THE SPHEROIDAL/ELLIPSOIDAL, VARIABLE MASS-LOSS, DECELERATED Be STAR MODEL (Review Paper)

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1 INTRODUCTION

The proposed model is empirical; it is based on analysis of the available data on Be stars obtained in all the observable spectral regions, and it is required to be thermodynamically self-consistent. Rather than trying to answer the question: "What is the origin of the Be-phenomenon?" We ask: First. "What phenomena characterize empirically Be stars?" Second. "What thermodynamic characteristics are implied by the existence of such phenomena?" Third. "What inferences may be made on the atmospheric structure of a Be star from these empirical and thermodynamical characteristics?"

The observed phenomena, their thermodynamical implications and the resulting model have each two aspects. On the one hand, the observational evidence for a nonradiatively heated, expanding chromosphere-corona implies the existence of both a nonradiative energy flux and a mass outflow from the photosphere. This first aspect is common to both Be and normal B stars, at least for the earliest subtypes. On the other hand, the observed strong variability of this mass outflow produces, either by self-interaction, or by interaction with the local stellar environment, a deceleration of the flow, which builds a "pulsating" reservoir structure of the outermost regions. This second aspect is characteristic of only Be stars among the low-luminosity B-type stars. These concepts and modelling implications were first applied to Be stars by Doazan, Kuhi, and Thomas (1980) who concluded, from their far UV and visual observations of 59 Cyg, that mass flux variability - as inferred from the superionized flow - is associated with Be star variability observed in the visible, particularly with phase changes (Be, Be-shell, B normal). They described a Be star atmosphere in terms of a chromosphere, a corona, and an extended envelope, whose characteristics are determined by nonthermal fluxes - produced by subatmospheric nonthermal storage modes (Thomas, 1973, Cannon and Thomas, 1977). The empirical and theoretical basis of our model, as well as its mathematical formulation, have been given by Doazan and Thomas (1982) in the Monograph Series on Nonthermal Phenomena in Stellar Atmospheres: "The B Stars With and Without Emission-lines". In the fourth volume of these Monographs: "Stellar Atmospheric Structural Patterns" Thomas (1983) places our model in the broader thermodynamic pattern of atmospheric structure for a wide variety of peculiar stars.

Our model defines a self-consistent radial sequence of atmospheric regions with different thermodynamic characters: hot and cold, quasi-static and highly dynamic, as required by those observations which show the existence of: (a) Subthermal velocities in the photosphere. (b) High velocities, thermal and superthermal, in the chromosphere-corona. (c) Low, but superthermal outflow and inflow velocities in the oscillating, cool Hα-emitting envelope. These characteristics identify the mass flow problem as a highly nonlinear one. We note that our sequence of regions describes the stellar atmosphere as a transition zone, which exhibits a multiregional pattern between the

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stellar interior -in quasi equilibrium- and the interstellar medium (ISM) - in non equilibrium (Gebbie and Thomas, 1968, 1971). It is thus clear that no particular region can be modeled ad hoc independently of the other regions. That is, any model constructed ad hoc for representing only one limited atmospheric region, cannot provide any sound conclusion on the structure of the Be star atmosphere nor, quite evidently, on its geometry, especially when the analysis is based on only one set of data, such as Balmer emission-lines or far IR energy distribution. Such information can only be obtained when the aerodynamic structure of the flow has been determined independently.
Our representation of a Be star atmosphere has evolved since 1982-1983. In particular, a substantial progress in our understanding of the dynamics of the cool Hα envelope and its relation with the underlying atmospheric regions has been made (Doazan and Thomas, 1986 a). This progress came mainly from the analysis of new observational results obtained from long term variability studies of a few Be stars observed simultaneously in the far UV and in the visual. Such a program, which has been initiated in 1978 with the observations of 59 Cyg, has been carried out during several years through a broad international collaboration, and continues until now. These studies have shown, for the first time, the existence of: (i) Associated, long-term variability patterns between superionized and subionized features; thus, providing evidence that superionized and subionized atmospheric regions, rather than evolving separately, are in continual interaction and dynamically linked (Doazan et al., 1985, 1986 a,b,d,f). (ii) An association between changes in the subphotosphere/photosphere and the occurrence of a shell phase (Doazan et al., 1986 c).
This talk is based on collaborative work with R.N. Thomas, and collaboration on specific points with others, as cited in the text. Section 2 presents the basic observational characteristics that any Be star model must be able to represent in a self-consistent way. Section 3 presents the basic thermodynamic conditions underlying Be star modelling, and defines, in a quantitative way, the radial sequence of regions which describes the entire Be star atmosphere.

2 BASIC OBSERVATIONAL CHARACTERISTICS OF Be STARS

A critical analysis and synthesis of the observations on Be stars made in all the observed spectral regions have been presented in the above-quoted B star Monograph (Doazan, 1982). We abstract from that Monograph those observations, whose modelling implications are important in our model and summarize new results which guided its evolution since then.

2.1 Main properties of the cool, extended, Hα-emitting envelope

A Be star is a B star of class III-V which shows, or has shown emission in the Balmer lines , at least at Hα. Thus, the primary characteristic of the Be-phenomenon, the emission at Hα, is variable. That characteristic usually persists during decade(s), but it may also be present only during periods of time of the order of year(s), month(s), or even day(s). Therefore, any model of a real Be star must allow the Hα-emitting region to exist at some epochs only. At those other epochs when Balmer emission is absent, which may last for decades, it has not yet been possible to distinguish the spectrum of a Be star from that of a normal B star by observations made in the visible region only. However, the remarkable variations exhibited by the far UV spectrum of θ CrB during a normal B phase strongly suggests that

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such a distinction exists, at least during some epochs, in the far UV (see Fig. 2). Doazan and Thomas (1984, 1986 a) proposed that a variable mass outflow characterizes normal B phases of Be stars, and that such a temporal behaviour distinguishes normal B phases of Be stars from normal B stars.
The presence of emission in the Balmer lines, which exhibit only small displacements, requires for these hot B-type stars, the existence of an extended, slowly-moving, cool outer-atmosphere. The existence of that extended atmosphere requires the existence of a mass-outflow from the underlying star. (Our model assumes that the Be-phenomenon arises in a single star and that binarity only renders the phenomenon more complex.) As a general rule, the intensity, the profiles, and the displacements of the emission-lines all vary. This indicates that the mass-content, the density, the size, and the velocity of the cool, extended, Hα-emitting region are also variable.
The variability of Be stars is such that they may exhibit at various epochs different types of spectra in the visible region: Be, Be-shell, and normal B. Under the disk/rotation model, the inclination of the star's rotational axis on the line-of-sight determines, once and for all, the type of spectrum, Be or Be-shell, that a given Be star may exhibit. Therefore, "shell stars" would be observed only equator-on, or nearly equator-on, while "Be stars" would be observed only at lower inclination angles. But, such an explanation of Be and shell-type spectra is strongly contradicted by the observed transitions from the Be to the Be-shell phase, and conversely, that several Be stars have undergone. We note that a spheroidal/ellipsoidal model, does not meet any difficulty when confronted with these observations. Rather than invoking the existence of a thin equatorial disk oriented in the direction of the line-of-sight, we proposed an entirely different interpretation of shell phases, based on observations of 88 Her, which links the occurrence of a shell phase to those subphotospheric/photospheric properties of Be stars, which produce an enhancement of mass outflow (Doazan et al., 1986 c).
From visual observations only, Be stars were thought to differ from normal B stars by the existence of a mass-outflow which produces that extended, cool envelope, where Balmer emission-lines originate. As long as the observations were limited to the visual region, the fundamental difference in the basic assumptions underlying models for Be and normal B stars was that the former possessed a mass outflow from the photosphere, whereas the latter (apparently) had none. By showing that both types of stars may share that property, far UV observations strongly contradicted such a viewpoint.

2.2 Main properties of the superionized regions

Far UV observations have revealed the presence of superionized features in the far UV spectrum of Be stars, i.e. of spectral features of higher ionization than would be expected from only the radiative energy flux of the star, implying the existence of a nonradiative energy flux. These superionized features usually exhibit large expansion velocities, often exceeding the escape velocity at the star's photosphere, implying the existence of a mass outflow from the photosphere. But, that does not necessarily imply the existence of a mass flux from the star (see Sect. 3). Far UV observations show that a nonradiative energy flux and a superionized mass outflow at superescape velocity cannot be considered as distinguishing characteristics of Be stars. They also exist in normal B stars, at least for the earliest subtypes. But, what seems to distinguish Be stars from normal B stars, is the temporal behaviour of these nonthermal fluxes. They are strongly variable in Be stars, while they are apparently constant in normal

