VIII. ATMOSPHERIC MODELS

MODEL ATMOSPHERES OF Be STARS

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1. INTRODUCTION

The basic concept of what a Be star is we owe to Struve (1931). His proposal that these stars are rapidly rotating and have an extended, disc-like, circumstellar envelope is still the basis for all models of Be stars. Unfortunately, progress in understanding the dynamics of Be stars has been painfully slow, a consequence of the very complex nature of the problem. As yet there does not exist a self-consistent unique model of any Be star.

Marlborough (1976) reviewed the state of Be star models at the last IAU Symposium (No. 70) on Be and Shell Stars. The emphasis of this review will be on the advancements in the modelling art made in the five years since that symposium. Then, as now, all models which attempted to relate directly to observed properties of Be stars were, to a greater or lesser extent, ad hoc.

2. GENERAL THEORY

The equations governing mass flow, the radiative transfer problems, and the role that turbulence and magnetic fields might play have been outlined by Marlborough (1976). Generally, the mass flow problem and the radiative transfer problems are dealt with separately, simultaneous solutions being very complicated.

2.1 Mass Flow

Much of what we think we know about mass loss in early type stars comes from models of stellar winds in O type stars. These models usually assume spherical symmetry so the problems are somewhat simpler than in the case of Be stars. It is useful to consider the O star wind models because much of what is learned there can be applied to Be stars.

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The radiatively-driven-wind models of Cassinelli and Castor (1973) and Castor, Abbott and Klein (1975) have, in recent times, had to be modified to incorporate a high temperature ($T > T_{PHOTOSPHERE}$) region. The need for such a modification arises out of the observations of lines from highly ionized species (e.g. O VI) in the spectra of O stars. A summary of the various wind models is given by Cassinelli, Castor and Lamers (1978) and Cassinelli (1979). Three models are proposed, a modified cool-wind model, a warm-wind model, and a corona-plus-cold-wind model. All of these models require some non-radiative heating, but all assume that it is solely the radiation pressure that drives the wind. Also, these models constrain the wind to accelerate smoothly through the transonic region. The radiatively-driven-wind models are successful in matching terminal velocities. Moreover, low metal abundance O stars in the LMC and SMC show little or no sign of stellar winds, which is probably linked to the lack of lines by which the wind is accelerated (Hutchings 1980; Prevot et al. 1980; Hutchings, private communication).

Cannon and Thomas (1977) argue that the non-radiative heating governs the flow and it is an artificial constraint to require a smooth transition through the sonic point. If the flow through the transonic region is not smooth, i.e. a shockwave exists in the flow, the flow may be unstable. This is consistent with the observed variability of the flow in O star winds. A hybrid model has been proposed by Mazurek (1980) in which the mass loss rate and the flow to the sonic point are controlled by the non-radiative energy input at the base of the wind. Once the flow becomes supersonic the wind cools rapidly and it is accelerated by radiation pressure.

Non-radiative heating is a common feature of all the models. The most commonly invoked sources of non-thermal energy involve either acoustic or magnetic waves which become shock waves when entering the low density regions above the photosphere. The dissipation of these shock waves results in the heating of the wind. Meridonal circulation currents may give rise to turbelence in the photosphere of a rotating star (Smith and Roxburgh 1977; Kodaira 1980). There is also the possibility of generating acoustic waves in the wind directly by radiative mechanisms (Martens 1979) and of shock waves in the flow as discussed by Cannon and Thomas (1977). Non-thermal structure in stellar atmospheres is the subject of a series of papers introduced by Cram (1980).

Be stars, unlike O star wind models, are probably not spherically symmetric. A key point here is that in spherically symmetric models one can only separate wind regions radially. Therefore the flux from the star must pass through all regions. This is not the case in Be stars. Very few of the O star wind models incorporate stellar rotation in their formulation, but the suggestion of enhanced equatorial mass loss has come up in the case of WR stars (Rempl 1980). Marlborough and Zamir (1975) extended the solution of Cassinelli and Castor (1973) to include the effects of rapid rotation. They found that a wind could exist in the equatorial plane of a rapidly rotating star, while at the same time the polar regions remained hydrostatic. Nerney (1980) points out that rotation can generate magnetic fields which could easily initiate mass loss. The field strengths required are small ($\sim$ 1 gauss at the stellar surface) and below the level of detection at the present time (Landstreet 1980). A search for magnetic fields in A type shell stars by Clayton and Marlborough (1980) proved negative at the 300 gauss level.

2.2 Radiation Transfer

The envelopes of Be stars appear to be rotating and moving radially with velocities much greater than the mean thermal velocity. The densities within these envelopes are such that one cannot assume LTE, nor can one ignore collisional transitions in determining level populations. Thus we have the worst possible case when trying to solve the radiation transfer problem.

A popular method of treating the line radiation transfer problem is the "mean escape probability" method (Sobolev 1960). Rybicki and Hummer (1978) give a generalized formulation of the method, and Surdej (1979) shows the results of the application of the method to a variety of radially accelerating and decelerating envelopes. The method is very useful when velocity gradients are large and line opacity small, but its usefulness at large line opacities has been questioned (Bernat and Robbins 1974; Hamman 1981).

In addition to the transfer problems one must also consider the non-LTE nature of the atomic level populations. Drake and Ulrich (1980) have calculated the spectrum of a slab of hydrogen at moderate densities and temperatures between 5000 K and 40000 K. Their calculations are based on a 20 level hydrogen atom, complete with radiative and collisional transitions, and an escape probability approach to the transfer problem. Drake and Ulrich assumed complete frequency redistribution in the line. It should be noted that if the line opacity is very large this assumption may not be valid (Chugai 1980). Figure 1 gives some examples of the computed spectra.

2.3 Rotation

A general discussion of stellar rotation is beyond the scope of this review, and the reader is directed to an excellent comprehensive look at stellar rotation given by Tassoul (1978). However, some aspects of rotation that bear directly on the models to be discussed in the remaining sections deserve mention.

Magnetic fields, apparently inevitable in rotating stars, have been incorporated in some models (Barker 1979, Nerney 1980, Barker _et al_. 1981). The consensus is that relatively weak fields, $\sim$ tens of gauss, may dramatically affect the dynamics of circumstellar envelopes.

The effects of rapid rotation on line profiles have been investi-

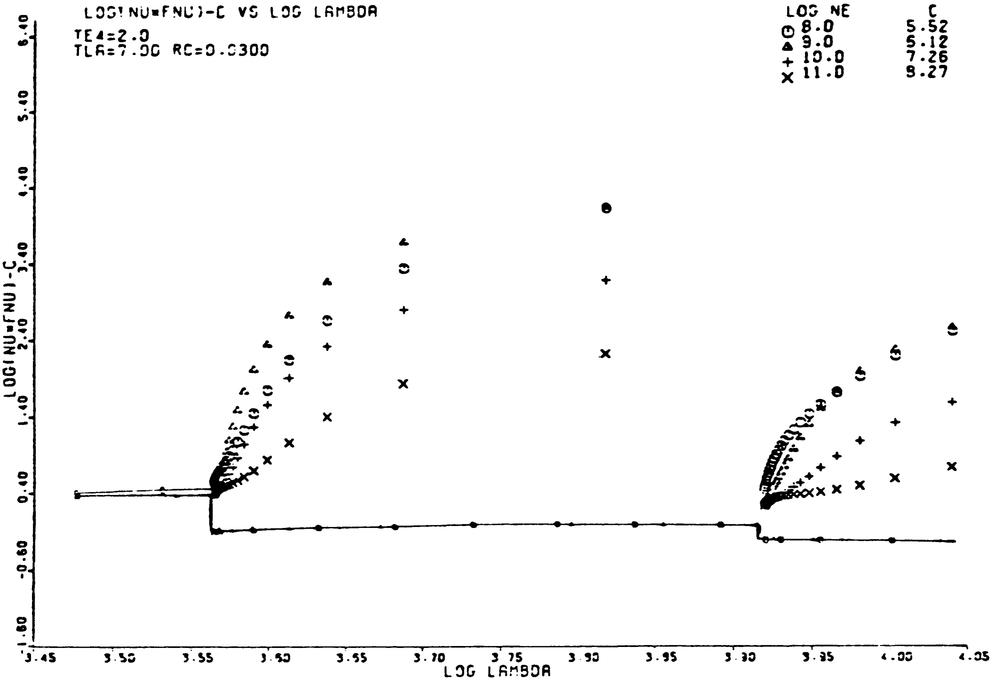

Figure 1. Energy distribution and line strengths for a slab of hydrogen at 20000 K and a large Lyman α optical depth. Various symbols indicate different densities (Drake 1980).

gated by Slettebak, Kuzma and Collins (1980). It appears that rapid rotators seen equator on will be classified later, by about 1.5 subclasses, and somewhat higher in luminosity (based on Hγ equivalent width) than an equivalent non-rotating star. Another aspect of rapid rotation relates to the fact that the measured V sin _i_ is dependent on the spectral line chosen for analysis. The effect is particularly noticeable when one compares ultraviolet and visible lines (Heap 1976). Hutchings (1976) and Hutchings, Nemec and Cassidy (1979) have used the difference to determine the inclination and equatorial of several stars. Sonneborn and Collins (1977) and Collins and Sonneborn (1977) give the results of detailed calculations comparing the Mg II λ 4481 and Si III λ 1113 line profiles in rapid rotators seen at various inclinations. It is heartening to find that the Von Zeipel gravity darkening law, used almost universally, is valid in early-type stars (Smith and Roburgh 1977).

