V. ROTATION AND BINARITY

ROTATION, EXPANSION AND DUPLICITY OF Be STARS

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1. INTRODUCTION

In recent years there is a general tendency to divide Be stars into different groups. Bidelman's (1976) division on supergiants, rapidly rotating single stars, interacting binaries, early type nebular variables and quasi (or young) planetary nebulae is often quoted. Another example is the classification by Lesh (1968) or a very recent classification by Jaschek et al (1980), limited a priori to "normal" Be stars i.e. stars of luminosity classes V to III. I do not think such an approach is recommendable. There is still no general agreement as to the nature of the Be phenomenon and all such classifications must be more or less descriptive. The possibility that the hydrogen emission observed in the spectra of apparently very different objects has always the same physical cause, and that the differences between these objects are caused only by continuously varying physical and/or geometrical parameters should seriously be considered, along with all other concepts. At the moment, I find it more promising to study Be stars in context of all early type emission objects, including supergiants, P Cyg stars, Beta Cep objects, WR stars, symbiotic stars and novae. Such a viewpoint is not new - - it was expressed already by Struve (1942).

Let us consider the case of supergiants in particular. Little is known about their long-term spectral variability. However their RV and photometric variations do seem to be rather similar to what is observed for Be III-V stars (c.f., e.g. Sterken 1977, Sterken and Wolf 1978 or Rufener et al 1978). Excluding the supergiants from considerations leads from time to time even to inconsistencies. In many catalogues, the c prefix of the spectral type is quoted from older sources and may refer to the shell spectrum of a Be III-V object. Thus, considering the above-mentioned facts, I prefer to let the subject of this study somewhat "undefined".

Until now, many different models have been suggested, or even computed, to explain various specific aspects of the Be phenomenon.

M. Jaschek and H.-G. Groth (eds.), Be Stars, 279-297.

Yet, as far as I know, there are only three general conceptions attempting to explain the Be phenomenon in its complexity:

1. The rotational hypothesis proposed originally by Struve (1931),
2. The hypothesis of radial outflow of matter, first suggested by Gerasimovič (1934), and
3. The binary hypothesis, formulated in a general way by Kříž and Harmanec (1975).

Here, I shall try to outline the basic principles and to evaluate successes and pitfalls of these three competing conceptions, in their relation to the available observational data. Inevitably, this evaluation will reflects my personal knowledge and interests and will be neither complete nor the only possible.

2. THE ROTATIONAL MODEL (RM)

This model starts from the observed correlation between rotational velocity and width and shape of emission lines in Be stars. It is assumed that Be stars are rotationally unstable at equator and eject matter, which forms envelopes and gives rise to the emission lines. Different shapes of the lines are easily explained by the aspect effect: Be stars with single-peaked narrow emission lines have also sharp absorption lines and are understood as rapidly rotating objects seen roughly pole-on. Also the observed proportionality of the width of the hydrogen emission lines to their wavelength, first recognized by Curtiss (1923), agrees well with RM. RM is thus based on assumption that a rapid axial rotation is a common property of all Be stars, a property which these stars gained during their contraction towards the ZAMS and during subsequent evolution. Sackmann and Anand (1970) showed that, on assumption of a rigid rotation, a B star evolving from the ZAMS becomes rotationally unstable at the equator very early and still long before the end of its main-sequence stage - unless the initial rotation is very slow. Also Strittmatter et al (1970) computed evolutionary models of uniformly rotating B stars, considering also the equatoreal mass loss which they found to be between 3×10^{-9} and 4×10^{-7} $M_\odot$/year in their particular case. Kippenhahn et al (1970) considered more complicated models in which local angular momentum conservation was assumed in regions of varying chemical composition and overall conservation of angular momentum and solid body rotation in all chemically homogeneous regions. Assuming the critical rotation at the ZAMS, they obtained equatoreal mass loss at the end of the main-sequence stage. On the other hand, models assuming local conservation of angular momentum in radiative regions and solid body rotation with overall conservation of angular momentum in convective layers, avoided the mass loss during the main--sequence evolution. Meyer-Hofmeister and Thomas (1971) repeated these computations taking the mass loss into account. They estimated the mass-loss rate to be of the order of 10^{-9} $M_\odot$/year. They also computed theoretical distribution of rotational velocities and compared it with the distribution observed for Be stars. Unfortunately, too many assumptions involved in this comparison do not allow to make any firm conclusion. Ostriker (1970) has shown that a contracting, rotating star will never shed mass at the equator unless also viscous and/or magnetic forces are taken into consideration. Summarizing the theoretical results, we can say that the available predictions of rotational instability are model dependent and therefore somewhat inconclusive.

