory at present time. But these difficulties are just the future research subjects to which much attention should be paid.

References

[1] Struve O. Ap. J., 1931, 73: 94

[2] Dachs J, Hanuschik R W, Kaiser D *et al.* Astron. Astrophys., 1986, 159: 276

[3] Dachs J, Hummel W, Hanuschik R W. Astron. Astrophys.Suppl., 1992, 95: 437

[4] Hanuschik R W. Astron. Astrophys., 1987, 173: 299

[5] Hanuschik R W. Astrophys. Space Sci., 1989, 161: 61

[6] Wright A E, Barlow M J. M.N.R.A.S., 1975, 170: 41

[7] Waters L B F M, Taylor A R, van den Heuvel E P J *et al.* Astron. Astrophys., 1988, 198: 200

[8] Waters L B F M, Marlborough J M. In: Balona L A, Henrichs H F, Le Contel J M eds. Pulsation, rotation and mass loss in early-type stars, Proc. of IAU symp. No.162, Juan-les-Pans, France, 1993, Dordrecht: Kluwer, 1994: 399

[9] Taylor A R, Waters L B F M, Bjorkman K S *et al.* Astron. Astrophys., 1990, 231: 453

[10] Balona L A, Henrichs H F, Le Contel J M. Pulsation, rotation and mass loss in early-type Stars, Proc. of IAU symp. No.162, Juan-les-Pans, France, 1993, Dordrecht:Kluwer, 1994

[11] Slettebak A, Snow T P. Physics of Be stars, Proc. of IAU colloq. No.92, Boulder, Colorado, USA, 1986, Cambridge: Cambridge Univ. Press, 1987

[12] Jaschek M, Groth H-G eds. Be stars, Proc. of IAU Symp. No.98, Munich, 1981, Dordrecht: Reidel, 1981

[13] Baade D *et al* eds. Rapid variability of OB-stars: Nature and diagnostic value. Garching: ESO, 1990

[14] Underhill A, Doazan V. B stars with and without emission lines, NASA SP-456, 1982

[15] Bjorkman J E and Cassinelli J P. Ap. J., 1993, 409: 429

[16] Owocki S P, Cranmer S R, Blondin J M. Ap. J., 1994, 424: 887

[17] Okazaki A T. Publ. Astron. Soc. Jpn., 1991, 43: 75

[18] Kato S. Publ. Astron. Soc. Jpn., 1983, 35: 249

[19] Hummel W, Hanuschik R W. In: Balona L A, Henrichs H F, Le Contel J M eds. Pulsation, rotation and mass loss in early-type stars, Proc. of IAU symp. No.162, Juan-les-Pans, France, 1993, Dordrecht: Kluwer, 1994: 382

[20] Okazaki A T. In: Balona L A, Henrichs H F, Le Contel J M eds. Pulsation, rotation and mass loss in early-type stars, Proc.of IAU symp. No. 162, Juan-les-Pans, France, 1993, Dordrecht: Kluwer, 1994: 380

[21] Maraschi L, Treves A, van den Heuvel E P J. Nature, 1976, 259: 292

[22] Corbet R H D. Astron. Astrophys., 1984, 141: 91

[23] Corbet R H D. M.N.R.A.S., 1986, 220: 1047

[24] Van den Heuvel E P J, Rappaport S. In: Slettebak A, Snow T P eds. Physics of Be stars, Proc. of IAU colloq. No.92, Boulder, Colorado, USA, 1986, Cambridge: Cambridge Univ. Press, 1987: 291

[25] Waters L B F M, Taylor A R, van den Heuvel E P J *et al.* Astron. Astrophys., 1988, 198: 200

[26] Waters L B F M. In: Hunt J, Battrick B eds. Proc. 23rd ESLAB symp. on two topic in X-ray astronomy, Bologna, Italy, 1989, ESA SP-296, 1989: 25