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THE Be STARS*

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ABSTRACT

Research on Be stars from the early work of Merrill and Struve to the present is reviewed, including recent observations from space. A number of models which have been proposed to explain the Be phenomenon are discussed, and the evolutionary status of Be stars is considered.

Key words: Be stars–shell stars

I. Introduction: Early Observations and the Rotational Model

"In the first half of the present century, one name stood out more than any other in the study of the Be stars—that of Paul Willard Merrill." So states J. B. Hearnshaw (1986) in his history of astronomical spectroscopy, *The Analysis of Starlight*. Certainly Merrill at Mount Wilson Observatory, Otto Struve at Yerkes Observatory, and Dean B. McLaughlin of the University of Michigan were the preeminent workers in the study of Be stars at that time. While Merrill made important contributions in many areas of stellar spectroscopy, he started his astronomical career with a study of Be stars at Lick Observatory (Merrill 1913) and continued to publish papers on Be stars throughout his lifetime. His pioneering Hα observations with objective-prism plates resulted in the discovery of hundreds of new Be stars and led to the Mount Wilson Catalog of Be Stars, published in four parts in collaboration with Cora G. Burwell (Merrill and Burwell 1933, 1943, 1949, 1950).

In the reprinted paper above, Merrill turned his attention to a subclass of Be stars known as shell stars. (Be stars themselves may be defined as "nonsupergiant B-type stars whose spectra have, or had at one time, one or more Balmer lines in emission". See Collins 1987.) As he suggested, some ambiguity in terminology exists here. Any star with an extended atmosphere could be called a shell star, but the term took on a special meaning when applied to B-type stars: stars with spectra showing emission wings in one or more of the hydrogen lines, sharp hydrogen-absorption cores plus narrow-absorption lines of ionized metals, and weak, diffuse absorption lines of neutral helium. Merrill presented a partial list of such shell stars in the above reprinted paper, with a more complete list in his third (1949) Mount Wilson Catalog paper with Burwell. Bright examples of shell stars defined in this way include γ Cassiopeiae, ϕ Persei, ψ Persei, Pleione (28 Tauri), ζ Tauri, and 48 Librae. It should be emphasized, however, that shell stars represent only one phase of the Be phenomenon. While all B-type shell stars are Be stars, not all Be stars show shell spectra as defined above. Some never show shell spectra (because of the inclination of the rotation axis, as will be discussed), while the shell spectrum comes and goes in others (e.g., Pleione).

Papers by Merrill and others, especially Struve, during the 1940s and early 1950s led to a better physical understanding of the shells, which were recognized to be analogous to the atmospheres of supergiant stars: cooler and less dense than the atmospheres of the underlying B-type stars. In a review article entitled "The Analysis of Peculiar Stellar Spectra", Struve (1951) designated Pleione as a "prototype shell star" and discussed its spectrum and spectral changes. Although Pleione had shown emission lines of hydrogen prior to 1905, those disappeared at that time and from then until 1938 its spectrum was similar to that of an ordinary, rapidly-rotating late B-type star. Then, in Struve's words,

> Quite suddenly in October 1938 the emission lines of hydrogen made their reappearance, and at the same time the spectrum showed a number of faint but exceedingly narrow absorption lines of Fe II, Cr II, and other ionized metals. . . . The sharp lines gave no indication of rotation; yet at the same time the broad lines of hydrogen and helium were still present, so that the conclusion was reached that the rapidly-rotating star had not appreciably changed, but that it had become surrounded by a ring or shell of tenuous gas with relatively small angular rotation. During the succeeding years the sharp lines became very strong, and the spectrum underwent some interesting changes. The hydrogen lines were characterized, from 1938 to 1950, by exceedingly sharp cores in absorption, superposed over the broad profiles of the normal stellar lines. The absence of Stark broadening in the

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> cores showed that the pressure of the shell or ring was lower than even in the atmosphere of a supergiant.