It seems that the observational evidence is more specific on this point. The diagrams showing the distribution of observed projected rotational velocities of Be stars (v.sin i) versus spectral type, with the line of critical rotation drawn, clearly show that the question of rotational instability does not represent any serious obstacle for RM (Slettebak 1976, 1979). Doazan (1970), measuring profiles of 26 Be stars, concluded that no correlation exists between the width of the H I emission lines and rotational velocities of underlying stars, casting thus some doubts on one of Struve's (1931) basic arguments. Nevertheless, Slettebak (1976) and Slettebak and Reynolds (1978) presented convincing evidence of this correlation, for a large group of Be stars. Hardorp and Strittmatter (1970) demonstrated a strong tendency of shell spectra to be observed mainly among most rapidly rotating Be stars. Poeckert and Marlborough (1976) observed a correlation between polarization of Be stars and v.sin i. All these pieces of evidence strongly support the view that the envelopes of Be stars are to a great extent axisymmetric, rather than spherically symmetric, and that their structure must strongly depend on rotation. This need not mean however that the high rotation causes the Be phenomenon.

Using Jaschek's et al (1980) homogenized data for 140 bright northern Be stars, I constructed histograms of v.sin i for B2e-B5e and B6e-B9e stars. They are shown in the upper panel of Fig.1. One interesting difference of these histograms is that while there is almost no qualitative difference between distribution of early and late type non-emission B stars, there exists a striking deficiency of slowly rotating B6e-B9e stars in comparison to B2e-B5e stars. In my opinion, one possible interpretation of this effect is that in fact many B6e-B9e stars are B2e-B5e stars seen roughly equator-on and that the corresponding parts of their envelopes simulate a later spectral type. (In the section devoted to binary models, I present further evidence supporting this view.) The whole problem may be further complicated by Collin's (1974) finding that rapid rotation strongly affects strengths of He I 447.2 and Mg II 448.1 lines in the sense that a rapidly rotating star appears to have a spectral type 2 or 3 subclasses too late in terms of that appropriate for its mass, radius and luminosity. According to him, high rotation of B stars systematically increases the number of B7-B9 stars at the expense of B3-B5 objects (i.e. in the region, where the He I/Mg II ratio is used as the main classification criterium). Due to above-mentioned facts, our knowledge of the distribution of true rotat-

https://doi.org/10.1017/S0074180900037955 Published online by Cambridge University Press

ional velocities (which several authors derived using either the method of Chandrasekhar and Münch 1950 or a different approach of Bernacca 1970) need not be reliable.

A great disadvantage of the original RM was that it had offered no clear explanation of the variations observed. It could, in principle, explain light and spectral variations with typical cycles

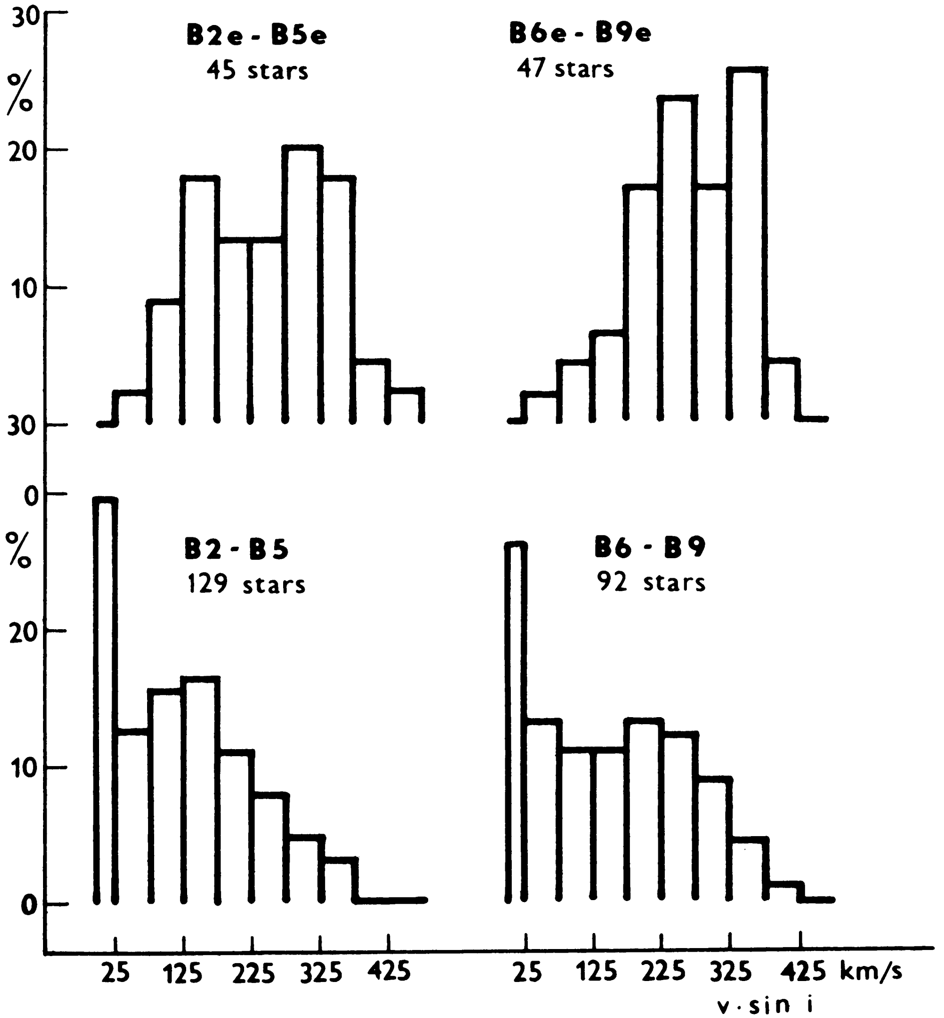

Fig. 1. Distribution of v.sin i for bright Be and B stars (the data for non-emission stars were adopted from Hardorp and Strittmatter (1970). The observed velocities are subdivided into intervals of 50 km/s, with the exception of the lowest interval which is only 25 km/s. The number of stars in this last group has been doubled in order to represent each star by the same area in the histogram.