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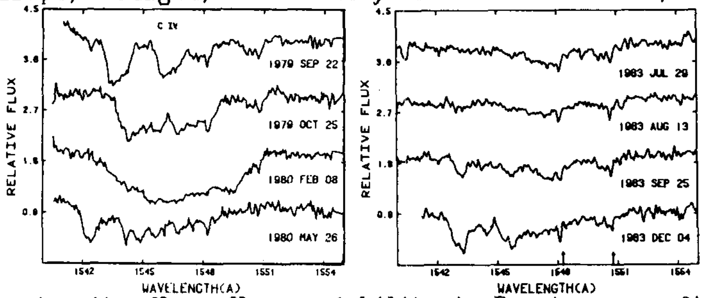
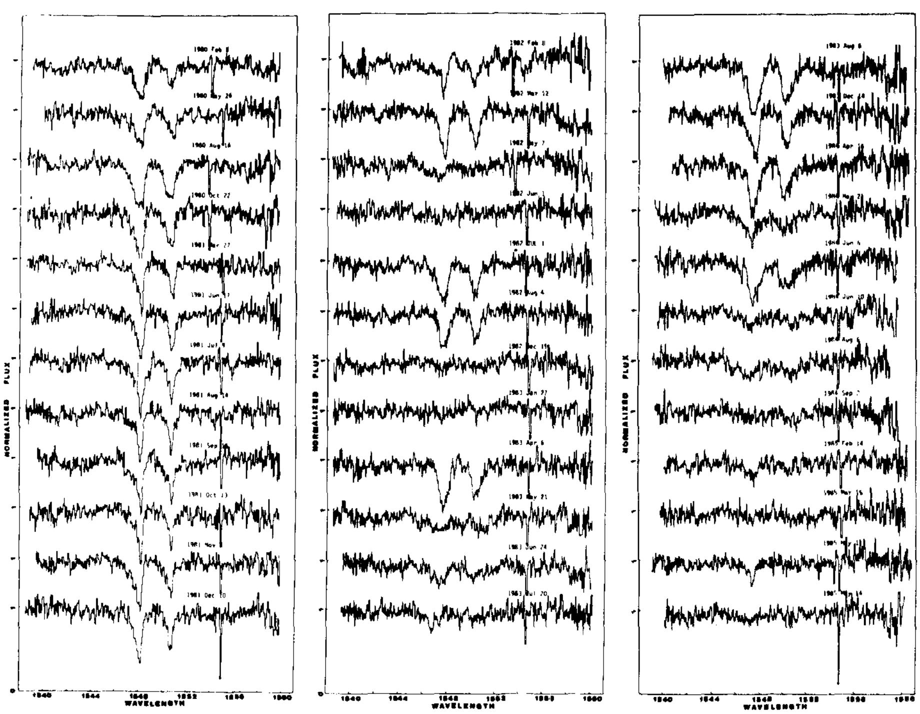
Fig. 1 Variability of the CIV lines in 59 Cyg. Note the changes in shape, strength, and velocity (from Doazan et al., 1985).



B stars of low luminosity. Mass flux variability in Be stars was first inferred from the striking variations exhibited by the superionized features observed in the far UV spectrum of 59 Cyg (Doazan, Kuhi, and Thomas, 1980). Subsequent observations showed that such a behaviour was exhibited by all well-observed Be stars, at least during some epochs. Figure 1 shows the behaviour of the CIV line-profiles of 59 Cyg, which has been systematically observed in the far UV and in the visible since 1978 in our long term

Fig. 2 Long term variability pattern of θ CrB at the end of a shell phase and during the normal B phase which followed it (from Doazan, et al., 1986a). The same variability pattern is observed for the superionized and normally/subionized lines.



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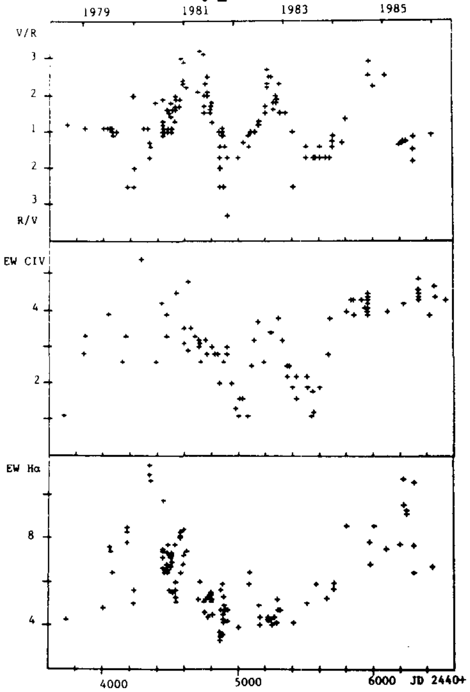
collaborative program (Doazan et al., 1985, 1986 d). That figure illustrates well several aspects of that far UV variability of Be stars: (i) The CIV profiles may completely change their shape and fine structure. For example, more than five narrow absorption components may appear/disappear at any part of the profile. (ii) The velocity may vary as much as 1150 km s^{-1}, as measured at maximum depth. (iii) The E.W. of the CIV resonance lines may vary by about a factor five, from less than 1 Å to more than 5 Å.
At some epochs, the CIV resonance lines may weaken to the point where they become undetectable, and then recover again. That phenomenon shown in Fig. 2 has been first observed for θ CrB (B6Ve), during a normal B phase which followed a shell phase (Doazan et al., 1984 a). That star exhibited during two years (1980-1982) strong CIV resonance lines with narrow absorption cores located at low expansion velocity (≃30 km s^{-1}), which did not show any conspicuous changes. By contrast, during the following years, several episodes of "disappearances" occurred (Doazan et al., 1986 a,b) when the lines became broader and the expansion velocity increased substantially (≳100 km s^{-1}). These "disappearances" may be due either to a decrease in the number of absorbing ions, or to a spreading of the C^{3+} ions over a larger velocity range, so that the number of absorbing ions becomes so small that the CIV lines become undetectable. Our IUE observations, made during that apparently quiescent period, strongly suggest that the second interpretation is the most plausible one.
The fact that the two nonthermal fluxes, mass and nonradiative energy, are observed among both B and Be stars imply that their modelling should include those atmospheric regions whose physical characteristics are determined by interaction with these fluxes. But, it is clear that the temporal behaviour of these two nonthermal fluxes differ fundamentally in these two types of stars by the amplitude of their variations: Normal B's are constant or only slightly variable, while Be's generally show large variations.

2.3 Associated, long term variability patterns exhibited by superionized and subionized regions

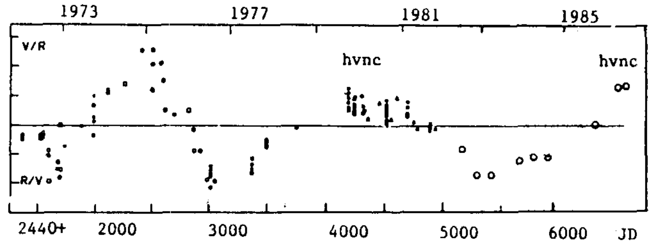
Long term, organized variability patterns, as opposed to erratic, disorganized changes, are long known to exist for Be stars from studies made in the visible. Their existence implies that any description of the Be-phenomenon must be time-dependent. The question whether the superionized and subionized regions of a Be star atmosphere evolve independently, or, on the contrary, are dynamically linked is obviously important in Be star modelling. It has been investigated in our long-term variability studies, which show that such an association exists in the long-term trend.
59 Cyg: The development of a new Be phase in 59 Cyg was accompanied by remarkable changes in the CIV resonance lines (Fig. 1) and changes of the emission at Hα, with large V/R variations. Figure 3 shows the behaviour of the V/R at Hα, the E.W. of CIV, and the E.W. of Hα emission in 1978-1986 (Doazan et al., 1985, 1986 d). We remark that although the V/R changes are regular, the emission intensity at Hα does not follow the V/R variations in a simple way, as is usually the case for "V/R variables". But, for the whole period 1978-1986, we observe an association between the strength of the CIV lines, the emission at Hα, and V/R, in the sense that the CIV lines are strong when the emission at Hα is strong, and V/R>1, and conversely, while at other epochs, a correlation between only two of these features is apparent. The important result is that, on the average, and in the long term trend, the behaviour of Hα emission reflects that of the CIV lines. But, we

Fig. 3 Long term variability of the V/R at Hα, E.W. of CIV, and E.W. of Hα emission in 59 Cyg (from Doazan et al., 1985, 1986d).



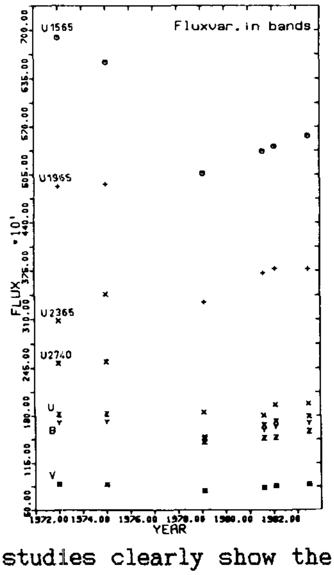
do not observe a one-to-one correlation, and even phase lags are suggested. γ Cas: The behaviour of γ Cas in the optical region during the last two decades is characterized by V/R changes with a 4-5 yrs cycle. In the far UV, the most remarkable changes are observed in the CIV resonance lines, where high-velocity narrow absorption components seem to occur erratically (Henrichs et al., 1983). However, by combining far UV and visual observations made in 1978-1986, we remark that the occurrence of these narrow components are associated with the long term behaviour of the Balmer emission-lines. They were present and strong in the NV, CIV, and SiIV resonance lines when V/R>1 (1978-1981); they were absent/undetectable/very weak when V/R<1 (1982-1985). In 1986, after a new change of V/R from < 1 to > 1, remarkably-strong, high-velocity, narrow components were observed in all our IUE spectra of that star (Doazan, 1986, Doazan and Thomas, 1986 b, Doazan et al., 1986 f). Figure 4 summarizes that association of long-term variability patterns of subionized and superionized features in γ Cas. Doazan et al. (1984 b) have suggested that a red wing feature in the SiIV lines is associated with V/R<1. But, they did not/could not (because the baseline in time was insufficient) propose any correlation between the high velocity components and V/R>1 (contrary to Snow and Stalio's, 1986, quotation).
θ CrB: The end of a shell phase of θ CrB and the normal B phase which followed it (1980-1986) are characterized by the same sequence of changes in the superionized and sub/normally ionized features. But these long term variability patterns exhibit a phase lag of ≃ 3 months (Doazan et al. 1986 a,b,c, see also Sect. 3).
Barker (1986) has observed a strongly correlated behaviour between the presence of high velocity components in the CIV lines and emission at Hα,

Fig. 4 Long term V/R variations at Hβ in γ Cas and the associated occurrence of high velocity narrow components (from Doazan and Thomas, 1986b)



which seems to be related to the modes of nonradial pulsations in λ Eri. That correlation shows the continuous interaction between the different regions of the atmosphere, from the subatmosphere to the outermost regions.