By 1951 the shell had nearly disappeared, as recorded by Merrill (1952), who measured radial velocities of the shell lines and noted that the motion of the material forming the shell was at first "... so slow that the observed radial velocity of the shell was the same as that of the star as a whole. Gradually the acceleration increased, and the outward velocity of the upper levels became appreciable. Eventually the supply of atoms failed, and the shell blew away". Pleione remained an ordinary Be star until 1972 when it started a new shell phase, which is just now ending in 1987–88.

Struve noted that while the spectrum of Pleione in the shell phase resembled that of the A-type supergiant, α Cygni, the Mg II λ4481 and Si II λλ4128–31 lines were abnormally weak. Unlike the lines of Fe II, Cr II, Ni II, Ti II, and the other ionized metals, all of which arise from metastable levels, the Mg II and Si II lines are the only ones whose lower levels are not metastable but are connected to the ground state via strong downward transitions. The diluted radiation which reaches the shell from the underlying star (fewer quanta per cubic centimeter than in the photosphere) therefore produces fewer absorptions than for the lines arising from metastable levels, resulting in weaker lines. Another bright shell star, similar to Pleione, is 48 Lib, which was studied by both Struve (1943) and Merrill (1953). A portion of its spectrum is shown in Figure 1.

Dilution effects were also found by Struve and his colleagues and collaborators in the spectra of shell stars of both earlier and later spectral type. Thus, the shell of the B1 IVe star ζ Tau was revealed by the fact that, in addition to the sharp absorption lines of Fe II and other ionized metals and the Balmer line cores, He I λ3965, which arises from a metastable level, is sharp while most other He I lines are broad and diffuse, due to the rapid rotation of the underlying star (Struve and Wurm 1938). The coolest shell stars found during those early years were the A-type expanding shell star 17 Leporis (Struve 1932) and the F0 III shell star 14 Comae Berenices (Morgan 1932).

Analysis of the shell spectra led to geometrical dilution factors of 0.1 to 0.01 (Struve 1942), with corresponding shell radii of two to five stellar radii. Studies of ionization in the shells led to temperatures somewhat cooler than the photospheric temperatures of the underlying stars, with electron densities of the order of 10^{11} cm^{-3}. A study of Balmer emission-line profiles in several bright Be stars by Burbidge and Burbidge (1953) led them to a lenticular model for the emitting regions, with radius several times the stellar radius, in general agreement with the earlier work.

In an important paper entitled "On the Origin of Bright Lines in Spectra of Stars of Class B", Struve (1931) suggested a rotational model for Be stars which influenced all future work on these objects. Having shown earlier with his collaborators G. Shajn (Shajn and Struve 1929) and C. T. Elvey (Elvey 1930; Struve 1930) that the broad and hazy "dish-shaped" profiles shown in lines of all elements in many early-type stars are due to Doppler broadening produced by axial rotation, Struve applied these ideas to explain the origin of the emission lines in Be stars. Showing that the emission-line widths are correlated with the degree of rotation (as determined from absorption-line widths) in Be stars, he suggested that "... rapidly rotating single stars of spectral class B are unstable, and form lens-shaped bodies which eject matter at the equator, thus forming a nebulous ring which revolves around the star and gives rise to emission lines. The inclination of the star's axis would then be responsible for the observed range in width of the emission lines". Struve's rotational model is shown schematically in Figure 2.

The spectra of shell stars could be readily understood in terms of the rotational model of Be stars. Since the shell stars show the largest line broadening (and, therefore, presumably have the largest $v \sin i$'s) of the Be stars (Struve 1942; Slettebak 1949), we must be viewing them essentially equatorially. If the material in the disk is sufficiently optically thick, we would then expect to observe narrow (because the material is moving essentially at right angles to the line of sight) absorption lines from that part of the disk which is projected in front of the underlying star, just as is observed in the spectra of shell stars. We will see later in this review, however, that while

FIG. 1–Spectrum of the shell star 48 Lib from Hγ to Hβ. Note the emission at Hβ, the sharp absorption cores in Hγ and Hβ, the many sharp absorption shell lines of Fe II and other ionized metals, and the broad He I λ4471 line from the underlying star (Cerro Tololo Inter-American Observatory spectrogram).