https://doi.org/10.1017/S0074180900037955 Published online by Cambridge University Press

around 1 day. However, to explain long-term E/C and RV and V/R variations of emission lines, some other mechanism had to be sought. Already Struve (1931) suggested a possibility to explain the cyclic V/R variations by assumption that the envelope has a form of an elliptical ring the line of apsides of which rotates slowly in space. McLaughlin (1961) formulated this model mathematically and showed that it gives correct amplitudes of RV variations. Huang (1973a) revived McLaughlin's ideas and computed also emission profiles of the ring, assuming that the ring is optically thin for line radiation. Although he showed that also the V/R changes are reproduced well by the model, the idea of elliptical ring was not generally accepted. It was not clear how such a narrow ring, arbitrarily tilted with respect to the observer, could produce the deep shell lines (see Marlborough 1976). However Kříž (1976, 1979a,b) using more realistic physical assumptions and assuming a geometrically thick elliptical envelope, was able to reproduce the observed profiles as well as their V/R and RV variations quite reasonably. The model thus seems to be very promising. The long-term E/C variations are much less understood and it is possible that several different types of these variations exist. Some ideas how to explain them within the framework of RM were proposed, for example, by Limber (1970,1976) or by Huang (1973b, 1976). Nevertheless, no quantitative theory is available to show whether the suggested mechanisms can work properly.

A new development of RM offers the study by Baade (1981). He suggests to interpret Be stars as analogs of Beta Cep objects subjected to a rapid axial rotation. Developing a crude theory of non-radial pulsations of rapidly rotating stars, he succeeded to explain the 1.37-day periodicity of RV and V/R variations of 28 CMa as a non--radial pulsation with waves travelling opposite to the sense of rotation. Baade pointed out that this retrograde mode is very sensitive to small changes in the angular velocity of rotation and may potentially be responsible for long-term V/R and RV variations of Be stars and their instability. Baade's idea is certainly quite promising but it needs further quantitative development. For example: assuming the pulsational period of a non-rotating star to be 0.25^d, Baade obtained a theoretical period of 1.2^d for 28 CMa, which he considers a reasonable agreement with the observed value of 1.37^d. However using 0.19^d (a more typical "average" period of Beta Cep stars), one obtains 0.46^d - a less satisfactory result. The question then arises whether such modelling is more than a "fitting of free parameters". One would like to see more independent theoretical predictions which could be confronted with observations. For example, if a long- and short-term variability is simultaneously observed in one star, can both these variations be identified with specific pulsational modes for the same value of angular velocity?

3. THE MODEL OF RADIAL OUTFLOW OF MATTER (OM)

Gerasimovič (1934,1935) was the first who introduced the concept of radial outflow of matter as an alternative how to explain presence

https://doi.org/10.1017/S0074180900037955 Published online by Cambridge University Press

of emission lines in the spectra of Be stars. He argued that in luminous stars like supergiants and P Cyg stars, the acceleration due to radiation pressure must outweight gravitation for hydrogen, resulting thus in the formation of a steady expanding envelope which he called a "non-static chromosphere". In less luminous rapidly rotating Be stars this radiative dissipation is facilitated by stellar rotation. Gerasimovič supposed that the gravitation does not allow the formation of a permanent non-static chromosphere. He expected that the outflow proceeds until the line optical thickness of the expanding chromosphere is sufficiently large to stop the outflow. Only after this chromosphere has sufficiently dispersed into space as a detached expanding shell, a new cycle of events begins. Supposing that the envelope is expanding with decreasing velocity, Gerasimovič was able to explain qualitatively central absorptions in double-peaked emissions. Gerasimovič (1935) outlined also some preliminary considerations how to explain even the long-term V/R changes as consequences of varying optical thickness of the expanding envelope.

It is beyond the scope of this paper to review all the work dealing with line formation in expanding atmospheres (readers may refer to Hummer's 1976 review). Here, I only want to mention a modification of OM represented by recent papers by Doazan et al (1980a, b,c). In some respect, their model represents a revival of old Gerasimovič's ideas. They suppose that the Be phenomenon is only an enhancement in the chromosphere-corona complex which should exist around every star. However instead of assuming, like most other advocates of OM, that the mass loss from massive stars is due to the radiatively-driven stellar wind, they accept the concept of Thomas (1973) and Cannon and Thomas (1977) that the flux of matter is caused by subatmospheric nonthermal storage modes. Their model of a radially expanding envelope of Gamma Cas (Doazan et al 1980c) predicts correctly the presence of highly ionized lines in the UV spectrum and of the X-ray emission, which should originate in the high-temperature regions close to the star. The H I emission should originate in cooler outer layers of the envelope, where the expansion velocity is decreasing outwards, as in Gerasimovič's model. The authors mention however that the <u>quantitative</u> agreement of their model with the observations in optical region is not satisfactory since the densities in outer layers are too low to give rise to the observed hydrogen emission.