The problem here, as far as modelling is concerned, is deciding on what value one chooses for V_{equ}, sin _i_ and T_{eff} to represent the star.

3. *Ad Hoc* Models

The raison d'etre of models is to give us an indication of the dynamics and physical conditions in and around stars. In principle, if one completely understood the dynamics (and could solve the relevant equations) the physical conditions would be known by default. We are far from this ideal situation. Observations reveal to us information on the physical conditions, not the dynamics. The role of the *ad hoc* model is to determine the physical conditions, from which we might infer the dynamics.

This is a highly interactive (often intuitive) process because *ad hoc* models are rarely unique. To decide which model is closer to the truth one must consider the number of observations a model fits, the quality of the fit and the dynamical picture inferred from the model. *Ad hoc* models are quite successful at matching observations, in part because they have the interesting property of gaining free parameters at will; few if any are dynamically sound.

3.1. The Elliptical Ring Model

Struve (1931) first proposed and Huang (1972, 1973) and Albert and Huang (1974) gave a quantitative framework to the elliptical ring model. The circumstellar material is thought to be contained in a narrow elliptical ring. Long term, apparently periodic, V/R variations are explained as uniform apsidal motion of the ring. Detailed line profiles have not been computed for the ring models, but a schematic picture is given by Huang (1975).

One of the difficulties faced by the elliptic ring model is that there are times when V/R variations are cyclic, separated by abrupt changes in V/R. In addition there is the case where the period and amplitude of the variations slowly changes over several cycles. Huang (1976, 1977) has proposed that sudden variations in V/R are due to gaseous outbursts from the star which disrupts the existing ring and forms a new, different ring. Huang (1978) has also investigated the effect that a continuous weak flow of gas would have on the elliptic ring. He finds that both apsidal motion and changes in the eccentricity and semi major axis can result from an interaction between the wind and the ring.

In order for the apsidal motion concept to be valid the ring should be thin, both radially and perpendicular to the ring plane. Marlborough (1976) outlined the problem of a small perpendicular extent. In essence it is difficult to form deep shell absorption lines with thin rings.

Kriz (1976, 1979a,b) has calculated line profiles (shown in Figure 2) for elliptical rings. He finds that such rings must be optically thick in Hα and the ring must have a large radial extent, $\sim$ 5 R_*, in order to match observed emission line profiles. Thus we are really

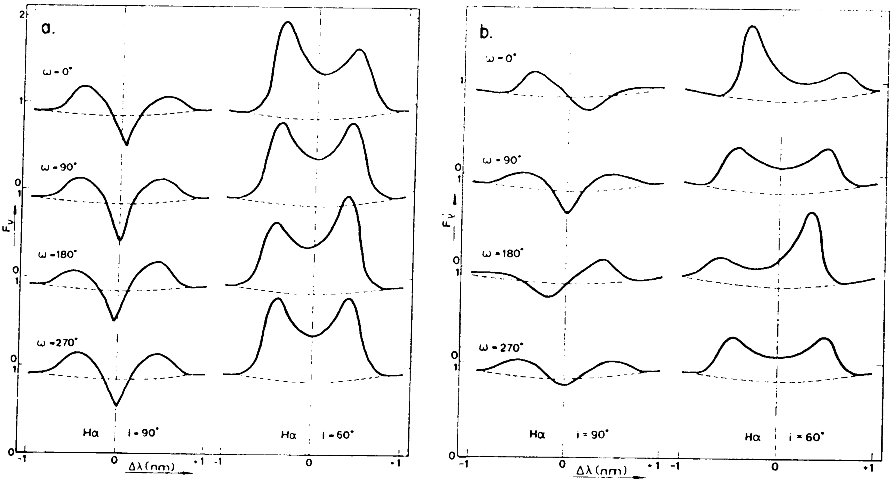

Figure 2. Line profiles for elliptic disks. Eccentricity of the disk is a) 0.1 and b) 0.3. The profiles are shown at two inclinations and four azimuthal angles.

talking about elliptic disks, not rings, and most of the dynamical arguments in favor of the ring model fail.

The problem with the elliptic disk model is that it is difficult to understand why the disk should rotate uniformly. Apsidal motion of an orbiting ring is no longer an attractive theory because a whole family of rings, all with the same eccentricity, must precess in unison. A hybrid model, in which only the outer part of the envelope is elliptic has not been considered in detail as yet. Such a model bears some semblance to the distorted disk model proposed by Marlborough, Snow and Slettebak (1978) for γ Cas.

The case for elliptical, or a least oval, structure in circumstellar envelopes is more convincing when the Be star is a member of a binary system.

3.2. Binary Star Models

Binary Be stars are the subject of another review paper (by Harmanec) in this volume, and will not be discussed at length here. Several Be stars are members of mass exchanging systems, e.g. HR 2142 (Peters 1972, 1976). In this case the secondary is believed to be losing mass through Roche lobe overflow.

A second scenario, one which does not explicitly require any mass exchange, has been proposed by Suzuki (1979). His model consists of a ring of gas in a stable periodic orbit. Quasi-circular, non intersecting stable periodic orbits exist for a range of binary configurations (Hernon and Gyot 1970). Suzuki applied his interpretation to the binary Be star ϕ Persei and predicted a mass ratio and separation for the system. Poeckert (1981) has confirmed Suzuki's parameters from independent observations and using a standard spectroscopic orbit analysis. One of the exciting results of this model is that the disk radius which best explains the ϕ Persei data is also close to the maximum radius for stable orbits.

Marlborough, Snow and Slettebak (1978) proposed that γ Cas has a neutron star companion. This could explain the observed X-ray flux from γCas and the V/R variations. The X-rays are produced when some of the stellar wind emanating from γ Cas is accreted onto the neutron star. The V/R variations arise because the outer envelope is tidally distorted. A similar model has been proposed for GX304-1 (Parkes, Murdin and Mason 1980) and X Persei (Persei, Viotti and Ferrari-Toniolo 1977). The secondary in the ϕ Persei system is also peculiar (Poeckert 1979).

3.3 Disk-like Models

Disk models are usually used in interpreting a restricted set of observations. The models tend to be highly simplified generally, but can be quite complex in the treatment of a specific problem.

3.3.1 Line Profiles

Kogure (1975), Hirata and Kogure (1977, 1978) and Kogure, Hirata and Asada (1978) analysed the residual flux in the Balmer shell lines of several Be stars. They derive the Hα optical depth, the fraction of the star that is occulted, and the outer radius of the envelope. A schematic representation of their model is shown in Figure 3, and an example of how the model fits the data is shown in Figure 4. Higurashi and Hirata (1978) applied a similar analyses to the metallic shell lines in the spectrum of the Be star HD 23862. They found that the fractional occultation increases with ionization potential, suggesting that the cooler part of the envelope is surrounded by the hotter region.

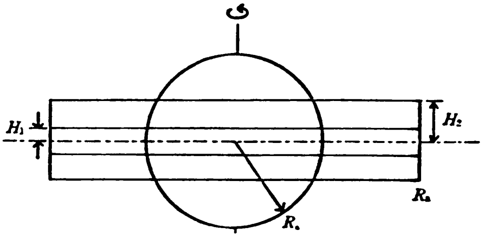

Figure 3. An equatorial view of the two disk model as proposed by Hirata and Kogure (1977).

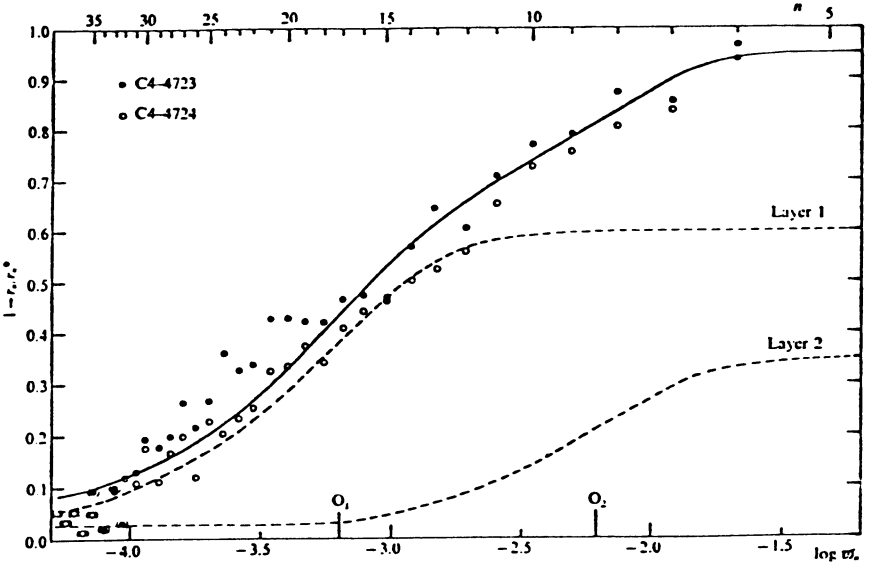

Figure 4. The fit of the two disk model to the observed residual flux in the Balmer shell lines of Pleione.

Van Blerkom (1978) and Kunasz and Van Blerkom (1978) have developed a model for P Cygni based on the Balmer line profiles. Ordinarily P Cygni is not included among classical Be stars, but their model has an expansion velocity which increases gradually and linearly with radius resulting in an inner, moderate-density envelope, much like Be star envelopes. Since rotation does not appear to be a factor in P Cygni the model is spherically symmetric.