Fig. 5 Long term luminosity changes from the far UV to the visual in 88 Her through phase changes (B → Be-shell).



Although these long term studies clearly show the existence of associated long-term variability patterns between the superionized and subionized features, we note that we do not observe a one-to-one correlation. The important result obtained in these studies is that both features show the same long term trend, in spite of the evident large dispersion of the observed points. We also note that there is evidence for the existence of a phase-lag in the long-term changes of these two features for θ Cr B and possibly for 59 Cyg.

Finally, there exists a remarkable correlation between the far UV and visual luminosity changes (Fig. 5). An abrupt luminosity decrease, observed from the far UV to the visible region, precedes the onset of a shell phase in 88 Her (Barylak and Doazan, 1986). Doazan et al. (1986 c) showed that such a luminosity decrease could not be produced by only opacity changes in the cool envelope, as is usually assumed in traditional Be star modelling, even

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if that envelope completely covers the stellar photosphere. They concluded that the major cause which produces the transition between the quasi-normal B phase to the shell phase is a decrease in photospheric temperature. Therefore, either the thermal energy of the photosphere is directly converted into mass outflow, or part of the star's thermal energy is diverted by the subphotosphere and converted into nonthermal energy modes, which produce and amplify mass outflow.

2.4 Symbiotic structure of a Be star atmosphere

The spectrum of a Be star observed in a broad wavelength range, from the X-ray to the far IR, exhibits in a striking way a symbiotic character by the presence of both superionized and subionized spectral features, neither of which can be produced by the star's radiative energy flux alone. These different spectral features originate in atmospheric regions whose physical conditions are diametrically opposed. On the one hand, the presence and characteristics of superionized features imply the existence of rapidly-expanding, variable, superionized regions. On the other hand, a much lower temperature than the photosphere is necessary for producing the subionized features - Balmer and singly-ionized metal emission/shell lines - whose presence and characteristics imply the existence of extended, variable, slowly-moving, subionized regions. Any realistic Be star model must describe in a physically consistent way that symbiotic structure of their atmosphere. Clearly, if the origin of the Be-phenomenon were known, it would have been possible to predict, at least to a zero order of approximation, the existence of these different atmospheric regions and their gross characteristics. However, the different conjectures for the origin of the Be-phenomenon have not yet been able to predict neither the symbiotic character of Be stars atmospheres nor their specific variable behaviour. An origin in critical rotation, long ago proposed by Struve, predicts a mass ejection confined to the equatorial region only, whereas far UV observations show that mass ejection occurs all over the surface of the star. Current suggestions for a pulsational origin have not yet provided any means for producing only in Be stars that cool extended Hα-emitting region which distinguishes them from the other pulsating B stars. The same remark holds for those suggestions invoking solar-like hydromagnetic phenomena

2.5 Searches for a privileged direction of the mass-outflow

Several studies have investigated whether there exists any observational evidence for a privileged direction of the mass-outflow from Be stars. If such a direction existed, a correlation between vsini values and the size of the mass outflow would necessarily exist, especially if all Be stars were either rotating at a critical rotation, as is assumed in the rotation model, or, if Be stars were only fast rotators.

2.5.1 The superionized flow. Snow and Marlborough (1976) find a correlation between the existence of mass loss and vsini, while Snow (1981), Doazan et al. (1982), and Slettebak and Carpenter (1983) do not. Barker et al. (1984) have studied the largest samples, 72 Be and 82 normal B. They find no correlation between the E.W. of the CIV resonance lines and vsini. But, Peters and Marlborough (1986), using a subset of 32 stars of Barker et al.'s sample, suggest a possible trend between these two quantities. Grady et al. (1986), using almost the same sample of stars as Barker et al., but a larger number of spectra, studied a particular feature often observed in the CIV resonance lines of Be stars and hot supergiants: narrow absorption components, which are seen in 63% of their Be stars. They find that these components are not

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shortward-shifted in Be stars with vsini < 150 km s^{-1}, contrary to most Be stars with vsini > 150 km s^{-1}. They conclude that such a result provides evidence for a dependence of the outflow on vsini in Be stars. However, they also show that a large fraction of their sample exhibit strong narrow components at low velocity, thus, rendering ambiguous/unclear their conclusion. We also note that these authors focus entirely on the properties of narrow components. It is not clear whether they consider that an outflow exists only when narrow components are observed, or whether they consider that a Be star which does not exhibit narrow absorption components (37% of their sample) does not have a mass outflow. For this reason, the conclusions of Grady et al. are difficult to incorporate as they stand into a model. Obviously, much work still remains to be done in order to interpret the narrow components and to derive firm and unambiguous conclusions.

Finally, let us examine what kind of vsini dependence would be expected if a Be star atmosphere consisted of a rapidly expanding, superionized, polar flow and a slowly-moving, subionized, equatorial flow, as has sometimes been suggested. If such were the case, then: (i) A clear correlation between the measured expansion velocities and vsini would be observed, in the sense that the largest velocities would occur for low vsini values. (ii) The strongest far IR radiation would be observed for the lowest vsini values. (iii) No correlation would be expected between the behaviour of the subionized and superionized features. We note that the observations do not show correlation (i). Even worse, the inverse correlation is suggested by Grady et al. Gehrz et al. (1974) did not find correlation (ii); even worse, the inverse correlation is suggested by Waters (1986 a). Concerning correlation (iii) the examples of 59 Cyg, γ Cas, and θ Cr B show that subionized and superionized regions are dynamically linked in their long term behaviour.

Given the contradictory results obtained, thus far, the only clear conclusion is that if any vsini dependence of the superionized outflow in Be stars exists, such a dependence is probably not a strong one. In fact, all well-documented observations show that the amplitude of variations of the CIV resonance lines in Be stars is much larger than any vsini dependence effect found thus far. Therefore, we shall assume, to a first approximation, that the properties of the outflow in the superionized regions, as reflected by the behaviour of the CIV resonance lines, do not show any significant dependence on vsini, so that the study of that superionized outflow in the radial direction provides a realistic description of these regions.

2.5.2 <u>The shape of the cool Hα-emitting envelope</u>. The question is then raised whether the shape of the cool Hα-emitting region is that of a thin disk, as has been assumed traditionally in the rotational model, or if it <u>envelopes</u> the chromosphere-corona, i.e. if it has a spheroidal/ellipsoidal shape. Our analysis of the available observations lead us to the conclusion that the second geometry is in better agreement with the observations and their model implications. The difficulties met by the disk model have been discussed at length by Doazan (1982). In abstract: (i) The equatorial disk representation of Be stars atmospheres is a direct consequence of the basic assumption of the rotation model which postulates that <u>all</u> Be stars rotate at the critical rotation and eject matter in the equatorial region <u>only</u>. But, it is long known that the assumption of critical rotation does not have any observational justification. On the contrary, by showing that matter is ejected in all directions over the surface of the star, far UV observations strongly <u>contradict</u> that basic postulate of the disk model. (ii) The observed transitions from Be to Be-shell, and vice-versa, show that if the shell spectrum is produced only when the line-of-sight lies inside the thin disk, then the disk cannot be always thin. On the contrary, a large extension above and below the equatorial plane is required. We also note that 50% of the Be stars contained in Slettebak's (1982) vsini catalogue have exhibited a shell spectrum (see Bidelman's 1976 catalogue of "shell stars"). Under the disk model, this result would imply that about 50 % of the stars in Slettebak's catalogue are observed equator-on, or nearly-equator-on, which is obviously absurd. (iii) The disk model predicts a tight correlation between the small IR excesses and the large inclination angles, i.e. high vsini values (Poeckert and Marlborough, 1978). At 12 μ, the star is about 2 mag fainter at the equator than at small inclination angles. That prediction is strongly contradicted by the observations (Gehrz et al., 1974, Waters, 1986 a). The absence of correlation would imply that the Hα-emitting region completely envelopes the chromosphere-corona. Concerning the conclusions derived on the geometry of Be stars atmospheres from ad hoc modelling of the far IR energy distribution (Lamers, this Symposium), we refer the reader to our comments given in our Introduction. (iv) The argument that the observed polarization in Be stars implies the existence of a thin Hα-emitting disk should be rethought in the light of the new observations. . Polarization indicates the existence of an asymmetry of the fully ionized regions of the atmosphere, not of the cool envelope - polarization across the emission-lines is very small. Because there does not exist any polarization calculation for any realistic Be star model, i.e. which includes both the superionized and subionized regions of the atmosphere, the degree of asymmetry needed for interpreting the observed polarization is presently unknown..