Another modification of OM was suggested, with some hesitation, by Snow et al (1979). They assumed the radiatively driven stellar wind model and a velocity field with expansion velocity <u>increasing</u> outwards. In their model, the hydrogen emission originates near the stellar surface, where the velocity is low; the UV shell lines, like Fe III, with expansion velocities around 100 km/s are formed above these layers. Finally, the high-velocity Si IV and N V lines, observed in some cases, originate in the outer layers of the envelope, where both, the acceleration of the expanding matter, and the degree of ionization, have increased substantially.

The trouble is that all available theoretical profiles of the H I lines originating in expanding atmospheres use the theory of radiatively driven stellar wind (e.g. Kunacz 1980). The resulting profiles differs substantially from the profiles observed in Be stars. As far as I know, no modern theoretical hydrogen-line profiles originating in an expanding atmosphere with the velocity fields assumed by Gerasimovič or by Doazan et al were published. On the other hand, the profiles computed on assumption of RM give satisfactory agreement with observed profiles (see, e.g., Poeckert and Marlborough 1978 or Kříž 1979a,b). From this point of view, the general validity of OM is open to further investigation. Similarly, one would like to see a quantitative explanation of different variations observed in Be stars within the framework of OM. As far as I know, this important problem was not tackled by the proponents of OM since the time of Gerasimovič's preliminary considerations.

4. THE BINARY MODEL (BM)

In a general form, BM was outlined by us in two papers six years ago (Kříž and Harmanec 1975, Harmanec and Kříž 1976). These papers contain also more or less complete references to all earlier work in this direction. Now, I take this opportunity to re-formulate the basic ideas of BM. A drawback of our original formulation was that it was too model-dependent. Many of the ideas have been demonstrated using the results of the theory of mass exchange in close binaries. Quite naturally, any prediction made on the assumption that a particular Be star is a case B mass-exchanging binary could be only as good (or, as wrong) as the theory of mass exchange itself. The observational data accumulated during recent years represent serious warning that this theory is still rather oversimplified and cannot provide us with reliable quantitative predictions. Indeed, some of the objections against BM were rather objections against the predictions of the theory of mass exchange. For this reason, I prefer to use analogy with really observed interacting binaries instead of comparison with some particular theoretical mode of mass exchange.

What is the essence of BM?

A. The Be envelope is formed by the matter transferred to the B star from the other component of the binary system. The most probable situation (let us call it mode 1) is that such an envelope is formed within the corresponding Roche lobe. To provide space enough for the envelopes with dimensions several times larger than the radius of a B star, the orbital periods of such systems must be relatively long. In one important parameter we thus have a simple geometrical sequence: short-period interacting systems (periods up to a few days) will appear as Algol binaries. Because of limited space around their mass-gaining stars (gainers), these systems exhibit mainly the absorption lines of gas streams but only moderate or no H emission lines (see Plavec and Polidan 1976). For longer periods (up to several hundreds of days or more) we observe a Be star (Peters 1980 found the H_α emission in almost all Algol systems with orbital period longer than 6 days). The other end of this sequence for very long orbital periods may be represented by symbiotic and VV Cep stars.

No doubt, the period is not the only important parameter. The masses of both components must also play an important role, and especially the mass ratio which may control the rate and the type of mass exchange. The appearance of real systems depends also on which of both stars dominates in the optical spectrum. Thus, the above-mentioned simple picture can be almost arbitrarily complicated. For example: if the mass transfer is strong enough, the emission may be associated with hot spots, especially in extremely short--periodic systems such as dwarf novae. Let us denote this situation as mode 2. Yet, it seems that most of Be stars with their double emission lines do not originate in this manner. Another consequence of a rapid mass transfer can be a substantial mass loss from the system. In principle, such material can form an outer envelope around the whole system (let us call it mode 3). Then, no apparent restriction of the orbital period of such binary can be predicted. Because the mass loss will be probably connected also with a substantial loss of angular momentum, a rather short orbital period is quite probable. With some fantasy, one could re-interpret Baade's observations of 28 CMa as such a configuration of two B stars seen nearly pole-on. Some emission may originate even in clouds corresponding to stable periodic orbits around the Lagrangian points L_4 and L_5 (see Wu 1975). In real systems, combinations of several modes are quite probable - as a further complication.

Concerning the nature of the mass-losing components (losers), I stress that we never claimed that it must be a late type star, as it is often quoted in literature. Already in our first paper we pointed out that the losers may be of very different spectral types in particular cases.

B. In any of the three modes considered, original Plavec's (1970) argument that the excess angular momentum brought to the gainer must increase its rotational velocity, is still valid. As the deviations of the equipotential surfaces from the spherical shape are significant only near the critical lobe, it is clear that especially for modes 1 and 3 there must be a high degree of axial symmetry, and that the models of single rotating stars with rotationally supported envelopes, are quite appropriate to describe such a configuration, at least as a good first-order approximation. Further, because the outer equipotentials enclosing a binary become more and more spherical with increasing distance and because it seems from the UV observations (Plavec 1980a,b) that the high-excitation emission lines are not associated with neither star in the observed systems, it is not surprising that OM gives good predictions for these lines. It is thus possible that one day all three (now competing) conceptions will join into one complex model.