3.3.2 Continuum Energy Distribution

Modelling the energy distribution of Be stars is usually approached as a problem concerning flux excesses. The comparisons made are with "normal" stars or "normal" model atmospheres. There is some degree of danger in this approach in that we already know that the stars are not "normal". One is apt to think of Be stars as "normal", but with an external, detached peculiarity. Cram (1980) has commented on the inconsistencies of this kind of modelling. On the other hand, Be stars that observationally lose their Be characteristics appear to be "normal" B-type stars, albeit rapidly rotating, and pole-on Be stars appear to be "normal" (Peters 1979) so comparison with "normal" stars may, after all, be justified.

Another problem in modelling the continuum energy distribution is correcting for interstellar extinction. There is substantial evidence for intrinsic reddening in Be stars (Schild 1976) which immediately calls into question the use of E_{B-V} in correcting for interstellar extinction.

The infrared excess observed in many Be stars is usually ascribed to free-free emission from the circumstellar envelope (Gehrz, Hackwell and Jones 1974), but in some "peculiar" Be stars, e.g. HD 45677, hot dust may also be present (Coyne and Vrba 1976).

Ferrari-Toniolo et al. (1978) have compared their infrared observations with models for the Be stars γ Cas, X Per, ϕ Per and ζ Tau. Their models consist of isothermal, constant density, spherical envelopes. They calculate the emission spectrum of such an envelope including free-free and bound-free processes. Scargle et al. (1978) also observed and modelled the infrared flux of γ Cas. They considered both disk and spherical models and found that either geometry would give satisfactory results. Figure 5 compares the γ Cas observations

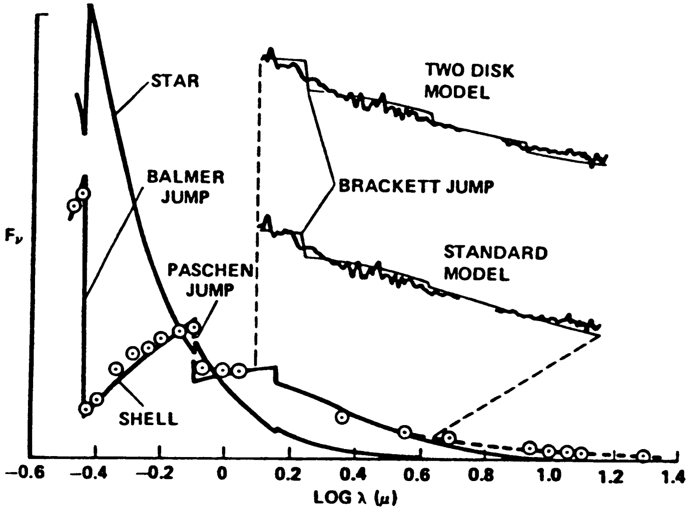

Figure 5. The flux excess (circles) and the model results for γ Cas. At 3751A the shell contribution is 11% of the total flux.

and best disk model from Scargle et al. Note that there is a significant flux contribution by the envelope in the Paschen continuum. This explains why Be stars appear to have intrinsic reddening as found by Schild (1976), and why interstellar reddening corrections based on E_{B-V} may be incorrect.

Haisch and Cassinelli (1976) and Hartmann (1978) consider spherically symmetric, scaled-down Wolf-Rayet star models, which they truncate into disks to produce linear polarization (see also section 3.3.3). These models are fundamentally different from those discussed so far in that they treat the envelope like an extended photosphere, rather than a separate disk or sphere surrounding a "normal" star.

3.3.3. Polarization

It is now generally accepted that the intrinsic linear polarization of Be stars is due to electron scattering in circumstellar disks. There are two problems which must be addressed, the transfer of radiation, which will determine the wavelength dependence of polarization, and geometry, which will determine the overall degree of polarization (although not exclusively).

Haisch and Cassinelli (1976) considered the polarization produced by a rotationally distorted star and disc-like envelope. The rotationally distorted (Roche) models produce only small, $< 0.2\%$, net polarization. This is consistent with the fact that rapidly rotating stars are not observed to have large intrinsic polarizations. Peraiah (1976), modelling early-type rotating supergiants, also looked into rotationally distorted models, but these had much more extended atmospheres than the models of Haisch and Cassinelli. Peraiah was able to produce polarizations up to 25% in envelopes with large scattering optical depths, $\tau_{sc} \sim 5$.

The disk models considered by Haisch and Cassinelli (1976) are based on the WR star models of Cassinelli and Hartmann (1975). A spherical model is truncated to a disk to produce a net polarization. Jones (1977, 1979) also considered a disc model. His approach was to divide the envelope into many ($\sim$ hundreds) cells and calculate the contribution of each cell to the total flux. The models incorporated free-free and free-bound processes, single and double scattering of stellar photons, and single scattering of photons originating within the envelope. Figure 6 shows the results of various models and the effects of various processes. It is clear that absorptive opacity is very important in determining the wavelength dependence of polarization. Jones' models are somewhat more successful than those of Haisch and Cassinelli in that they fit the observations of the Balmer jump polarization better and the overall polarization is higher. Observed Be star polarizations go as high as 2%, a value easily obtained by Jones' models, while the models of Haisch and Cassinelli were limited to net polarizations under 1.2%.

Another approach to the disc model was made by Johns (1975). He determined the net polarization due to a simple disk and star by using a Monte Carlo technique to solve the radiation transfer problem. Johns concludes that the wavelength dependence of polarization is the result of competing opacities, bound-free and free-free absorption and electron scattering. Free-free and free-bound emission, "diluting" the polarization, plays only a minor role. Johns adds that the disc which best reproduces the observed wavelength dependence and magnitude of polarization in Be stars is optically thick to electron scattering and is relatively thin compared to the stellar radius. These conclusions are different from other studies which usually find $\tau_{sc} < 1$, and a disk thickness of $\sim 2\ R*$.

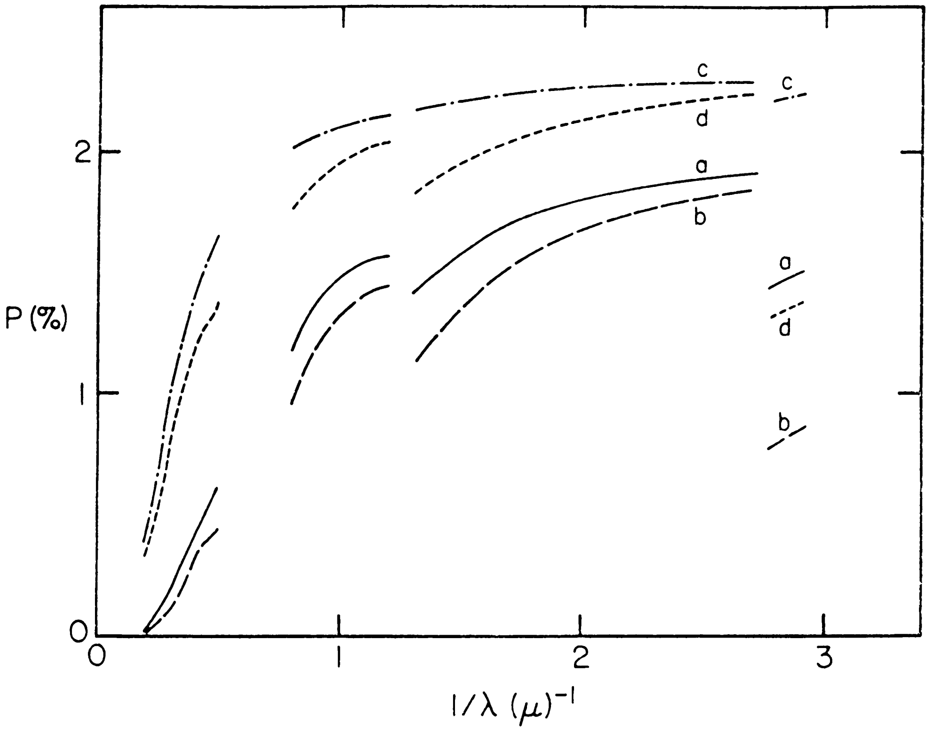

Figure 6. Polarization from a disk at 10000 K, 1 R_* thick and 5 R_* in radius. The curves represent a) only free-free opacity included, b) free-free and bound-free opacity included c) scattering of envelope photons included, but no bound-free opacity, and d) everything included (Jones, 1979).

Brown and McLean (1977) outline the basic geometry problem in electron scattering from circumstellar envelopes. The simplifying assumptions that are made in order to give an analytic solution are that the star is a point source, the density distribution can be described by a series of uniaxial ellilpsoids or cylinders, and the envelope is optically thin. The result is that the polarization of the scattered radiation is given by

$$P(\beta,\underline{i}) = \sin^2\underline{i}/(2\alpha + \sin^2\underline{i}),$$

where

$$\alpha = (1+\beta)/1-3\beta),$$

$\underline{i}$ is the inclination and β is a "shape factor" describing the density distribution. The importance of such an analytic solution cannot be overemphasized because it can give far greater insight into a problem than the more involved numerical analyses.