So, even for interpreting observations made in the visible region only, the disk picture is not satisfactory: in most cases, the disk should extend to high latitudes. Quite little of the "thin" disk picture would then remain; a spheroid/ellipsoid would be a better geometrical approximation and would give a greater flexibility to the model. (Such a representation, quite evidently, does not forbid the envelope to rotate, nor the angular momentum to be transferred from the star to the outer-atmosphere). The contradictions encountered by the disk model are not new, but they are strongly enhanced by the new observations obtained since more than one decade.

3 MAIN CHARACTERISTICS OF THE MODEL

The stellar atmospheric structure is determined by the various fluxes, thermal and nonthermal, which exist in the star and by gravity. Modern observations show that nonthermal fluxes of matter and energy exist among both Be and normal B stars. The existence of such nonthermal fluxes requires that both types of stars be modelled as open, nonthermal systems (Thomas, 1973). Such nonthermal fluxes produce exophotospheric regions which exhibit various regional structural patterns (Thomas, 1983). If these fluxes vary, we expect that those atmospheric regions whose physical characteristics are determined by these fluxes, also vary (Doazan, Kuhi, and Thomas, 1980). Unlike normal B stars, all fluxes vary in Be stars: non-thermal fluxes as well as thermal (Doazan et al., 1986c). In our model, the Be-phenomenon is associated with that variable mass outflow produced by those nonthermal subatmospheric modes, which characterize Be stars.

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The mass outflow may be modelled in two ways: First, as the simple outflow of a normal star, which is accelerated and then eventually cooled. Such properties for the wind are not likely to produce these low velocity, dense regions characteristic of Be stars. Second, as an accelerated flow which is then decelerated. Such a flow produces a low velocity, dense region, where cooling is facilitated by the higher density of the flow. In our model, such a decelerated mass-outflow is produced by interaction of mass flows of different velocities which, occur at different epochs, or between the mass outflow and the local stellar environment. But, the interaction must be strong (see Sect. 3.1.5 and our answer to Bruhweiler in this talk).
For the reasons given in Sect. 2.5, our model describes, to a first approximation, a Be star as a spheroidal atmosphere. Rather than imposing an a priori strong constraint on the shape of the atmosphere, we left that question open. In this talk, we suggest that, due to the coupling of the star's rotation with the expanding flow, the shape of the Be star atmosphere is ellipsoidal, with a time-dependent degree of flattening.

3.1 A radial sequence of atmospheric regions

The first problem is to establish the relative locations of the superionized, rapidly-expanding regions and the subionized, slowly-moving ones. We abstract the arguments given by Doazan and Thomas (1982): (i) Because the outflow in the superionized regions does not show any clear/ strong correlation with vsini, the properties of the chromospheric-coronal regions are quasi-spherically symmetric, at least to a first approximation. (ii) It is long known that the observed emission in the Balmer lines requires the existence of a large emitting volume, thus an extended envelope. (iii) The fact that superionized lines are observed in absorption indicates that these lines are formed close to the star, in a small volume. We may, thus, conclude that the quasi spherically symmetric superionized regions immediately follow the photosphere and that the cool, extended, Hα-emitting region is located after the chromosphere-corona.
Before defining the radial sequence of atmospheric regions which describes our Be star model, it is important to recall that the mass outflow has a strong time-dependent character in Be stars. Moreover, in our model, the flow is decelerated. Therefore, we must not expect, as is done in all the other existing models, that the mass-outflow, determined by the expression $M' = 4\pi r^2 \rho(r) U(r)$ (where r is the distance expressed in stellar radii, ρ the density, and U the mass-outflow velocity) should be the same at all radii, as would be the case in a time-independent, monotonically expanding flow. Therefore, it is necessary to be precise in what region the mass outflow M' is determined. If M' is measured in the outermost regions of the atmosphere, it provides the value of the mass loss from the Be star. But, if it refers to regions close to the photosphere, i.e. if M' is determined from the superionized lines, that expression gives the value of the mass loss of the underlying star, as it would be observed in the absence of the cool envelope, whose presence distinguishes Be stars atmospheres from normal B's. This remark holds for any type of star where the outflow cannot be represented by a steady state. Indeed, "mass-loss" values inferred from superionized lines and Balmer emission-lines are usually different (Snow, 1981), with generally $M'_{UV} < M'_{H\alpha}$. Such a result is expected in our model, since the superionized flow "fills" the Hα cavity.

3.1.1 A quasi-thermal photosphere (RE, HE, $U \leq q/3$). The photosphere is the deepest atmospheric region that is directly observed at any wavelength. In

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that region $U \leqslant q/3$, where U is the outflow velocity and q the one-dimensional thermal velocity. So long as $U \leqslant q/3$, the flow does not affect by more than 10% the hydrostatic equilibrium (HE) equation, and does not dissipate mechanical energy, so that radiative equilibrium (RE) is preserved. These three conditions define a quasi thermal atmospheric region. The classical models describe its structure up to the point where $U = q/3$ (the thermal point in our model). Therefore, below the thermal point, the outflow velocity U can be determined from these models from the value of M'_{ph} at the photospheric level ($M'_{ph} = 4\pi r^2 \rho[\tau]\ U[\tau]$).

If $U \geqslant q/3$ at $\tau = 1$, the photosphere loses its quasi thermal character. For example, for a B0 star like γ Cas, Teff = 30,000 K, $R_* = 10\ R_\odot$, and the particle concentration $n_H(\tau=1) \simeq 5.8\times10^{14}\ cm^{-3}$ (from Mihalas's NLTE models). Therefore, the quasi-thermal character of the photosphere is preserved for that star if $M'_{ph} < 4\pi R_*2\rho(\tau=1)q(Teff) \simeq 10^{-4}$, where M' is expressed in $M_\odot\ yr^{-1}$. We note that this value lies near, but is less than the value of M' inferred from observations of WR stars, whose photospheres do not seem to have a quasi-thermal character.

The photosphere ends where RE becomes invalid due to the dissipation of a nonradiative energy. If that energy does not transport mass, RE is invalid before HE fails. Therefore, a chromosphere exists after the photosphere.

3.1.2 A chromosphere (HE, nonRE, $U \leqslant q/3$). This region begins where the nonradiative energy flux dissipates sufficient energy to raise the temperature significantly above the photospheric value, so that RE is no more valid. But if the condition $U \leqslant q/3$ is still satisfied, then HE remains valid. The chromosphere ends where HE becomes invalid, i.e. at the thermal point, where U first exceeds q/3. So long as $U \leqslant q/3$, the density distribution below the thermal point does not change, it is that of HE (at the chromospheric Te). A change in M'_{ph} only changes the velocity distribution U(r) below the thermal point and the height of the thermal point. Therefore, if M'_{ph} is time-dependent, U(r) is also time-dependent and reflects the changes of M'_{ph}.

Using a method of successive iterations, Doazan and Thomas (1982) have determined the distance where the HE density distribution ends, for different values of M'_{ph} and chromospheric temperatures (see their Tables 13.2 and 13.4). These tables show that the density at which the exponential decrease (HE) of the density distribution ends (i.e. the end of the chromosphere) and where a dynamic density distribution, as $(Ur^2)^{-1}$, begins is mainly determined by the size of the mass flux. We note that changes in the values of Te and gravity introduce only minor changes in that density value. Whatever the values of Te, M'_{ph} and g, the transition between the exponential decrease in density and the decrease as $(Ur^2)^{-1}$ occurs low in the atmosphere, $r_{ch} \simeq 1.007\text{-}1.01 R_*$ (cf. Thomas, 1973, for demonstration of this low-lying nature of chromospheres all across the HR diagram).

This substantial reduction of the density to the end of the chromosphere has important consequences for all those Be star models which ignore the existence of a chromosphere and begin the dynamic density distribution (as r^{-2}) in the photosphere, because they assume a density value which is too high at the bottom of the cool extended envelope. In fact, the situation is even worse, because the Hα-emitting envelope does not begin at the end of the chromosphere, but only after the corona. That region will introduce an additional density decrease at the base of the cool envelope.

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3.1.3 A corona (nonRE, nonHE). The corona is a region where both RE and HE are invalid, the former being already invalid in the chromosphere. Much more than the chromosphere, the corona is a region which is too hot for contributing significantly to the observed emission in the Balmer lines. Like the chromosphere, it creates a "hole" in the Be star atmosphere as observed in the visible region, which renews the old picture suggested by Mc Laughlin for a Be star: "a little planetary nebula". But, in the present picture, the hole is filled with superionized, rapidly expanding gas, whose dynamic impact on the cool envelope acts like a piston, which activates the oscillations of an amorphous reservoir of gas (Doazan and Thomas, 1986a). Unlike the photosphere and chromosphere, where the density decreases exponentially under HE, the coronal and post coronal regions are characterized by a dynamic density distribution, as $(Ur^2)^{-1}$. Two regions may be distinguished in the corona: The lower corona which begins at the thermal point and the upper corona which begins at the escape point.