C. Besides the formation of the envelope, the other component may be responsible for the long-term RV and V/R variations observed for many Be stars. Computations by Kříž and Harmanec (1975) showed that the envelope around the gainer produced by a variable mass transfer may have a form of an elliptical ring whose line of apsides slowly rotates due to the perturbing force of the secondary component. Thus, BM can explain the origin of the elliptical envelope discussed already in section 2. The excellent quantitative agreement of Kříž's and Harmanec's computations with the observed variations of ζ Tau is probably one of the greatest goals of BM. The long-term RV and V/R variations are far the most pronounced changes observed in Be stars and no other theory has offered their quantitative explanation in such a consistent way. Similar computations were further developed by Castle (1977), who discussed a whole grid of models, including those corresponding to what I call mode 3. Castle confirmed the applicability of the model to Be stars and pointed out that elliptical disks can produce radial velocity-excitation gradients of either sign. To be honest, I must say that this model will probably work even if the elliptical envelope would be formed by another process than by mass transfer from the other star. Yet, it seems that the role of the secondary, as the perturbing agent forcing the line of apsides of the envelope to rotate, is substantial. Even Marlborough et al (1978) had to suppose an invisible secondary for explaining the observed V/R changes of γ Cas, though they had not accepted some other aspects of BM.

D. From analogy with other types of binaries it seems that the secondary may be responsible even for the long-term E/C variations of Be stars. Outbursts of reccurent novae are also cyclic, but not periodic phenomena, similarly as the less pronounced changes of many other binaries. Olson (1980a,b), observing U Cep, found that a brightening of the loser always preceded formation of an accretion disk around the B gainer and appearance of the H emission in the spectrum. Olson (1981, private comm.) can show that for several Algol binaries a size increase of the loser preceded a mass-transfer event. If a similar correlation could be found in some known Be binary, it would be a strong argument in favour of BM.

E. If Be stars are really binaries, they should manifest themselves by periodic variations due to the orbital motion. One should observe RV curves of both components, periodic V/R variations of double emission lines, additional absorptions from gas streams at certain orbital phases etc. Some Be stars should appear as eclipsing binaries and others could still manifest themselves by periodic light variations due to ellipticity or eclipses by gaseous streams and/or disks. Though all the above-mentioned kinds of variations were really found in particular cases, the search for them was so far negative in others. Some variations on a time scale of weeks or months were usually detected but it was impossible to find a periodicity for them.

F. The light and spectral variations (often pseudoperiodic) taking place on a time scale around one day or shorter may have various causes. Some possibilities to be mentioned are:

i. Effects of differential rotation coupled with unhomogeneous distribution of surface brightness.

ii. Analogy of flickering of dwarf novae in larger geometrical scale.

iii. A pulsation of the B star (see the considerations by Percy 1979, 1980 and by Baade 1980).

iv. Effects of binary motion in a short-periodic system, the most probably mode 3 binary. I suggest that the peculiar eclipsing binary EM Cep ($P=0.806^d$) may be an example (see Breinhorst and Karimie 1980 and references herein). The duplicity of EM Cep is still questionable, its light variations may well be a more regular case of the changes observed for EW Lac or V923 Aql, but Tremko (1981, private comm.) believes that he has detected lines of two components in the spectrum.

v. Effects of binary motion in a long-periodic binary, important only in some orbital phases. The short-living shell phase of HR 2142, observed every 80.86 days, may serve as a good example (see Peters 1976). The whole secondary shell phase, with very pronounced spectral variations, lasts one day only. An accidental observer would probably conclude that he has observed rapid variability of the envelope of HR 2142 on a time scale of <u>hours</u>, having no apparent periodicity!

Two main objections were raised against BM. One is the negative result of the search of duplicity in particular Be stars. The other (by Plavec 1976) is: if all Be stars were semidetached binaries, we should observe more eclipsing binaries among them.

Let us consider the first problem. In the majority of cases, when we dot not observe the secondary directly, the detection of duplicity of a Be star is uneasy and possible only after accumulation of long series of observations, or impossible in less favourable cases. For mode 1 binaries, a typical semi-amplitude of the RV curve of the Be component must be of the order of 10 km/s or less. For mode 3 binaries, with opaque outer envelope, the situation may be even worse because the envelope lines reflect only a small fraction of the orbital motion of underlying stars (Kříž and Harmanec 1975). Castle (1977) pointed out that also the presence of long-term RV variations can delay or advance maxima and minima of orbital RV changes for more than one tenth of the period making thus period finding very difficult. Rapid (probably irregular) variations of the envelopes very complicate period finding, too. Olson (1980a,b) observed photometric changes in the disk of U Cep on a time scale as short as four orbital periods. Strong interference of orbital and non-orbital variations was found also by Kříž et al (1980) in RX Cas or by Koubský et al (1980) in CX Dra. Gulliver (1977) was not able to detect duplicity of Pleione. I compiled most of published RV's of Pleione and averaged them over about 100 days. It resulted in a smooth RV curve, with a possible period of about 13000 days, which is in phase with appearance of shell phases. This RV curve perhaps represent some slow atmospheric motions but it is tempting to speculate whether Pleione is not a long-periodic binary and whether its shell phases are not