Brown, McLean and Emslie (1978) extended the results of Brown and McLean to binary stars (two illuminating sources) and McLean (1979) applied their results to Be star envelopes. McLean discusses the variation of polarization across emission lines in Be stars. The decrease in polarization within an emission line (as observed by Clarke and McLean 1974 and Poeckert 1975) is due to an increase in absorptive opacity and "dilution" by the line emission. The variations in position angle of polarization as observed in γ Cas by Poeckert and Marlborough (1977) are due to the doppler shifted absorptive opacity. McLean found that the amplitude of these position angle variations is expected to vary as cos $\underline{i}$.

Powerful as the analytic analyses are one must keep in mind the assumptions which make them possible. The assumption of a point source star is invalid if the envelope is close to the star. Rudy (1978) has looked into the effects of a finite sized illuminating source and finds that the analytic solutions are valid if the envelope is symmetric about the equatorial plane. If the envelope is comparable in size with the illuminating source there will be occultation effects. For example, Piirola (1980) has observed eclipse effects in U Cephei.

The assumption that envelopes are optically thin must also be questioned. The models of Johns (1975), Haisch and Cassinelli (1976) and Jones (1977) all have substantial scattering optical depths, $\tau_{sc} > 0.5$. Absorptive opacity is usually comparable to or greater than the scattering opacity. All these points must be kept in mind when applying the analytic results to the interpretation of polarization data.

Daniel (1980) compared the analytic results of Brown, McLean and Emslie (1978) to his own calculations, which involved a Monte Carlo approach. Daniel determined the polarization of ellipsoidal envelopes in which the scattering optical depth was large. He found that the analytic results were valid only for very thin envelopes, $\tau_{sc} < 0.1$. The problems of interpretation of data using the analytic results is demonstrated by Daniel (1981) in the case of Cyg X-1.

Electron scattering is not the only mechanism for producing intrinsic polarization. Coyne and Vrba (1976) measured the polarization of HD 45677. They did not find the canonical Be star wavelength dependence of polarization. They argue that the polarization and peculiar infrared excess are consistent with a dust ring 45 AU from the star, $\sim$ 15 AU thick and clumpy.

3.3.4 Time Variations

Temporal variations in flux and polarization are a well established facet of the Be problem. The variations occur over long time periods, e.g. the $\sim$ 1000 day V/R variations (see section 3.1), and short time periods, $\sim$ minutes. Purely radial axisymmetric variations should have periods > 1 day (Morgan 1975).

The long-term variations (P > week) can be understood in terms of binaries (section 3.2), elliptic disks (section 3.1) or a variable mass loss rate (e.g. Limber's (1969) model for Pleione). Short-term (< 1 day) variations in the continuum flux have been attributed to pulsation (cf. Percy, Jakate and Matthews 1981) and temperature changes in the atmosphere of the central star (Lester 1975). In the case of EW Lac Lester argues that the lack of variations in the equivalent width of Hα rules out changes in envelope emission or absorption causing the continuum variations. However, Lester assumes that the envelope is optically thin, which is certainly not the case in Hα in EW Lac.

Short-term variations in polarization in the star γ Cas have been reported by Poeckert and Marlborough (1977), Rodriquez (1979) and Piirola (1979). The variations occur on a time scale of hours, but are not large with respect to the total polarization. Hayes (1980) looked for polarization variations in pole-on Be stars. If azimuthal variations occur in the envelope one can expect to see them in pole-on stars as well as the more active high V sin *i* stars. Hayes found no short-term (days) variations in the pole on stars suggesting that the envelopes are axisymmetric, at least in the regions near the star.

3.3.5. Stellar Wind Models

Poeckert and Marlborough (1977, 1978a, 1978b) reinvestigated the stellar wind models first presented by Marlborough (1969). A typical density distribution is shown in Figure 7. Also shown in Figure 7 is the ionization structure in such an envelope (from Poeckert and Marlborough 1981).

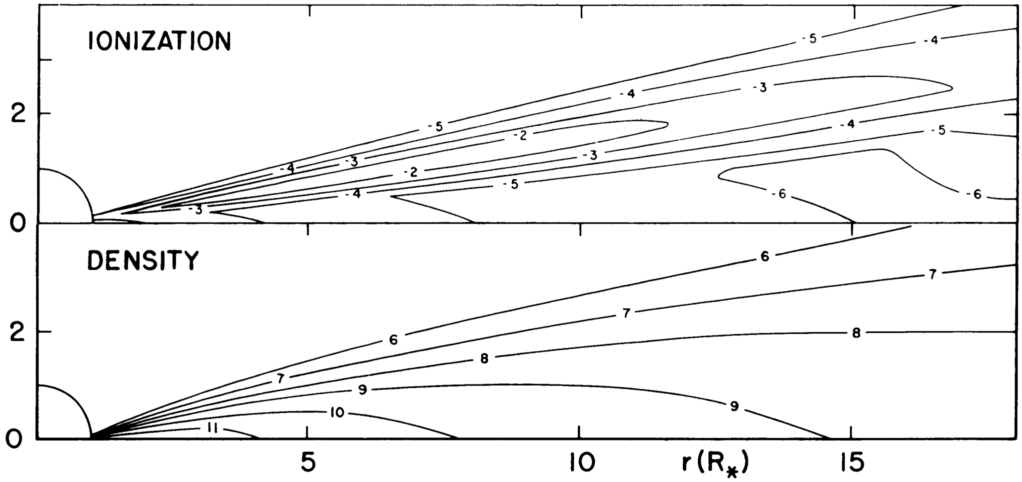

Figure 7. Density distribution and fractional ionization for a model envelope (T_{eff} = 15000 K, T_e = 10500 K). Contours are labelled in a) log N_H/N, b) log N. The solid circle represents the sun to scale.

The emergent flux is calculated at 200 frequencies in the Balmer lines and 33 frequencies in the continuum, between 1000 A and 11 cm. Polarized radiation (singly scattered stellar photons) is incorporated in all the calculations. The central star is spherical and its flux is assumed to be given by a single normal model atmosphere. Gravity darkening is neglected. The finite size of the star is taken into account explicitly.

The model for γ Cas (Poeckert and Marlborough 1977, 1978a) matches the observed Hα profile and polarization (Figure 8), and the continuum polarization. Note the position angle variations across the Hα line. The model was also used to predict the continuum energy distribution. Figure 9 shows the various components of the continuum energy distribution between 1000 A and 20μ. At 3.7 and 11 cm the flux is predicted to be 4.2 and 0.5 mJy, respectively, which is at the threshold for detection (Purton 1976).

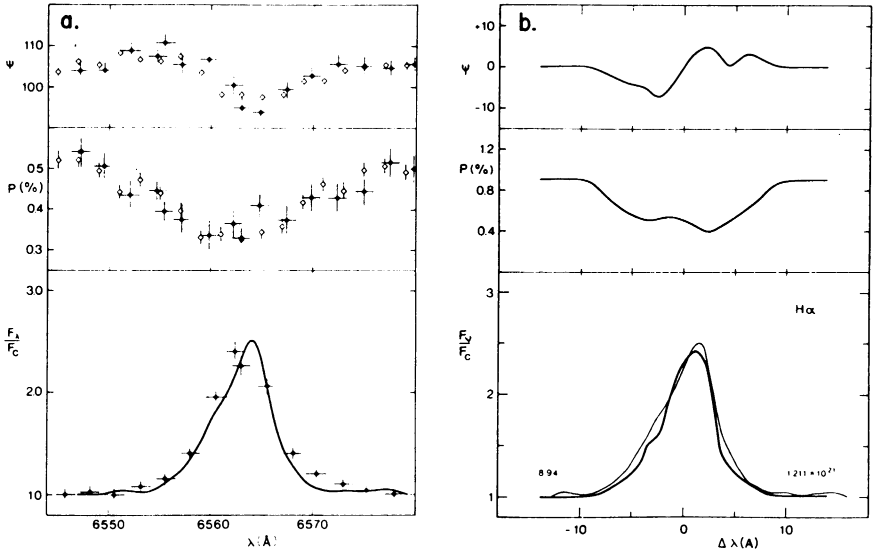

Figure 8. a) Observed Hα profile and polarization for γ Cas. b) Computed profile and polarization. (Position angle (ψ) is given in degrees).

The effects of inclination and envelope density were investigated by Poeckert and Marlborough (1978b). Figure 10 shows the effect of inclination on the Hα line profile and polarization. Note the increase in position angle variations at smaller inclinations. McLean (1979) determined that the amplitude of such variations is proportional to cos i. The Hα profile for the equator-on view is a typical type III P Cygni profile (Beals 1951). This profile is not typical of Be stars, but is seen in some other early-type stars. (cf. Mihalas and Conti 1980).