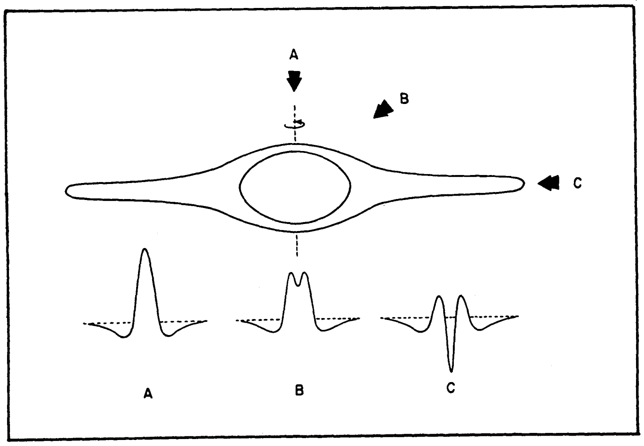

FIG. 2–Struve's rotational model of a Be star, shown schematically. The rapidly-rotating star with equatorial gaseous shell produces the Balmer-line profiles labeled A, B, and C when viewed by an observer from the directions A, B, and C, respectively (Slettebak 1979).

the rotational model is supported by infrared and polarization studies, ultraviolet observations suggest that the total picture is not so simple.

II. Later Ground-Based Observations and Models

Research on Be stars has expanded enormously since the work of Merrill and Struve. The best indication of the great activity in this field is the fact that numerous review articles have been written and three IAU conferences on Be stars have been held since 1975. This review can only touch on some aspects of this research; the reader may find details and references in the recent general reviews by Doazan (1982), Kogure and Hirata (1982), Hirata and Kogure (1984), and Slettebak (1979). Many review and individual papers in specific areas of Be-star research are included in the *Proceedings of IAU Symposium 70* (*Be and Shell Stars*, ed. A. Slettebak, Dordrecht: Reidel, 1976), *IAU Symposium 98* (*Be Stars*, ed. M. Jaschek and H.-G. Groth, Dordrecht: Reidel, 1982), and *IAU Colloquium 92* (*Physics of Be Stars*, ed. A. Slettebak and T. P. Snow, Cambridge: Cambridge University Press, 1987).

It has been clear from the earliest observations of Be stars that they are variable stars. The case of Pleione, which changes from ordinary B or Be star to shell star and back on time scales of a decade or two, has already been mentioned. McLaughlin, much of whose work was devoted to the study of variability of Be and shell stars, described three types of variability in a review paper (McLaughlin 1961): (1) changes in the ratio of intensity of the emission lines to the neighboring continuous spectrum, called *E/C* variation; (2) changes in the ratio of the intensity of the violet to the red component of double-emission lines, called *V/R* variation; and (3) appearance and disappearance of a shell-absorption spectrum. As McLaughlin pointed out, the three types are not mutually exclusive. Research during the past decade or so (see the review paper by Percy 1987) has also made clear that both photometric and spectroscopic changes may occur during very short time intervals. A range of time scales is therefore involved, from years and decades for the shell appearances and disappearances to days and even hours for certain line-profile changes.

Changes in the shell spectrum of 48 Lib to 1962 were summarized by Underhill (1966). The radial-velocity measurements suggest an oscillation of the shell with a period of about ten years, accompanied by complex line asymmetries and changes in equivalent width. Subsequent studies of this interesting object include those by Delplace and Chambon (1976) and Aydin and Faraggiana (1978).

Underhill (1966) also summarized the observations of the bright shell star ζ Tau from 1902 until 1964. Although the shell appeared to be stationary until 1952 at least, inflow and outflow velocities as large as 100 km s^{-1}, interpreted as due to streams of gas, were reported in the 1960s. Delplace and Chambon (1976) discussed further oscillations of the shell to 1974. In a recent paper, Rachkovskaya and Nasibova (1986) summarize earlier work and report the shell to have been relatively inactive during 1983–84.