https://doi.org/10.1017/S0074180900037955 Published online by Cambridge University Press

analogies of shell phases of HR 2142, occuring in larger dimensions. Also o And ($P=10000^d$?), 59 Cyg or γ Cas may be candidates of such interpretation. Speckle interferometry may help to answer. So far, only φ And, η Ori, ν Gem, λ Cyg (a triple system) and o And (a triple system?) are known speckle-interferometric binaries with a Be component (McAlister 1981, private comm.).

Tentatively, one can conclude that the absence of clear periodic variations need not a priori exclude the binary nature of a particular Be star. Clearly, it is necessary to seek other ways how to confirm or clearly deny the binary nature of individual Be stars.

Let us proceed to the problem of "missing" Be eclipsing binaries. Poeckert (1979,1981) and Suzuki (1976,1980) published very important studies of φ Per. Poeckert, using new high-dispersion spectrograms, detected He II 468.6 emission, apparently associated with the secondary. Measuring also the RV curve of the primary, defined by broad absorption wings of H I and He I, and by Fe II emission, he arrived at component masses $m_1 \sin^3 i = 21.1 \pm 5.6\ M_\odot$ and $m_2 \sin^3 i = 3.4 \pm 0.8\ M_\odot$. Shell lines of H I and He I follow the RV curve of the primary, with the exception of a "bump" on the descending branch. Weaker "secondary" shell lines of He I follow the RV curve of the secondary. Apparently, the secondary is <u>well detached</u> from its Roche lobe, otherwise it would be much brighter than the primary. Poeckert (1981) suggests a model consisting of a Be primary enclosed by a nearly circular disk emitting Fe II and most of H I emission, and of a small hot secondary with a disk emitting He II emission. φ Per thus seems to consist of a Be primary and a WR secondary. Poeckert's (1981) data clearly show an increase in the strength of some shell lines around the conjunction with the secondary in front, followed in later phases by an increase in their RV's. There are at least two possible explanations of this effect. Either, we suppose (like Struve 1941) that we observe a projection of a gas stream flowing from the secondary to the primary, or we have to postulate (like Suzuki 1976,1980) that the motion of the outer parts of the disk around the primary corresponds to stable periodic orbits of the restricted problem of three bodies. The first possibility needs a special geometry of the stream because the maximum velocity of the shell lines is observed <u>after</u>, not before the conjunction as it is usual for Algol binaries. Kříž (1981, private comm.) computed some trajectories of particles flowing from the rotating disk around the secondary and obtained indeed a stream with needed geometry. Yet, before his continuing computations will convince me, I see further objections against the gas-stream interpretation. The observed v.sin i of the primary, 450 km/s, indicates that the value of sin i can hardly be smaller than, say, 0.75. The velocity of the stream in the vicinity of the gainer should be of the order of several hundreds of km/s. Why, then, should we observe only a small fraction of this velocity, of the order of several km/s, projected against the disk of the primary? The same applies also to other Be binaries showing "bumps" on their shell-velocity curves (ζ Tau, 4 Her, KX And). In all cases, the secondary maximum of the shell velocity represents only a fraction of projected orbital velocity of the star in question. I thus prefer Suzuki's interpretation of the effect. Suzuki applied his model of stable orbits to Hynek's (1940,1944) measurements of φ Per. Assuming sin i = 1, he arrived at the values of $m_1=20\ M_\odot$ and $m_2=4\ M_\odot$ for the masses of both stars, in excellent agreement with the above-mentioned result of Poeckert (1981)! Suzuki's model does not explain the strengthening of the shell lines around the conjunction. Stable periodic orbits are symmetric with respect to the line joining the stars and one would expect that a similar strengthening should occur also a half period later, which is not the case. Tentatively, I suggest that the observed strengthening is caused by absorption in an outer part of the disk around the secondary, projected against the disk of the primary in phases near conjunction. Such geometry needs the orbital inclination to be close to, but differ from 90°, which is quite probable. If my explanation is a correct one, Suzuki's analysis remains sound, because the velocity of additional absorption should be close to the systemic velocity, in agreement with the velocity of the "normal" shell lines.

The new development in our understanding of φ Per is important also in that sense that φ Per is a prototype of a Be binary in which mass transfer between components - if present at all - is driven by some other mechanism than the Roche-lobe overflow, and in which the secondary is well detached and quite small. If a non-negligible fraction of Be stars are binaries similar to φ Per, then the problem of "missing" eclipsing binaries among Be stars does not longer exist.

In conclusion, I shall discuss some promises of a statistical approach to the problem: Recently Dr. Kříž called my attention to the results of Burki and Maeder (1977) who found that the percentage of Be stars and binaries among B0-B4 stars both exhibit the same dependence on galactic longitude, reaching a maximum between 30° and 90°. Such a finding is certainly interesting from the viewpoint of BM.