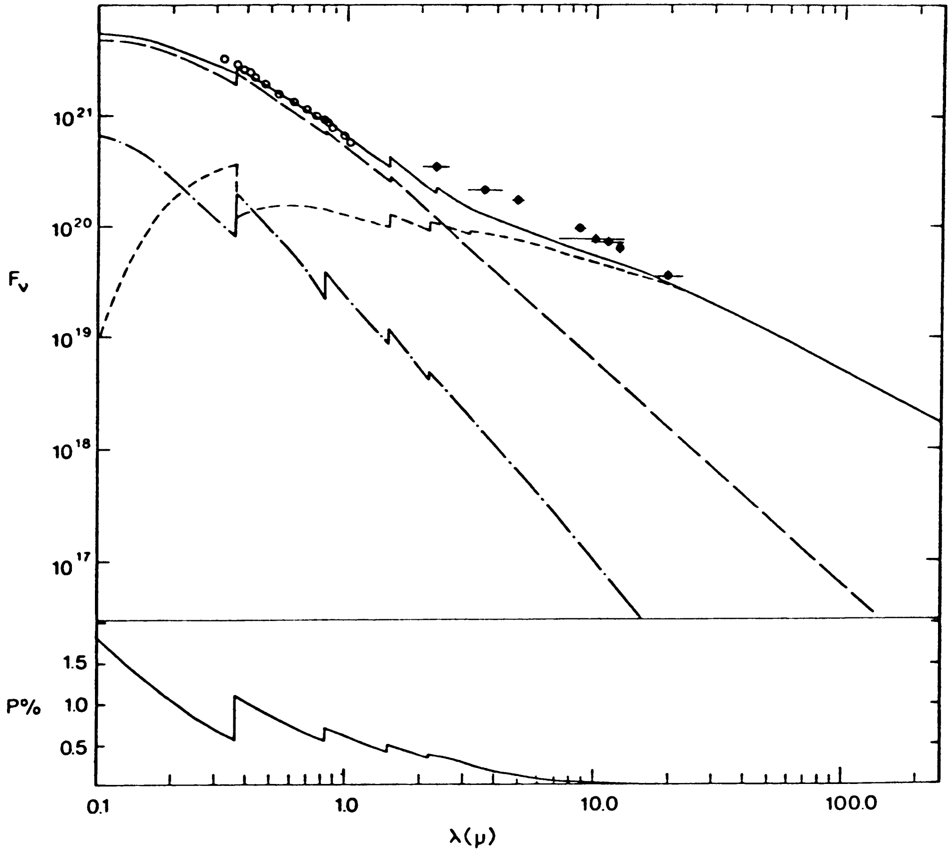

Figure 9. Continuum energy distribution and polarization for γ Cas model.

Figure 11 shows the effects of inclination on magnitude excess and colours. Pole-on stars are brighter and redder (in B-V) than equator-on stars. Figure 12 shows the effects of envelope density on the continuum energy distribution.

Figure 13 shows the effect of envelope density on polarization. Note that at large densities polarization shortward of the Balmer jump decreases, while polarization in the Paschen continuum increases, with increasing density. Several Be stars show this effect (Poeckert, Bastien and Landstreet 1979).

The effect of electron scattering-on the Balmer line profiles was investigated by Poeckert and Marlborough (1979). Figure 14 shows the Hα and Hβ profiles for a dense envelope. The calculations confirm the

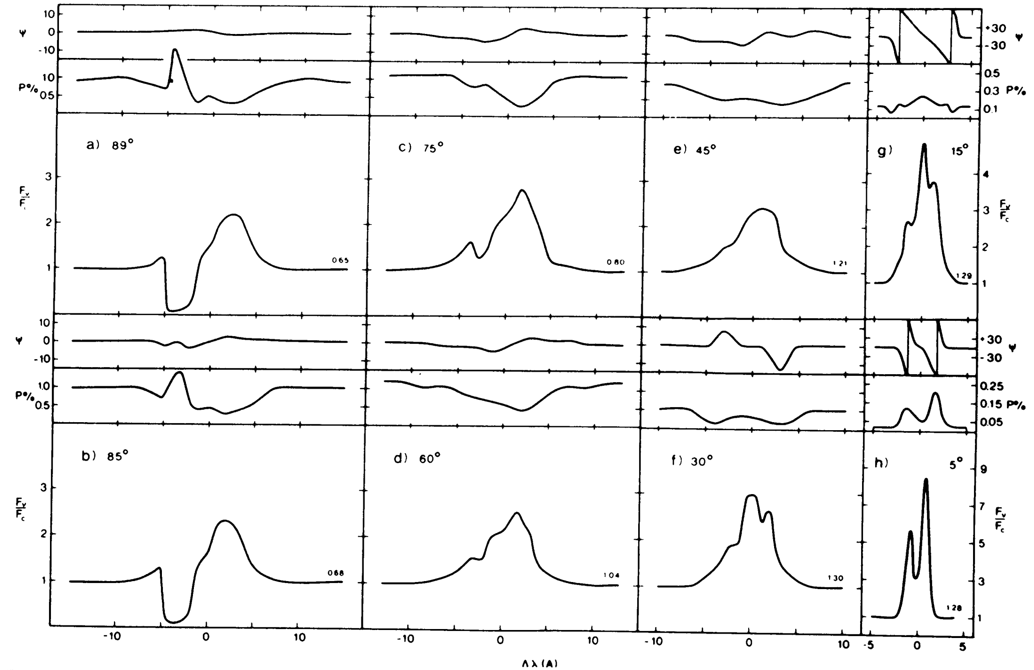

Figure 10. Hα profile and polarization as a function of inclination. Note the scale change in panels g and h. The continuum flux levels are given in the lower right of each panel.

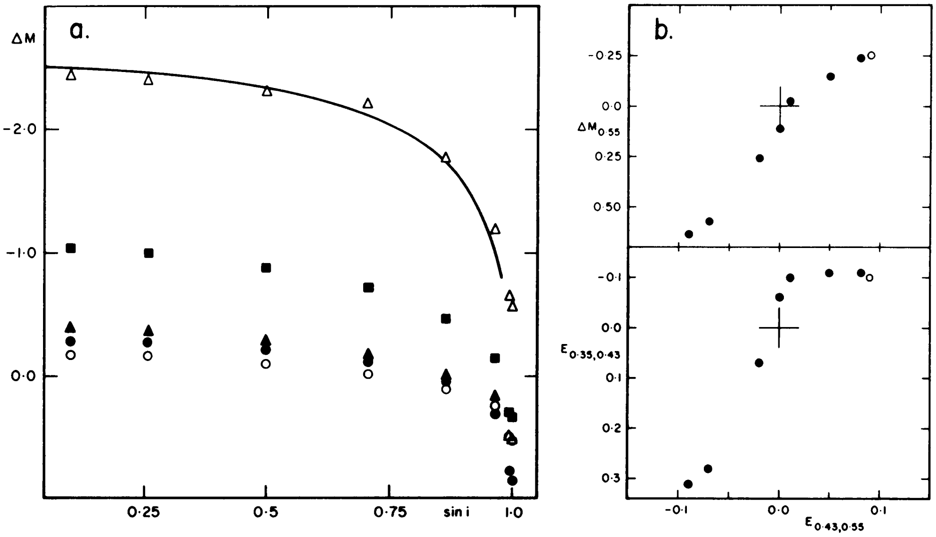

Figure 11. a) Magnitude excess as a function of sin *i* and wavelength (open triangles), 10μm; filled circles, 0.35μm; open circles, 0.43 μm). b) ΔV and E_{U-B} as a function of inclination (from 5° (open circle) to 15°, 30°, 45°, 60°, 75°, 85° and 90°).

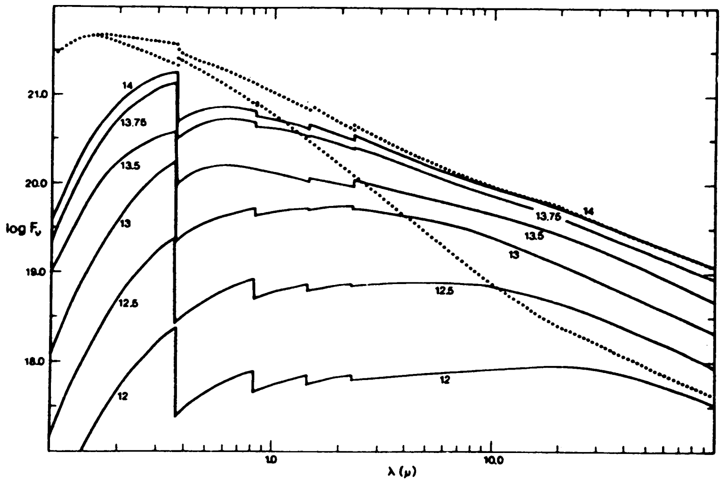

Figure 12. Continuum energy distribution for envelopes of various density (at 45° inclination). Solid lines represent envelope emission (labelled in log density). Dotted lines represent the extremes for the total flux.

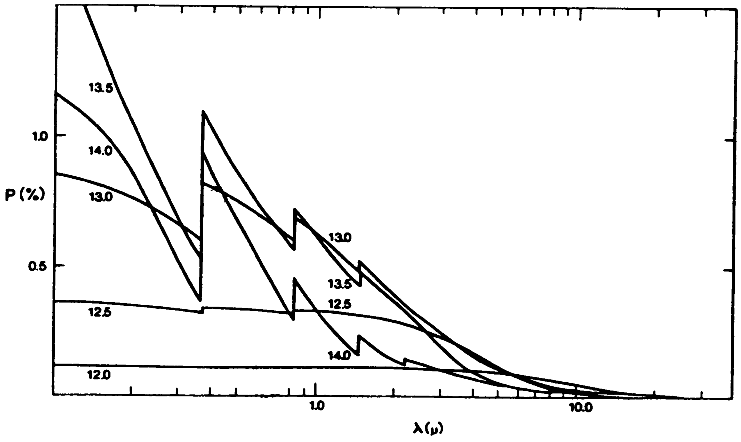

Figure 13. Continuum polarization for envelopes of various density (at 45° inclination).