(i) A lower corona (nonHE, nonRE, $U=q\pm\epsilon$, where ϵ is small and random). This region lies between the thermal point ($U=q/3$) and the escape point ($U=q=[GM/2r]^{1/2}$). In our model, the flow is not forced to reach the thermal velocity for the first time at the escape point, contrary to other models (see Thomas, 1983). If the outflow is accelerated above the thermal velocity before it reaches the escape point, the flow reacts by producing a shock, which decelerates it to subthermal values, and dissipates mechanical energy. If the flow is again accelerated, so that U exceeds q, the deceleration-heating process repeats. Therefore, the value of U fluctuates about q, and its average value remains close to, but just below q: the flow is transthermal. It is a locally unstable, time-dependent flow, even though the flow may be time-independent in the adjacent subthermic and superthermic regions. Since, when $U \geqslant q/3$, the local value of ρ depends on U as well as on gravity and on the thermal pressure, the local value of ρ will also fluctuate, hence be time-dependent, even though M'_{ph} is time-independent. Because the temperature Te(r) increases outward in that region, the outflow velocity increases outward and follows the variations of q(Te).

Let us examine now what happens when the value of M'_{ph} increases. We saw that $\rho(r)$ in the photosphere and chromosphere does not change when M'_{ph} changes, but the outflow velocity U increases, since it follows the changes of M'_{ph} ($= 4\pi r^2\rho[r]U[r]$). Therefore, the thermal point occurs at a lower height in the atmosphere, hence, at a higher density. In the transthermal flow of the lower corona, the situation is different. Let us first suppose, for simplification, that a change in the value of M'_{ph} is not accompanied by a change in the temperature distribution Te(r), i.e. the nonradiative heating is not due to energy dissipation of the flow. If the value of M'_{ph} increases, the density after the thermal point also increases. Thus, a change in the value of M'_{ph} is entirely reflected after the thermal point as a change of $\rho(r)$, which propagates outward with the outflow speed $U(r) = q$. Therefore, a variable mass outflow M'_{ph} at the photospheric level produces a variation of the outflow velocity in the photosphere and chromosphere, while in the lower corona, it produces a density variation, which propagates outward at the thermal velocity.

The effect of a variable mass outflow at the photospheric level is reflected in the lower corona with a phase-lag, whose maximum value depends on the location of the escape point (fixed by the temperature of the corona), since the chromosphere is always low-lying ($r_{ch} \simeq 1.01$). For a coronal temperature

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$Te = 10^7$ K, the escape point $r_{esc} \simeq 2$, and for $Te = 10^6$ K, $r_{esc} = 14$. Assuming a mean speed of the outflow of $\simeq 100$ km s^{-1}, the phase-lag may vary from a fraction of a day to several days. For a Be star similar to γ Cas, the phase-lag between a change of $\dot{M}'_{ph}$ at the photospheric level and its effect on the density at the escape point is of the order of a day for a corona with $Te = 10^7$ K, and about 2 days for $Te = 5{\times}10^6$ K.
These density changes of the outflowing gas in the lower corona, due to a variable $\dot{M}'_{ph}$ at the photospheric level, changes the opacity of the corona, hence, the chromospheric-coronal radiation field. For a particle concentration $n_H \simeq 10^{11}$-10^{12} cm $^{-3}$ at the thermal point, and 10^{10} cm^{-3} at the escape point, the opacity of the lower corona is $\tau \simeq 10^{-2}$-10^{-1}. Therefore, when $\dot{M}'_{ph}$ increases, the radiation field of the chromosphere-corona builds up rapidly and accelerates the flow before the arrival of the density perturbation at the escape point.
(ii) An upper corona (nonRE, nonHE, U>q)
The lower corona ends, and the upper corona begins, where the outflow velocity is accelerated above the thermal velocity, and remains above it, i.e. the flow leaves the transsonic regime and enters the supersonic regime. The upper corona ends, where this nonradiative energy dissipation, which produces the chromosphere-corona, becomes insignificant. If the flow is accelerated outward, either by radiative acceleration, or by some unknown mechanism, the flow velocity will exceed the escape velocity at some point. Such an acceleration exists, at least during some phases of the star's variation, because superescape velocities are observed. It is clear that a radiatively driven wind due to the photospheric radiation field cannot be invoked for most Be stars whose luminosity is less than the luminosity limit. Moreover, the observed variability of the outflow would rule out such an interpretation. We have suggested that the observed superescape velocities are due to radiative acceleration from a chromospheric-coronal radiation field and that the observed velocity changes are produced by changes in radiative acceleration due to the variable opacity of the chromosphere-corona. These velocity changes depend on the changes of both the temperature and the opacity of the chromosphere-corona produced by the variable mass-outflow at the photospheric level.
3.1.4 A post corona. In the post corona, the flow begins to cool, since nonradiative heating has ceased in that region. But it continues to be accelerated by the chromospheric-coronal radiation field, at least during some phases of the star's variation. Up to this point, normal B and Be stars have the same regional atmospheric structure, although these two types of stars differ profoundly in the temporal behaviour of the nonthermal fluxes, which determine that structure. The fundamental difference between the atmospheric structure of normal B and Be stars resides in the fact that the sequence of regions defined above describes the entire atmosphere of normal B stars, while for Be stars, there exists an additional, low-velocity, cool, extended envelope - where emission/shell Balmer lines originate during Be and shell phases - which may or may not be followed by a dust shell.
3.1.5 A low-velocity, cool, extended, Hα-emitting envelope. The cool envelope is probably the most complex region of the Be star atmosphere. It is formed after a shock in the post corona, but its location is imprecise. It may be described as a pulsating cavity, which is feeded by the variable mass outflow from the underlying star.

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The sequence of regions described above interprets in a self-consistent way the observed changes of the superionized lines in Be stars by changes in the value of M'_{ph} at the photospheric level and changes in the nonradiative energy flux, which determines the temperature distribution Te(r) in the chromosphere-corona. Depending on the size of these fluxes, i.e. on the epoch of variation, the variability of these two nonthermal fluxes may produce a deceleration of the flow in two different ways: (i) By self-interaction of mass-outflows of different velocities. (ii) By interaction of the radiatively accelerated outflow with the existent local environment. In the first case, the radiation field of the chromosphere-corona is insufficient to radiatively accelerate the flow, while in the second case, it is.

(i) If the opacity of the chromosphere-corona is too small to radiatively accelerate the flow, the maximum outflow velocity is determined by the temperature of the corona. We already saw that a change in the value of M'_{ph} changes the density of the flow after the thermal point, and that a change in the value of the nonradiative energy flux (i.e. the temperature of the corona) changes the location of the escape point, hence, the velocity at that point. Therefore, by increasing the nonradiative energy flux, which may or may not accompany an increase of M'_{ph}, the higher velocity flow will be decelerated, by overtaking the lower-velocity flow from a preceding epoch. That case is similar to the situation modeled by Kwok (1981) and discussed by Thomas (1983). After an abrupt temperature rise due to the shock, the flow cools rapidly because of its high density, and forms that low velocity extended region, where Balmer emission lines originate.

(ii) Let us now examine what happens when the chromospheric-coronal radiation field is efficient for accelerating the flow. Let us suppose that M'_{ph} increases from M'_{ph1} to M'_{ph2}, keeping Te(r) constant for simplicity. The density and the opacity between the thermal point and the escape point increases steadily as the density perturbation propagates from the thermal point to the escape point, hence, the radiation field increases steadily. Therefore, the velocity of the mass outflow which reaches the Hα envelope increases regularly during that interval of time, of the order of day(s). After the escape point, the acceleration is the same everywhere in the post coronal region (if we neglect absorption effects) so that adjacent regions of the flow will not show any abrupt velocity changes between them. Hence, there will not be any strong interaction nor shocks between successive flows. But, these flows will interact with the cool envelope formed earlier by the process (i) when the opacity of the chromosphere-corona was too small to radiatively accelerate the flow. Our far UV observations of θ CrB have shown that even during a normal B phase there exists a variable nonradiative heating and a variable mass flux from the Be star (Doazan et al., 1984 a, 1986 a,b). Therefore, already during its normal B phase the Be star creates its local environment, but its density is too low to be detected. When the flow reaches the cool envelope, it is continuously decelerated by interacting with that environment through a series of shocks. The process is similar to a variable piston driving an amorphous mass, which is the cool envelope. If the envelope is very thin, the post coronal "equivalent piston" acts like a snowplough. If the envelope is very massive, the impact of the flow on the envelope propagates as a perturbation travelling at the local thermal velocity. We note that while the variation of M'_{ph} may be driven by stellar pulsation, of whatever variety, the impact of the "equivalent piston" formed by the variable superionized outflow on the cool envelope will inevitably produce some kind of pulsation of the Hα-emitting cavity. It is thus obvious that the interaction of the post corona with the Hα envelope is strong, and that the interacting region which transmits the impact of the superionized flow on the cool envelope is of crucial importance in our model (Stalio's, 1985, comments on our model should be rectified accordingly).