Kogure (1981) presented a statistical study of the relations between Be/Ae binaries and their non-emission counterparts. He restricted himself to stars of luminosity classes III to V and studied period distributions for B and A stars separately. He found a double-peaked distribution for Be binaries, in contrast to a single-peaked distribution for all B binaries, and he concluded that the Be binaries may be divided into two groups: short-periodic binaries ($P < 30$ days), which are essentially Algol-type interacting binaries, and long-periodic binaries, which have statistically higher v.sin i and in which the Be phenomenon is due to a high rotation, as in single Be stars. I do not agree with this interpretation. The "short-periodic" group consists almost exclusively from eclipsing binaries and reflects thus probably selection effects due to decreasing probability of discovery of eclipses for long-periodic systems and due to exclusion of "high-luminosity" systems. Kogure himself remarks that after inclusion of the systems classified I, II or c, the short- and long-periodic groups become almost unseparable. But I realized another

https://doi.org/10.1017/S0074180900037955 Published online by Cambridge University Press

interesting outcome of Kogure's statistics: with the exception of 17 Lep, all the Ae binaries are eclipsing binaries! Together with the histograms mentioned when discussing RM, it may indicate that all these systems in fact contain a B star which excites the H I emission , and the spectrum of which is masked by the accretion disk, seen equator-on and simulating a later spectral type. This view is even strengthened by Plavec's (1980a,b) results. Plavec showed that the UV spectra of the emission-line binaries SX Cas and W Ser contain hot continua corresponding to B stars. These continua are eclipsed in primary minima and are therefore associated with the hotter components of the systems, which however are classified A6 IIIe and F5 II-IIIe, respectively, from the optical spectra! Plavec interprets these continua as originating from accretion of matter in the inner parts of narrow equatoreal disks in these systems subjected to a heavy mass transfer. (In systems with low rates of transfer, he found no contradiction between optical and UV spectral types.) I suggest an alternative explanation - to suppose that the main role of the heavy mass transfer is to produce a flattened, optically thick envelope, which - seen roughly equator-on - almost screens the star. In my interpretation both, SX Cas and W Ser do contain B stars whose radiation from less screened polar regions is detected in the UV spectrum. The cooler continua, seen in the optical spectra, originate in "photospheres" of the accretion envelopes. As a speculation, I suggest an effect not considered so far. The reservoir of the thermal energy contained in gas flow from loser must be smaller when the matter is flowing from a cool star then when it comes from a hot object. May it not be, at least partly, a consequence of this effect that we observe cooler optical continua in SX Cas and W Ser, but not in β Lyr (in spite of its even higher rate of mass transfer) in which the loser is a B8 star?

I wish to thank Dr. S. Kříž for many stimulating discussions and for a critical reading of the manuscript.

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https://doi.org/10.1017/S0074180900037955 Published online by Cambridge University Press

DISCUSSION

Slettebak: In the histograms showing the number of Be stars versus v sin i, the small number of Be stars with low v sin i is precisely what would be expected if all the stars in that group rotate with nearly the same (critical) equatorial velocity and have their rotation axes randomly distributed in space. Therefore, I do not see the need for your suggestion that Be stars of late type may actually have early-type stars inside their envelopes.

Harmanec: My argument was the following: While the distributions for early and late type non-emission B stars are very similar to each other, there is a notable difference between late- and early-type Be stars in the sense that late-type Be stars have a peak for high v sin i while the distribution of early Be stars is much flatter. What is important is that I used a homogenous sample of objects. I am not going to say that all late Be stars are early Be stars seen roughly equator-on. Rather, I guess that the sample of late-type Be stars can be contaminated by such objects.

Sonneborn: The recent work by Slettebak et al. on the effect of rotation on spectral classification shows that the shift to later types can be only as large as 2 subtypes. It is not possible for a B2 star to appear spectroscopically as a B8 or B9 star because of rotational effects alone.

Harmanec: Well, I speculate that the equatorial parts of the envelope must (or better: could) simulate a later spectral type even in continuum.

Selvelli: I would like to anticipate some results about 17 Lep that will be presented tomorrow. 17 Lep is seen almost pole-on. From IUE observations we have found the presence of a very thick shell fully covering the system. From the shell lines we have derive a temperature around 8000 K in agreement with that derived from the UV continuum. It seems likely, therefore, that the observed continuum is formed in the thick shell surrounding the primary.

Peters: 1. The list of higher temperature Be stars mimicing stars of later spectral type is endless. I will cite two examples:
TT Hya is usually classified as an A 2 star but inspection of the "blue spectrum" reveals the presence of a B7 - B8 star. RZ Oph ($P=262^d$) has been classified as an F giant, but whereas the Fe II and similar lines are sharp, the Mg II 4481 line is broad, indicating that the rotational velocity at the photosphere is relatively high.
2. We agree that hot spots exist (probably in the region where the gas stream impacts the disk) because we observe strong (variable) N V in some objects.
3. In his analysis of the IR Ca II triplet emission in Be stars, Polidan concluded that a relatively cool (6000 K) dense external disk was required to explain the existence of the optically thick triplet

lines. Since a higher percentage of the calcium triplet emitters are confirmed to be binaries, we approve of your suggestion that semi-detached systems can be surrounded by a circum system disk.
4. Suzuki's calculations pertained only to the orbital plane. It is not clear what the situation is at the higher latitudes through which our lines of sight presumably pass.