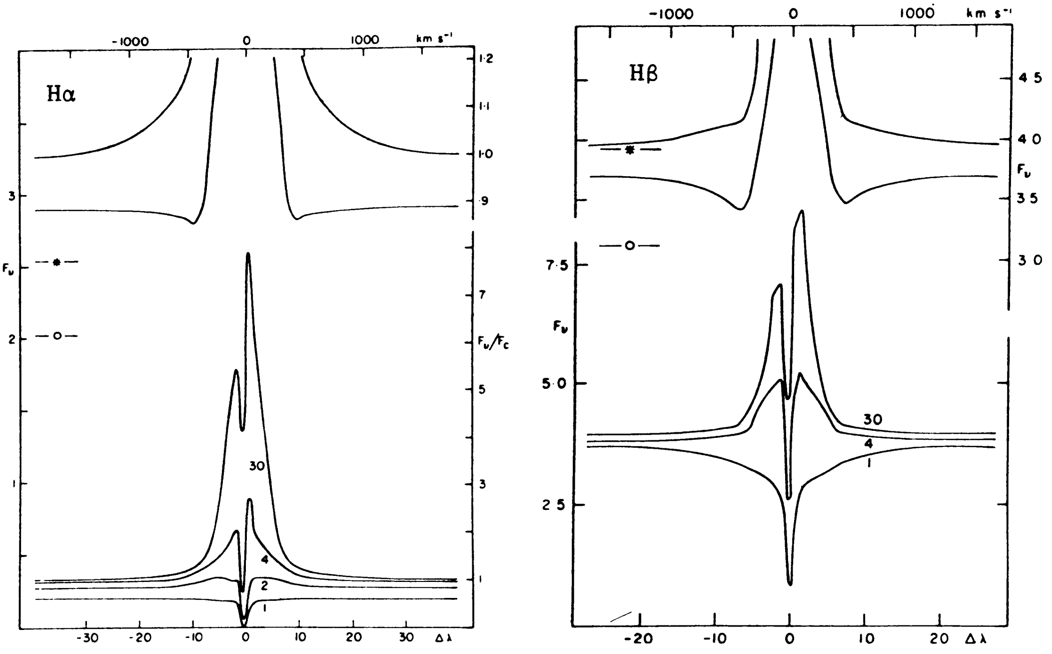

Figure 14. Hα and Hβ line profiles showing the effects of electron scattering. The upper curves show the details of the line wings with and without the effect of electron scattering. The lower curves show the line profiles broken down by impact parameter (in R_*).

suggestion made by Marlborough (1969) that the broad wings seen at Hα in some Be stars are due to electron scattering. Bernat and Lambert (1978) invoked electron scattering as the cause of the broad Hα wings in P Cygni.

Poeckert, Gulliver and Marlborough (1981) have computed a stellar wind model for the Be star o And. They interpret the waning of the most recent shell episode in that star as a decrease in envelope density propagating outward. Figure 15 summarizes the observations while figure 16 presents the results for the model. The mass loss rate is assumed to decrease by a factor of 20 over 300 days, and the density decrease propagates outward at 12 km s^{-1}. It takes several hundred days for the entire envelope to respond to the decreasing mass loss rate.

3.3.6 Coronal Models

Many studies of the ultraviolet spectra of Be stars have found lines of highly ionized species, e.g. N V and O VI (cf. Snow and Marlborough 1976; Marlborough 1977a; Marlborough and Snow 1980; Doazan, Kuhi and Thomas 1980; Dachs 1980; Heinrichs, Hammerschlag-Hensberge and

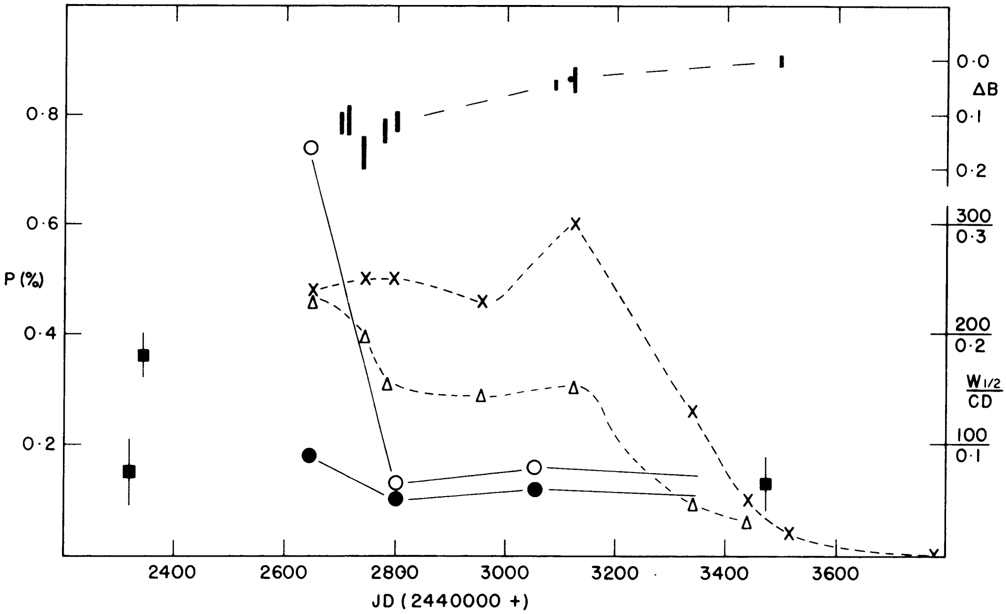

Figure 15. Intrinsic polarization (open circles, 4050A; filled circles, 3450A; filled squares, V), ΔB (solid bars; length of bar indicates diurnal variations), shell line depth (crosses) and shell line half width (triangles) for o And between JD 2442200 and JD 2443800.

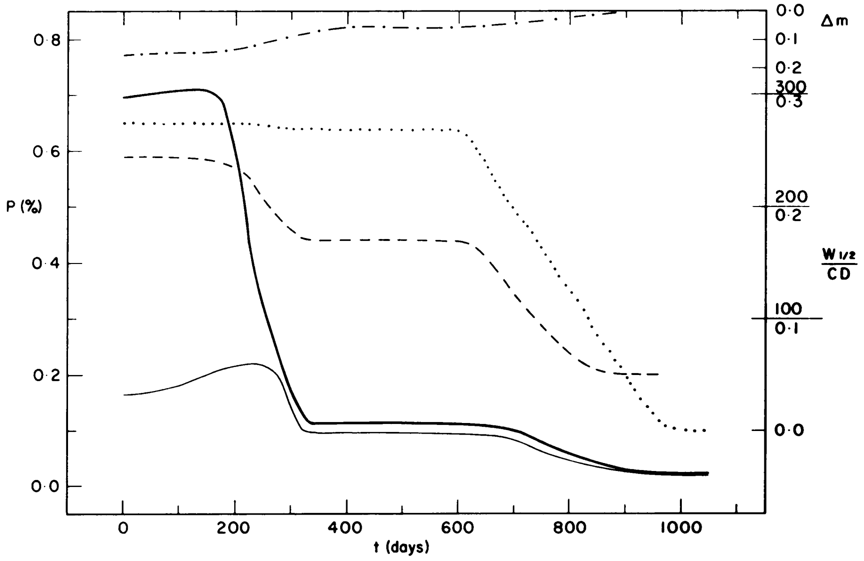

Figure 16. Polarization (light line, 3500A; heavy line 4000A), ΔB (dot dash), Hγ shell line depth (dots) and half width (dashed line) for the model as a function of time (days after start of density decrease).

Lamers 1980). In almost all cases such lines indicate suprathermal outflow velocities. The spectra of OB supergiants also show such lines and their presence is taken as a sign of coronal regions in the winds of these stars. Many OB supergiants, and some Be stars, also have unexpectedly large X-ray fluxes, another possible indicator of coronae. The models for OB supergiants generally assume spherical symmetry and the corona is placed just above the photosphere (see section 2.1). The situation in Be stars is somewhat more ambiguous.

Marlborough, Snow and Slettebak (1978) proposed a model for γ Cas in which the cool region of the envelope can be described by the stellar wind model of Poeckert and Marlborough (1978a), the coronal region lies above the higher density disk. It is suggested that the differential rotation in the cool disk leads to turbulence, and this turbulence forms shock waves when it enters the lower density region above the disk resulting in a corona. Icke (1976) proposed just such a scenario for accretion disks. He found that temperatures up to 10^6 K can be achieved, well above the temperature required to provide N V lines.

Marlborough (1977b) has shown that the X-ray emission from γ Cas requires a corona with $T_e \sim 2 \times 10^7$ K if the emission is due to bremsstrahlung. Marlborough, Snow and Slettebak suggest that the X-ray emission arises from an accretion disk around a neutron star companion. There is no direct evidence for such a companion, but the period (4 yrs) and the mass ratio (17:1) would make radial velocity variations undetectable. However, it is suggested that the outer region of the cool disk is tidally distorted, resulting in V/R variations in the Balmer emission lines. Such V/R variation should be synchronized with the binary period and their amplitude should increase with increasing Balmer emission.

Time variability in the lines of highly ionized species is common place in most early-type stars with winds. In OB supergiants it appears to be primarily a variation in optical depth not velocity, i.e. the terminal velocity is constant. The Be stars show variability in both optical depth and velocity. The latter can be quite dramatic, e.g. in 59 Cyg the velocity has changed from -50 km s^{-1} to -750 km s^{-1} (Doazan *et al*. 1980a).