The location of the envelope is such that the observed velocities ($\leqslant$100 km s^{-1}) are near the escape value. The variable momentum supply provided by the "piston-like" post-coronal flow can drive the material up to escape velocity at some epochs, and retard it below that value at other epochs. The whole envelope may be essentially static, or pulsating, or slowly expanding, or contracting, depending on the time-history of the flow. Therefore, the existence of a mass-outflow at superescape velocities from the underlying star does not imply that the Be star always loses mass and we should not expect that the values of M'_{UV} should be the same, in general, as $M'_{H\alpha}$.

In the above picture, the largest variations occur at the base of the cool envelope, while the variations are damped in the outermost regions. That difference in the behaviour of the inner and outer regions of the cool envelope has been observed in several Be stars (Doazan, 1965, Delplace, 1970). Depending on the location of the interacting region and on the size of the velocity in that region, the cool envelope will exhibit outflows as well as inflows, and given the time-dependent character of the flow, the velocity law in the envelope may be accelerated, decelerated, or constant. Obviously, the fact that the flow has been decelerated, does not imply that the velocity law is decelerated in the cool envelope (as Waters, 1986b, has wrongly stated when discussing our model). Consequently, our Hα cool envelope may produce emission-line profiles with V/R>1, <1, or=1, as well as positive, negative, or constant Balmer progressions, while only V/R$\leqslant$1 and negative or constant progressions are allowed in all those models which represent the cool envelope as a time-independent, simple outflow.

Velocity laws inferred from the observed emission-line profiles, or far IR energy distribution (via the density distribution) have been derived under the assumption that the envelope is in a steady state. Clearly, observations of Be stars do not support such an assumption, and the velocity/density distribution which describes the envelope at a given time does not describe the velocity/density distribution of the flow as it travels from the underlying star to the outermost regions (several days/weeks). For that reason, the conclusions derived under the assumption of a steady state flow have probably very little in common with the real situation in Be stars, putting aside the ad hoc character of the models used for deriving these velocity laws. Obviously, there still remains much work to be done on that problem.

3.2 Radial distribution of density in a Be star atmosphere

The radial distribution of density in a Be star atmosphere may be determined in a quantitative way by using the method given by Doazan and Thomas (1982), or by simply using their Tables 13.2 and 13.4 - given the classical stellar parameters, Teff and g, and M'_{ph} and the temperature of the chromosphere and the corona, which may be inferred from the observed spectrum of the star in a broad spectral range.

Let us take once again the example of γ Cas, with Teff = 30,000 K, logg = 4, and $n_H(\tau=1) = 5.8\times10^{14}$ cm^{-3}. We consider two values of M'_{ph}: 10^{-7} and 10^{-9}, and determine first the outflow velocity in the photosphere at τ=1.

For $M' = 10^{-7}$, $U(\tau=1) = 10.5$ m s^{-1}; for $M' = 10^{-9}$, $U(\tau=1) = 10$ cm s^{-1}

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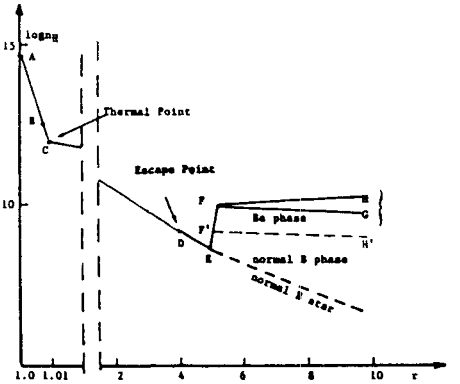
This shows that the flow is slow in that region.
From Table 13.2 of Doazan and Thomas (1982), we obtain the values of n_H at U=q. To get the value of n_H at the thermal point, U=q/3, we simply multiply by 3 the values given in that Table. For a chromospheric temperature Te = 80,000 K (q/3 = 12 km s^{-1}), we obtain the following values:
For M' = 10^{-7}, $n_H \simeq 10^{12}$ cm^{-3} at r = 1.01
For M' = 10^{-9}, $n_H \simeq 10^{10}$ cm^{-3} at r = 1.01
For a corona with Te = 5×10^6 K (q = 290 km s^{-1}), the escape point (U=q) is located at $4R_*$. Table 13.5 from Doazan and Thomas(1982) gives the following values for n_H: For M' = 10^{-7}, $n_H \simeq 10^9$ cm^{-3}; for M' = 10^{-9}, $n_H \simeq 10^7$ cm^{-3}. The large decrease in density (as $[Ur^2]^{-1}$) between the thermal point and the escape point is due to the increase in velocity from 12 to 290 km s^{-1}, and to the increase in radius from 1 to $4R_*$. Thus, we see that the presence of a chromosphere-corona strongly reduces the density in the post coronal region. The extent of the region where the flow is accelerated after the escape point is still unknown. It depends on the time-history of the flow, and on the accelerating mechanism and efficiency. Let's assume that the flow is accelerated over $1R_*$ after the escape point, and that the deceleration occurs at $5R_*$. For γ Cas, we know that the flow is accelerated at some epochs up to ≃ 1500 km s^{-1}. Therefore, at the end of the post coronal region, the density has decreased by a factor ≃ 8, so that $n_H \simeq 2\times10^8$ cm^{-3}. The observed velocity in the Hα-emitting region is of the order of 30 km s^{-1}. Therefore, the deceleration produces an increase in density of about a factor 50. Thus, at the base of the post shock region, $n_H \simeq 10^{10}$ cm^{-3}. Doazan and Thomas (1986c) have shown that for such a value of n_H, the observed Hα emission-line is optically thick at the line center and at three Doppler widths, and the extent of the Hα-emitting envelope is $r_{env} \simeq 10.6$, in agreement with its observed diameter (Thom et al., 1986). We give in Figure 6 our model representation of the atmosphere of γ Cas as defined above. The density distribution of a Be star during its Be/shell phase is represented by ABCDEF(GH). The density in the post coronal region of an undecelerated flow is too low for producing the observed Balmer emission-lines in a moderate/strong Be phase. A normal B star is also represented in this figure for an accelerated flow. In order to exhibit Be/shell characteristics, the star must "fill" the cavity between the normal B star and the Be/shell phase. Before our far UV observations of θ CrB, we would have represented a Be star in its normal B phase by the same density/velocity/temperature distribution as that normal B star. But these observations have shown that, even during its normal B phase, the mass outflow is variable in a Be star. Hence, some enhancement of the density in the post coronal region - some filling of the cavity - which may start at a lower radius, will be produced by interaction of successive flows, at least at some epochs. Therefore, normal B phases of Be stars have, at some epochs and on the average, post coronal regions of higher density than normal B stars. Thus, the normal B phase of a Be star lies between the normal B star density distribution and the region where the density begins to be just sufficient for detecting Be/shell spectral features, ABCDEF'H' on Fig. 6. Doazan, Stalio, and Thomas (1981) gave in their Figure 4 a schematic representation of the regional atmospheric structure of γ Cas. That sequence of regions, which has been defined by Heidman and Thomas (1980) has been first proposed by Doazan, Kuhi, and Thomas (1980) for modelling and interpreting the mass flux variabilty in Be stars, on the basis of their far UV observations of 59 Cyg made in 1978.

Fig.6 Schematic representation of a Be star atmosphere (γ Cas). $M'_{ph}=10^{-7}$. AB: photosphere (RE, HE); $\tau=1$ at A. Nonradiative heating renders RE invalid at B. BC: chromosphere, nonRE, HE; at the thermal point C ($U=q/3=12$ km s^{-1}), $Te_{ch}=80{,}000$ K. CD: lower corona (nonRE, nonHE); transthermal flow, $U \simeq q$, $Te_{cor}=5\times10^{6}$K, D: escape point ($U=q=290$ km s^{-1}). DE: upper and post corona, accelerated flow; at E, $U=1500-2000$ km s^{-1}. EF: decelerating region. F(GH): cool Hα pulsating envelope, $U \simeq$ 30-100 km s^{-1}, $Te= 1-2\times10^{4}$ K. The normal B phase lies between the normal B star and F'H', where the density becomes just sufficient for detecting Be/shell spectral features.



Unfortunately, as has been concluded by Doazan, Stalio, and Thomas (1981), that 1981 figure fails to represent the cool envelope of a Be star, because the density is too low in the post coronal region to produce the observed Hα emission. In that 1981 paper, the problem of the representation of the Be phase, i.e. of the filling in of the cool Hα envelope was left completely open. For that reason, that 1981 figure represents a Be star in its normal B phase, not in its Be phase. Therefore, the description of our model given by Stalio (1985) and Snow and Stalio (1986) should be rectified, accordingly. But, we note from the above discussion, and under our present evolved model, that that 1981 figure does not even represent a Be star in its normal B phase, but simply a normal B star (Doazan and Thomas, 1984).