Harmanec: Thank you for your comments. To your fourth remark I can only comment that Dr. Suzuki is probably doing something to generalize his model because recently I received a preprint of his new study in which he tries to interpret our observations of 4 Her by his model assuming an inclination of 50°. I cannot tell you more details, unfortunately, because the paper is written in Japanese language.

Hubert-Delplace: In the case of ζ Tau, you mentioned that the 7 year period is well explained by the elliptic ring, but after the 7 year cycle observed in 1960-1967, we have observed a 4 year, then again a 7 year cycle. How do you explain the change of period, what physical parameter change in the model that you propose?

Harmanec: In the model we suggested the elliptical envelope is formed by a short-living mass transfer event lasting only a fraction of the 133-day orbital period. It appears quite natural to me that - in absence of further mass transfer activity - viscous and/or magnetic forces in the discs will tend to destroy the original structure of the elliptical envelope and to force it to rotate with the orbital period. Thus, the period of the long-term variation should decrease and after a few cycles disappear completely. It should probably convert gradually into an envelope of Suzuki's type which maintains stable configuration with respect to the line joining the binary components exhibiting thus only variations with orbital period. It may happen, however, that a new mass transfer event will occur causing a new long-term variability.

Baade: M. Smith has made a survey of bright narrow-lined B stars of the northern hemisphere. He found that an extremely high percentage of these objects shows variable line profiles. This suggests that some type of pulsational instability is quite common in this region of the HRD. If we think that there is no observational evidence for pulsations of Be stars, we shall have to explain such a difference between B and Be stars. So, regardless which result we expect, we must study the problem of oscillations of Be stars.

Bolton: Equatorial pulsation in a Cepheid type atmosphere is unlikely as both, Baade and I, see variations in the He I lines. We should be careful in talking about pulsation in Be stars until we have a better understanding of pulsation in ordinary B stars.

Thomas: You questioned our model, I resume:
A) 1. Our model, being empirical, can give large atmospheric densities if F_M is large. E.g. to get 3×10^{13} at base of atmosphere we need

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F_M 10^{-5}M /y.
2. Our velocity first increases outward, to v(max), fixed observationally; then eventually decreases to reach the $\gtrsim$100 km/s required by H and Fe II displacements.
3. Agreed - we produce Fe II and Balmer lines outside the superionized lines; I do not see, with the observed data, you can do otherwise.
B) I would be cautious of eclipsing binary location at atmopsheric features. I think only the Sun, V444 Cyg, and ζ Aur (+ 31 Cyg etc.) have been sufficiently analyzed to date to be sure of what occurs where.
4. I do know of computations from any model which gives the observed range of e.g. 59 Cyg Hα profiles.

Harmanec: Thank you for your explanatory comments. But could you comment on my argument concerning SX Cas in particular? The emission-line component of this star is being totally eclipsed by the star every 36 days. During this eclipse, H emission exhibit strong variations, while the UV emission lines of N V, C IV etc. remain completely unchanged (see Plavec 1980 a,b). For me it speaks in favour of the hypothesis that the H emission originates closer to the star than the UV lines, in this particular star, of course.

Thomas: I have never seen the data on SX Cas; and never do I draw conclusions before looking myself at the data.

Giovanelli: About RX Cas, would you like to point out the reason why it is possible to look at the orbital period in one colour and not in the other ones.

Harmanec: You clearly see that while the V curve reproduces quite well from one cycle to another, the light level in the U varies, but the time scale in these variations is longer than one orbital period because the curve in each particular cycle is defined. The U curve seems to reflect effects of gas streaming, detectable also spectroscopically. In contrary, in KX And we observe stable U curve and larger scatter in the V curve.

de Loore: Do you have ideas about the progenitor system for Be-binaries, I mean mass ranges, mass ratios leading to such systems?
A second point is, how will these systems evolve later on?

Harmanec: Six years ago I had. Now I am much less sure. Essentially, Be binaries should originate from detached MS binaries with periods of a few days. If such a system survives the first, probably the most rapid phase of mass exchange without losing too much mass and angular momentum, its period must increase substantially, to the range of period giving sufficient space for the Be envelope to be formed within the Roche lobe. As the mass ratio is usually more than reversed by this process, you may obtain a B star even from a binary composed originally from two A stars, say. This effect is able to explain the observed high percentage of Be stars among B stars (see Kriz and Harmanec, 1975).

After the Helium burning or the electron degeneracy stops, the mass transfer from the loser will probably shrink rapidly. Consequently, its rotation must increase substantially and you should obtain something like a WR object, hot small Helium star with a rapidly rotating envelope. As already mentioned here by Dr. Poeckert, ϕ Per may be just in this evolutionary phase. However, to predict original masses may be uneasy because we still do not know how much of mass and angular momentum can be lost from the system. That at least some fraction is lost seems to be well established now - see the evidence of an outer envelope around β Lyr and other interacting binaries or the UV observation of the mass loss.