Heinrichs, Hammerschlag-Hensberge and Lamers (1980) propose a model for γ Cas which attempts to explain the sudden appearance and disappearance of high velocity features in the ultraviolet lines. They suggest that there is a stellar wind which has a rapid transition from low to high velocity. A "puff" of material is blown off the star and it rapidly accelerates to the terminal velocity. The result is that lines are not seen at intermediate velocities, only at low velocities, because the density is high, and at high velocities, because the "puffs" reach the terminal velocity quickly.

A competing model has been proposed by Doazan *et al*. (1980b).

They suggest that the lack of intermediate velocity lines is due to the temperature structure in the corona. In this model the temperature rises to ∿ 10^6 K and then falls again. Lines of N V, for example, are only formed at temperatures ∿ 10^5 K, so we would expect two regions, one pre-coronal and one post-coronal, in which such lines can be formed. The post-coronal region has a large outflow velocity. It is also suggested that the highest temperature region is responsible for the X-ray flux.

Some correlation between the coronal line variations and Balmer emission line variations is apparently observed in 59 Cyg (Doazan et al. 1980a), but a model tying the coronal region to the cooler region has not been developed (with the exception of the model of Marlborough, Snow and Slettebak (1978) which did not address the problem of coronal line variations).

4. Conclusions

A solution to the basic equations governing the structure and dynamics of Be star envelopes is as remote as it was five years ago. In fact, the advent of coronae in stellar wind models has made the entire process even more complex than it was. At present the ad hoc models still provide our best picture of Be stars.

There are several aspects of the Be phenomenon which desperately need clarification. First, the location of the coronal region. Marlborough, Snow and Slettebak (1978) suggest such a region exists above the higher density cool disk. If such is the case one might expect to see substantial differences between pole-on and equator-on Be stars. At present the limited amount of data indicates no dependence on inclination of the coronal lines (Dachs 1980). The possibility of having a coronal region at the base of the disk is small since we see no high outflow velocity in the disk and a high temperature high density region is ruled out by the polarization observations (Marlborough and Poeckert, in preparation).

The V/R variations are also a puzzle. The elliptic ring model proposed by Huang (1975) has serious difficulty in matching all, but the V/R variations. The models of Kriz (1979) are more compatible with the data, but the dynamical arguments in favor of precessing elliptic rings are lost in the case of a disk. The fact that V/R variations might be due to a secondary star distorting the envelope has been proposed by Marlborough, Snow and Slettebak (1978), but the changes in period of V/R variations argues against such a model for all Be stars.

Several Be stars are X-ray sources and this has been interpreted as evidence for very hot coronae or degenerate secondaries. It is interesting that ϕ Persei, a star which shows He II λ 4686 in emission and appears to have a peculiar companion, is not an X-ray source (Hutchings 1981).

Finally, it is worthwhile repeating the admonition given by Marlborough (1976), do not believe everything you see in print!

I wish to thank R. Haapala and D. Duncan for help in preparing the manuscript, and all those, particularly J.M. Marlborough, with whom I have had discussions in the last few years concerning Be star models.

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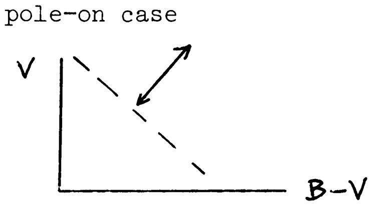
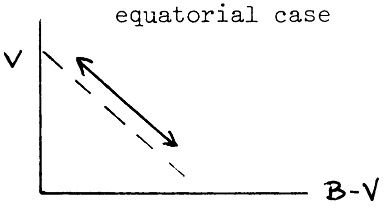
DISCUSSION

Traving: The models which are actually computed should depend critically on the radiative transfer in Ly - α line. So the proper choice of the redistribution function should matter.

Poeckert: Treating the Lyman line transfer problem correctly is very difficult and is only handled in a very simplified form in our model.

Endal: Do your models predict the type of movement in the colour-magnitude diagram discussed by Hirata for Be stars with disks of time-varying density?


pole-on case


equatorial case

Poeckert: In the pole-on case, yes. However, this type of behaviour is what you expect whenever you add a cool envelope, without obscuring the star. In the equatorial case the models suggest an increase in V is accompanied by a decrease in B-V; due to bound-free absorption. I should stress that this only happens in cases when the envelope density is high (resulting Hα equivalent widths in excess of 90 A), and no large V or colour changes are predicted for less dense envelopes.

Peters: According to a recent paper by Hayes, the polarization observed in ω Ori secularly decreased from .7% to .2% during a 7 months interval of time just prior to my IUE observation which showed the presence of the high velocity shell lines. Would you care to comment on this observation? What would the two observations taken together imply about the causes (and/or nature) of the interesting mass loss in this star?

Poeckert: Hayes also found that some pole-on stars are not variable polarimetrically. I don't find it surprising that during an outburst the polarization is variable since asymmetric (non-axissymmetric) mass loss is certainly possible.

Harmanec: Have you some idea what could happen to 88 Her which - on a time scale of years - became brighter and bluer and at the same time almost lost the Hα emission?

Poeckert: The models presented by Marlborough and myself do not show this kind of behaviour. It may be possible to get the kind of behaviour you describe in a dense envelope which partially obscurs the stellar disk.

Stalio: 1. When you say that radiatively driven wind models predict the terminal velocity of the wind, do you mean the relation $V_\alpha=3xV_{esc}$? If yes, I inform you that nobody considers it true anymore.
2. The word "puffs" has been coined by Lamers, Kondo and myself (ApJ 220, 1978) in order to explain the appearance and disappearance of MgII shell lines in β Ori.

Poeckert: 1. As I am not an expert on OB wind theory I accept whatever results appear in print. If that has changed, then I'm sorry that I'm not as up-to-date as I should be.
2. The term "puffs" is not something I attribute to anyone, but myself, as I did not see it in the literature. I apologize for not recognizing your prior coining of the word.

Hirata: If my memory is correct, o And became fainter before the shell appearance. If so it seems to me that this is an important information on the shell activity mechanism.

Poeckert: As far as I am aware the actual onset of the shell was not observed. The shell was well developed spectroscopically when it was discovered. Hence, I am not sure the decrease in brightness preceeds the shell phase.

Snow: In reviewing the model for O-star winds, you omitted one that might be relevant to the Be stars. The x-ray observations show that soft x-ray emission arises from high levels in the wind; that is, far from the star. This suggests that heating occurs in the wind, not just at the stellar surface. One proposed explanation is that the star emits a steady stream of blobs or "bullets", which have a substantial velocity relative to the lower-density material, and this causes shock-heating, producing x-rays. If this idea is realistic for O-stars, it ought to be considered for Be stars as well, especially in view of what we heard about "puffs" and blobs in the winds represented by the narrow, high-velocity components.

Thomas: 1. All the Be- and B star data I know are compatible with a low-lying, coronal x-ray emission (cf τ Sco and ρ Oph). Same, for T Tauri stars. I.e., the more extended the atmosphere, the "brighter" Hα the less I(x-ray).
2. The "bullet" model you mention, by White and Lucy(?) at Columbia is aerodynamic nonsense. They assume the "bullets" (which are gas bubbles) are not distorted when moving at 1-3000 km/s. Impossible.

Thomas: The 26-level hydrogen calculation that ignores photoionisation for levels $n \geq 2$ is arithmetic only, not applicable to any Be-star or even solar situation ($\tau(\mathrm{Lyc}) \sim 10^7$). So it is a good example of what not waste your time with. Better refer to Avrett et.al. at Harvard Smithsonian, who do 7-level atoms with all transitions, radiative and collisional, included. Myself, for our present leveled Be calculations, I think 3-levels with transfer in LyC and BaC and H_α is quite sufficient.

Poeckert: Now I think it is probably worthwile to consider an overall scenario for Be stars. We have seen in the preceding four days that the Be stars have cool and hot envelopes (or winds), are variable on a variety of timescales, and rotate rapidly. We have heard each of these aspects discussed individually, but there has been no attempt to conceil any large fraction of the data in one model. I hesitate to include what follows in my review paper because there is a great danger that the wild speculations presented here will be taken too literally by some and perhaps even be cited as a discussion of Be star models in some future paper. This discussion is meant primarily to present in a concrete manner what has been discussed informally over the last week and what has been suggested in the literature in order that we may have a frame work for future debate. I will address myself to what I consider the dominant problem, the juxaposition of the cool and hot envelopes. I will assume that any time variability can be incorporated in some way in each of the scenarios discussed below. A related problem to the positioning of the cool and hot region is how and where the non-thermal energy input occurs, a region which I will refer to as the transition zone.