3.3 The asymmetry of the Be star atmosphere

We note first that if the mass outflow is variable with time and if we neglect the star's rotation, the interaction between the different outflows, or between the outflow and the local stellar environment, is the same in all directions. The Be star atmosphere is spherically symmetric everywhere and its structure is described in all directions by the same radial sequence of atmospheric regions, which is given in the preceding section. When the star's rotation is taken into account, two effects may introduce an asymmetry in the flow: First, due to the star's rotation, the escape velocity, hence the location of the escape point is different at the equator than at the pole (Doazan and Thomas, 1982). Second, the coupling between the star's rotation and the expanding flow may introduce a differential latitude effect, because the decrease in angular momentum from the equator to the pole produces a differential structure in the local stellar environment. Due to the latitude dependence of the total velocity (radial and rotational), the interaction will be stronger at the equator than at the pole.

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Consequently, the largest increase in density in the post shock region is expected to occur at the equator. The resultant configuration of the post shock region would no more be spherically symmetric, but ellipsoidal, "egg-shaped". Such an asymmetry may produce the observed linear polarization of the radiation in Be stars. In that picture, the observed polarization may occur in two atmospheric regions: in the chromosphere-corona, and at the base of the cool envelope. As has been said in Section 2, it is necessary to reexamine the conclusions derived, thus far, on the degree of asymmetry needed for producing the observed polarization in Be stars, because these conclusions are based on the assumption that the entire Be star atmosphere consists of only a cool envelope. Since one decade, we know that, even to a zero order of approximation, such an assumption is illegitimate. Clearly, calculations based on more reasonable assumptions are still needed for deriving sound conclusions on that subject.

Under the above picture, the degree of departure from spherical symmetry will depend on both the rate of the star's rotation and on the size of the mass outflow, hence, the degree of asymmetry will be time-dependent. Hence, the same star may exhibit a whole range of degrees of asymmetry, from the spheroidal to the highly ellipsoidal configuration, as a function of time. But, for the same size of the mass-outflow, the departure from spherical symmetry will be the largest for the fastest rotating stars, and conversely. That conclusion is in agreement with polarization surveys which show that, on the one hand, only few Be stars have both a small vsini value and a large polarization and, on the other hand, stars having high vsini values exhibit both small and large polarization rates (Mc Lean and Brown, 1978).

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DISCUSSION FOLLOWING DOAZAN

Slettebak:

With regard to your comment that 50% of the stars in my catalogue of Be stars brighter than the sixth magnitude are in Bidelman's list of shell stars (Proceedings of IAU Colloquium No. 70), I should point out that Bidelman's definition of "shell star" is a very generous one. If I remember correctly, he calls any Be star a shell star if the central absorption in the $H\alpha$ emission line drops below the stellar continuum.

Doazan:

But, this is the way a shell spectrum is usually recognized observationally!

Plavec:

In interacting binaries which display total eclipses, we observe two types of emission lines: a) Balmer line emission at $H\alpha$ (sometimes at higher Balmer lines). This emission seems to arise in a rotating ring, which may be totally eclipsed if the secondary is large enough; b) High-ionization UV emission lines (NV, CIV, SiIV, FeIII,...) which must be formed in a larger region, since they are at most only partially eclipsed. These lines do not originate in the chromospheres of the cooler components, since they are several orders of magnitude stronger. Their energy is most likely generated by the release of the gravitational potential energy of the mass-transferring stream.

Doazan:

I am afraid that we are not speaking about the same features since in all the *IUE* spectra of Be stars I have inspected or analyzed (and they are numerous) I have never observed any emission lines in the NV, CIV, and SiIV resonance lines. These lines are always in absorption.

Snow:

I've been trying to find clear-cut observational tests of models, and perhaps I can suggest one for your picture. It seems clear that in your model, regardless of details of the geometry, the region where the high-velocity wind exists is *inside* the region where $H\alpha$ arises. Therefore, wouldn't your model predict that disturbances propagating outward should be observed in the UV before they show up in $H\alpha$? If so, this suggests that simultaneous UV and $H\alpha$ observations over times of hours could definitively test whether the high-velocity wind is inside the $H\alpha$ region or not. Perhaps the discrete absorption components seen in the UV would provide this test, if these components represent mass flux enhancements that would also affect $H\alpha$.

Doazan:

What you say is perfectly correct. Any change in the superionized flow should produce a change in the $H\alpha$-emitting region. Our scenario may be understood in two steps: (i) An increase in mass-outflow at the photospheric level produces, as explained in the talk, an increase of the density at the coronal level, hence a rise in the coronal opacity, i.e. in the radiation intensity from the corona, and consequently in the coronal acceleration of the flow after the escape point (assuming that Te(r) does not change when the photosphere changes). But, the coronal opacity increases at the speed of the outflowing matter, i.e., $\sim$ 100-400 kms^{-1} at the escape point, while the coronal radiative acceleration propagates at the speed of light. Therefore, the effects of the change of radiative acceleration at the *beginning* of the $H\alpha$-envelope are felt *before* the effects of the new mass outflow-of higher density in the post coronal region-is observed. If the distance between the escape point and the interacting region is 1 R_*, then a flow at 1000 kms^{-1} has a delay time of $\sim$ 0.1 day

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between these two regions. (ii) The largest phase lag comes between the bottom and the top of the Hα envelope. Assume a flow of 100 kms^{-1}. It will traverse a 10 R_* envelope in about 10 days, if it were undecelerated by the existing environment and gravity. If it were decelerated, it would propagate at the speed of sound $\sim$ 10 kms^{-1}. Therefore, the phase lag would be about 100 days. In fact, the phase lag should be between these two numbers for such an extended envelope. Clearly, if the envelope extent is much smaller, such as that of 59 Cyg in 1978-1985, the phase lag would be smaller. This means that in order to follow the "disturbance", it is necessary to observe several parts of the cool envelope, as for example the whole Balmer series. The existence of such a phase lag in that cool envelope has been noted several times from the different epochs at which V/R changes occur in the Balmer lines. This is why we observe the whole Balmer series in our Be star monitoring program. The important result of our long term study of 59 Cyg and θ CrB is the existence of an associated variable behavior between CIV and Hα emission. We do not expect, nor do we observe a tight correlation.

Prinja:

In the UV observations of variability in the resonance lines, it is not easily possible to differentiate between ionization and density effects without sampling the dominant species.

Baade:

Would you not expect to see emission lines due to the shock assumed in your model? I know from experience with other observations that I can reach a S/N of $\sim$ 20,000 at a resolving power of $\sim$ 15,000. Would it, with this sensitivity, be worthwhile to search for such emission?

Doazan:

This is a long-standing problem. The initial shock gives a high kinetic temperature, which rapidly decreases via translation into collisional excitation of internal energy of the gas. This hot region will, therefore, produce emission-lines and x-ray emission. But, of what size and in what region, that, we don't yet know.

Underhill:

What do you see in the CII resonance lines-emission? Absorption lines? Or nothing other than IS lines? These compared with the observed CIV lines put limits on the physical state of the plasma around the star. It would be helpful also to track the apparent abundance of CIII by means of the 1176 Å multiplet.

Doazan:

No, I have never observed any emission in the CII resonance lines in any *IUE* spectra of Be stars. But I have observed small changes in the depth of the narrow absorption, interstellar-like, cores of the line in θ CrB, for example, as has been reported in our paper on the long term changes of this star.

An abundance analysis by means of the CIII multiplet at 1175 seems to me quite uncertain, because the extraction of the data in this region of the *IUE* spectra causes severe problems.

Underhill:

What you describe can be said to be a result of interaction with the environment, with the interstellar medium surrounding the stars. The character of the *environment* determines where the external shock lies and the behavior of much of your model.

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Doazan:

No. Contrary to what you say, in our model the interaction is produced between different *stellar* outflows, not between stellar outflow and interstellar environment, as in the interstellar bubble model. The best illustration of what happens in a Be star is given by θ CrB for which variable mass outflows are observed during a "normal B phase", as evidence by the variations of the CIV resonance line. This variable outflow builds a local *stellar* environment into which runs the following stellar outflow.

Marlborough:

Many of the Be stars, whose UV spectra I have seen, show strong CII resonance lines at λ 1335 in absorption. There appears to be emission.

Dachs:

In constructing your model, you purposely left aside all available information on relations between vsini and emission- line profiles in optical spectra. I anticipate you will run into large difficulties with trying to integrate these observational findings into your model.

Doazan:

The only conclusion that our model does not retain - and which is usually postulated in Be star models based on only visual observations - is that Be stars rotate at the critical rotation, and therefore, eject matter in the equatorial region *only*. We never said that Be stars do not rotate! Clearly they do! Therefore, as the photosphere rotates, the envelope will also rotate, because angular momentum will be transferred from the photosphere to the envelope. The situation in our model is similar to that of any other Be star model, and a *loose* correlation with vsini is expected. This correlation will depend on the mechanism of transfer of that angular momentum, that nobody has solved until now, as is well known. I do not see why and how the visual observations will cause any particular difficulty for our model.

Smith, M.A.:

You are perfectly right, of course, that the "pulsation people" provide you with particular non-radial mode identifications and associated correlable factors. The problem is a simple but severe one: The stars that you consider and model here do not allow us to see *bona fide* photospheric features. So, it is very difficult for us to tie these kinds of observations, in particular line profile variations, to the subset of stars you are most interested in. For a good while yet the pulsation people are going to have to break off a very small part of the problem that can be understood.