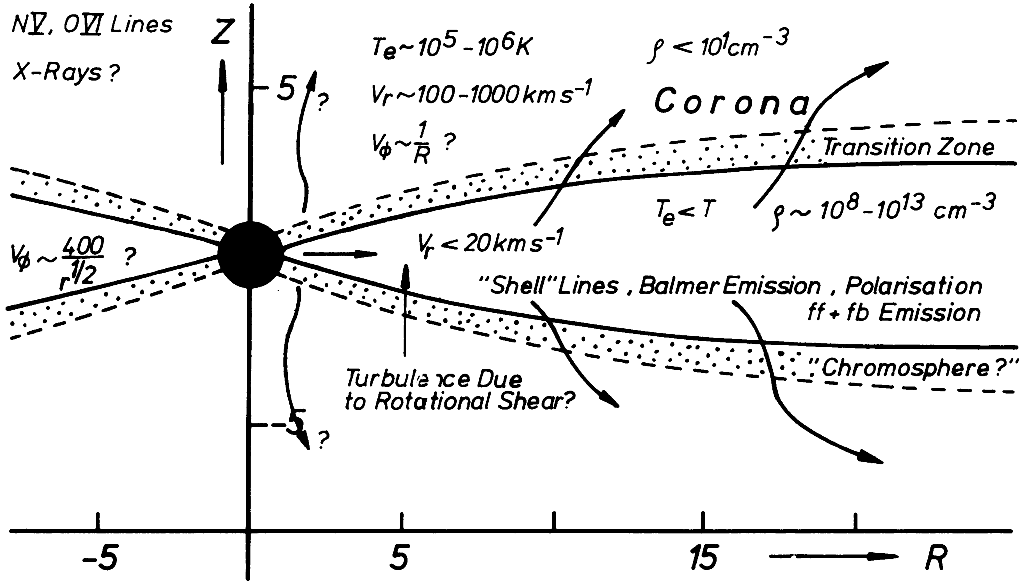
The first scenario I present is one suggested several years ago by J.M. Marlborough and formally put forward by Marlborough, Snow and Slettebak (1978). The cool envelope is thought to be a disk à la Poeckert and Marlborough (1978a). The inner part of the disk rotates rapidly and differentially leading to turbulence. The turbulence becomes super sonic along the upper and lower edge of the disk (the density falls rapidly) resulting in heating (transition zone) of the low density region above (and below) the disk. The expansion velocity in the disk is small, but in the hot region it is large. This scenario is nice in that it ties the cool and hot region together and also suggests a possible source for the non-thermal energy (cf. Icke 1976). One might expect to see differences in the hot wind depending on the inclination. "Pole-on" stars would be expected to have somewhat different winds from "equator-on" stars. Also, a star whose cool region decreases in density, so that the star is no longer considered to be a Be star, should show a marked change in the hot wind.

The second scenario and the one I prefer at the moment also has a cool disk, but in this case the transition zone is at the stellar surface. The transition zone covers the entire star and under normal circumstances would lead to a hot wind in all directions. However, the density in the equatorial plane is sufficiently high that the gas cools almost immediately resulting in the formation of a cool disk. This scenario is different from the preceding one in that there is no direct link between the cool and hot envelopes. Moreover this scenario leads itself to explain hot winds in all early type stars. The only distinction between "normal" OB stars and Be stars is that the letter have dense, and therefore cool equatorial regions. This is most likely a consequence of rapid rotation. The transition zone must be small ($\leq .3R_*$) otherwise it will be detectable in the visible polarization and Balmer emission line profiles. One would also expect that a Be star that loses its Balmer emission would continue to show the presence of the hot wind.

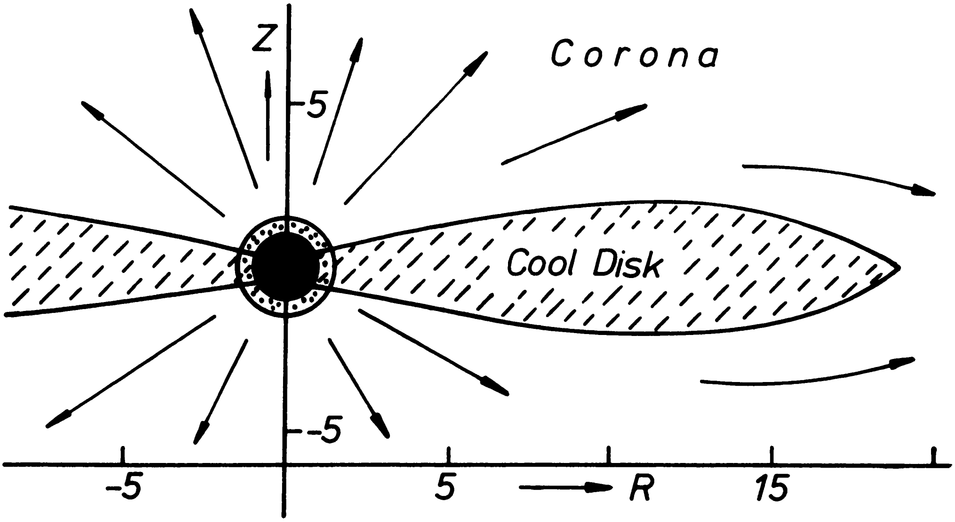
The third scenario places the transition region at some large ($\gtrsim 20\ R_*$) radial distance out in the disk. In this case the region above and below the disk (and $r < 20\ R_*$) does not contribute in any way to the observed spectrum. Once the gas passes through the transition zone it is very hot and it expands rapidly, both radially and latitudinally. It must expand latitudinally otherwise we would not see hot winds in "pole-on" stars.

The fourth, and final, scenario is one suggested by R.N. Thomas and a discussion of the proposal follows this afternoon. In essence, the transition zone is at the stellar surface and a hot wind flows away from the star more or less spherically symmetric. At some large radial distance ($r > 10\ R_*$) the gas decelerates, passes through a shock wave (cooling it) and forms a high density cool envelope. Rotation plays no major role in this proposal; the envelope is essentially spherically symmetric. The difficulty with this proposal is, that it does not address itself to the vast amount of data which suggest a non-spherically symmetric envelope (eg. polarization) and the overwhelming circumstantial evidence which points to v sin i (rotation) as a major influence on the observed spectrum (e.g. shell lines are seen predominatly in the rapid rotators).

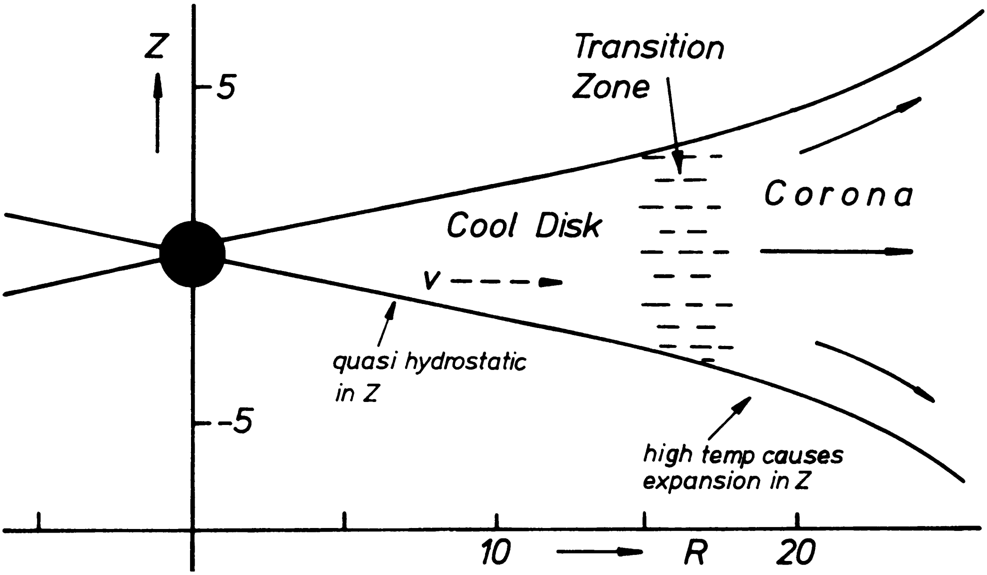
Again I must emphasize that these scenarios are very speculative and should not be considered too literally. Moreover, the actual situation in the case of a Be star may not necessarily be any one of the scenarios discussed, but it may be a combination; or more likely, a scenario which has not even occured to me as yet.



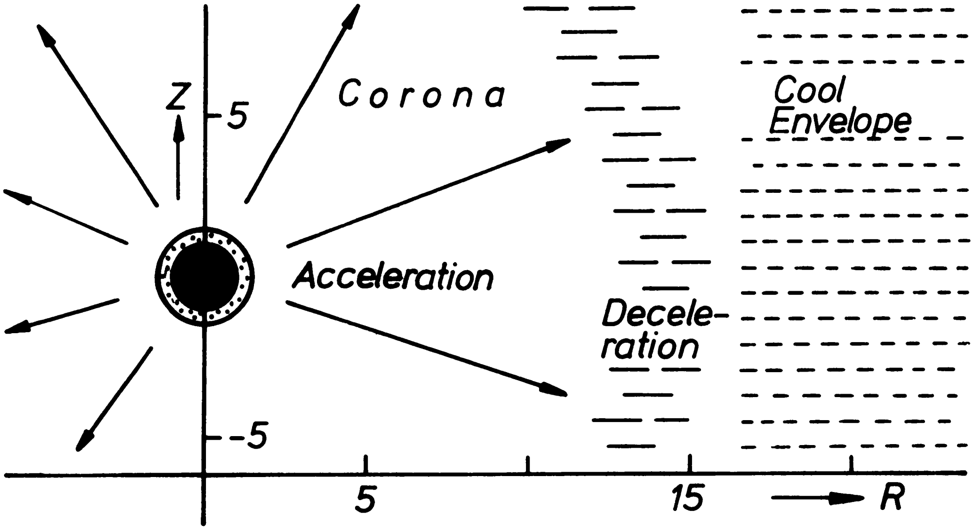
Scenario 1



Scenario 2



Scenario 3



Scenario 4