Doazan:

The results given in this table refer to Be stars which exhibit a wide range of characteristics: Be (59 Cyg, γ Cas), 88 Her (Be-shell), θ CrB (B normal). Therefore, I wonder what other kind of characteristics you would like to see exhibited. I would think that θ CrB should provide you an excellent example of a Be star where photospheric lines are perfectly "clean" for studying changes in the photosphere.

Baade:

It has been said (van den Heuvel, these proceedings) that the x-ray observations of Be stars are inconclusive, as far as a general comment is concerned. From the work by Pauldrach (1986) it further seems possible that superionization is a non-LTE effect in a cool wind, *a la* Castor, Abbott, and Klein. If one *hypothetically* assumes that Be stars do not have a corona/ chromosphere, would you then still see a possibility to place the

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high-velocity wind below the low-velocity, high-density region? Please do not just discuss the justification of such an assumption but who also implications in the framework of your model.

Doazan:

My understanding of van den Heuvel's talk is that x-ray observations of γ Cas did not show any reliable data for identifying a compact companion. This seems to me rather strange because γ Cas is the best observed Be star. Because coronal x-ray emission is observed all across the H-R diagram, in particular, in a number of normal B stars as well as in Be stars, I do not see how one may exclude, *a priori*, the existence of such coronal emission in Be stars. We observe such x-ray emission in τ Sco, as well as in ζ Oph! Note that the existence of a dense cool envelope in Be stars will render the detection of x-ray emission even more difficult for these stars. Therefore, unless one is able to explain x-ray emission by non-LTE effects I do not see how you can avoid the existence of superionization. Note that the work of Pauldrach is not able to explain the presence of OVI in τ Sco!

If you want to speculate that Be stars do not have superionization, i.e. nonradiative heating, then the observations would still require that the high-velocity outflow lies inside the low-velocity flow simply because we observe only absorption lines with high-velocity flow, which is compatible with an origin in a small emitting volume, instead of emission lines, which would require a much larger volume. By contrast, emission lines, which require a large emitting volume, are observed in the low- velocity flow. This large extent has been confirmed by direct interferometric observations made by Granes on γ Cas. This point is a strong-one on which our Be star model is based (Doazan and Thomas, 1982, Thomas, 1983).

Grady:

Your model predicts that strong and variable winds should be present (or detectable in CIV, SiIV, etc.) at all latitudes. This is inconsistent with the absence of enhanced winds and shortward-shifted discrete components in Be stars with vsini $<$ 150 km s^{-1}. If one assumes that the chromosphere/corona is ellipsoidal due to rapid stellar rotation, one expects enhanced emission in the stars viewed at high latitude compared to the stars viewed at low latitudes. If the low vsini Be stars correspond to the stars viewed at polar latitudes, the low vsini Be stars should show enhanced emission compared to higher vsini Be stars. This is not observed.

Doazan:

Our model is empirical, i.e. it is based on the observed properties of Be stars. Statistical studies made on the vsini dependence of the behavior of the NV, CIV, and SiIV resonance of Be stars, or that of mass loss derived from these same lines, have given confusing and contradictory results. Clearly, if a strong dependence of these quantities on vsini existed, this confusing/contradictory situation would not exist, and a clear correlation with vsini would have rapidly emerged from the considerable amount of available data. This situation led us to simply assume, to a first approximation, that the same radial sequence of atmospheric layers was observed in all directions. We also clearly stated that any asymmetry demanded by the data could be included in our model. In this paper we introduce the effect of rotation, which produces a slight asymmetry.

Our model does not predict any significant emission from the chromosphere-corona because this region has a small extension; this is in agreement with the observations.

Ballereau:

How can you explain large radial velocity variations of the whole emission in Hα and Hβ lines, in correlation with V/R?

Doazan:

I do not think our model causes more problems than any other model. In fact, it suppresses several of these problems. As I have schematically indicated, our model is compatible with both V/R $>$ 1 and V/R $<$ 1 at the emission-lines, as well as in the positive and negative Balmer progressions. This is not the case for Poeckert and Marlborough's models.

Concerning the shift of the whole emission-line when V/R changes from $>$ 1 to $<$ 1, and vice-versa, we suggest that such a shift arises due to occultation effects, which may be quite important in our model. Because our cool Hα envelope begins at $\sim 2-4$ R_*, contrary to other models where the cool envelope immediately follows the photosphere, significant occultation effects are expected in our model. These will cut the red emission wings when V/R $<$ 1 and, therefore, produce an apparent shift of the whole line toward the violet, and vice-versa.

Ballereau:

How can you explain long distances covered by matter when you observe very large negative radial velocities (-50 to -100 kms^{-1}) over several years, which may represent 500 to 1000 R_*? (ex. 48 Lib, HD184279 and other V/R type stars?)

Doazan:

Your comment assumes you observe the *same material* for several years. You don't. You observe the *same region* of the outflow. So, you cannot say that the material covers long distances.

Granes:

Presently, our interferometric measurements seem to be in agreement with your model concerning the size of the envelope in the U plane and the symmetry in respect to the central star. Are you able to give a major axis/minor axis ratio; and if not, is this ratio big enough to be detected by interferometry as a different diameter than the actual?

Doazan:

When we calculate with our model the upper and lower limit of the diameter of the cool Hα-emitting envelope of γ Cas from the Hα emission measure determined at the epoch of your interferometric measurement, we determine a diameter where $\tau=1$ in agreement with your value. But we must still find, in a more precise way, to what value of τ in the Hα line your observations refer. Clearly these observations are very important for discriminating among various models. I would like to remind you that the emission at Hα is about 2.5 times stronger than the value used in the Poeckert and Marlborough model. The present Hα emission would therefore produce, under this model, a much bigger envelope diameter than the one derived in the published model.

Concerning the ratio of the major and minor axis of the envelope, we are not yet able to give a value.

Harmanec:

One possible test of the relative position of the different regions you postulate in your model is that the width of different observed lines should agree with the expected velocity field in photosphere/chromosphere/corona/cool envelope.

Doazan:

In order to determine line widths and line profiles, it is necessary to solve the transfer problem in the whole atmosphere, in a self-consistent way. Nobody has ever solved it in the case of complex atmospheric structures, such as those of Be stars. In particular, when there exists even a small rotational velocity field, the curves of constant radial velocity are closed and the line of sight intersects each of the curves in two different regions of the atmosphere. In this case the Sobolev approximation does not hold and a complete transfer solution must be made.

In our model, it is clear that the relatively small extent of the superionized region will not produce any significant emission component in the superionized lines, and the absorption lines will reflect mainly the radial velocity field, i.e. the expansion velocities, which show a large range of values. This is precisely what is observed. On the contrary, the subionized regions, which are the most extended, will produce emission lines - as is observed in the Balmer lines. On the one hand, this region being already decelerated will exhibit lower velocities and a lower range in velocities than in the superionized regions. On the other hand, the rotational broadening, which is the largest at the two edges of the envelope, will provide the main broadening of the emission-lines.

Harmanec:

A second test has to do with the fact that I have always had the impression that the observations of eclipsing binaries by Mirec Plavec and his collaborators indicate that the Hα emission region is closer to the star than the region producing the UV resonance lines because the Hα emission disappears during the total eclipses while the UV resonant lines do not. Can somebody comment on this point?

Doazan:

The *IUE* spectra of eclipsing binaries show a much more complex behavior than those of Be stars. The studies and spectra I have seen do not convince me that it is as simple as you say to separate the contribution of the two components of the binary.

Bruhweiler:

Surely, you can make more quantitative models. Also, your model is very similar to the "interstellar bubble" model as presented in Weaver et al. (1978) and also McCray et al (1975). I would think that this would be not a difficult task.

Doazan:

Our model has some similarity with the interstellar bubble in the sense that it involves collisional deceleration of an outflow as it meets a previously existing medium. But, in another sense, our model is quite different. In the "bubble" model, the deceleration is produced by interaction of the stellar outflow with the interstellar medium and the bubble is formed at some parsecs from the star. In our Be star model, the deceleration is produced by interaction between the stellar outflow at one epoch with a preceding slow flow, and the envelope is produced within a few stellar radii from the star. So, clearly, there is a big difference between the "bubble" and the Hα envelope.

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Bruhweiler:

The mass loss in Be stars can be measured. At least one can make some estimate of the gross parameters (i.e. density, radius of evacuated cavity, density distribution surrounding shell, and emission measure in observable spectral lines). This should not be too difficult to do.

Thomas:

Let me be more specific on what Vera said. The "bubble" model of McCray et al. consists of a mass-outflow from, e.g., a Wolf-Rayet star which is assumed to sweep up all the interstellar-medium between the star and wherever the bubble forms. Roughly, the mass outflow from the star sweeps up the interstellar medium to such a radius that the momentum sent out in the stellar wind is balanced by the amount of swept-up interstellar matter. This is *not at all* the picture for either a Be-star, a T Tauri star - or even the planetary nebulae, in, for example, Kwok's model of the latter. Crudely, these stars have no cavity in the interstellar medium. The bubble model begins at parsecs from the star. The Hα-envelope of Be stars begins at a few radii.

We view the Hα-envelope as a "storage-balloon", continually being filled but the envelope need not transmit all that it receives; that it does not explains the phase changes of Be stars. The density in the Hα-envelope grows, not simply because the photospheric outflow increases or decreases - which it does, observationally - but because the envelope does not simply transmit what it receives.