Spectroscopic observations of Pleione as it entered its latest shell phase in 1972 were reported by Hirata and Kogure (1976, 1977, 1978) and by Gulliver (1977). Radial-velocity measurements showed the shell to be slowly expanding, while also increasing in mass, by 1976. This particular shell phase is apparently ending in 1987–88, as noted earlier; the metallic shell lines were rapidly fading, though the hydrogen lines still showed sharp shell cores (Garrison 1987).

Detailed accounts of the fascinating changes over the years in the spectrum of Pleione, as well as the bright shell stars γ Cas, 59 Cygni, 88 Herculis, and EW Lacertae, may be found in the review by Doazan (1982). These changes (over a 23-year period, from 1953 to 1976) are shown on photographic reproductions of spectra of 35 bright Be and shell stars in the Hubert-Delplace and Hubert (1979) *Atlas of Be Stars*.

Shell stars, as defined at the beginning of this article, are found over a range of spectral types from the earliest B types with relatively hot shells (e.g., γ Cas, a B0.5 IVe star, which showed sharp He I λ3889 and λ3965 lines arising from metastable levels during its shell phase) to A and F types. The latter usually do not show hydrogen emission, presumably because the shells are too cool, but reveal their shell nature by the simultaneous presence of rotationally-broadened absorption lines from the underlying star plus sharp hydrogen and/or Ca II K-line absorption cores and/or certain Ti II lines which arise from metastable levels less than 1 eV above the ground state (Abt and Moyd 1973).

Recent work on optical spectra of Be stars was reviewed by Dachs (1987). He finds (see also Dachs *et al.* 1986) that Hα observations support the model for cool, Balmer-line emitting regions of Be-star envelopes consisting of a differentially rotating disk surrounding the equatorial belt of the star.

Especially interesting are several recent attempts to measure the sizes of Be-star shells directly. One technique utilizes lunar occultations in Hα light to determine the dimensions of the Hα-emitting shell (see White and Slettebak 1980). Schmidtke and Africano (1984) recorded an occultation of the bright shell star ζ Tau but were unable to resolve its shell in Hα light. They found an upper limit to the shell size of ≃ 4 stellar radii. Granes, Thom, and Vakili (1987), on the other hand, used interferometric techniques in Hα light to measure the angular diameter of the hydrogen envelope of γ Cas. They recorded an angular diameter of 60 milliarc sec, which they find to be consistent with the predicted values (3 to 15 stellar radii) for the Hα line-formation region in the model of Poeckert and Marlborough (1978).

Perhaps the strongest observational evidence in support of the rotating flattened disk model for Be-star shells comes from polarization measurements. Review articles by Coyne (1976), Coyne and McLean (1982), and Cassinelli (1987) have emphasized that "The mere fact that the optical radiation from Be stars is observed to be intrinsically linearly polarized provides perhaps our most conclusive clue that the circumstellar shells of these stars are disklike in nature" (Coyne and McLean 1982). Models based on polarization data suggest that disks with electron temperatures of ≃ 10,000 K, electron densities of ≃ 10^{12} cm^{-3}, and extent three to ten stellar radii are consistent with the observations. These numbers are similar to those derived from spectroscopic observations of shell stars.

Ground-based infrared observations of Be stars (Johnson 1967; Woolf, Stein, and Strittmatter 1970; Allen 1973), while showing that Be stars have an excess of near-infrared radiation which arises from a circumstellar shell, could not at first be used to distinguish unambiguously between free-free and dust emission. The work of Gehrz, Hackwell, and Jones (1974), based on observations of 33 Be stars between 2.3 μ and 19.5 μ, first made clear that the dust-emission model did not fit the observed infrared-energy distribution. They found free-free emission from a hot ($T \geq 10,000$ K) circumstellar plasma shell to be the most likely source of the excess infrared radiation, with a typical Be-star shell characterized by an electron density ≃ 4×10^{11} cm^{-3} and a radius of about four stellar radii. Figure 3, from Gehrz *et al.* (1974), shows the flux curve for the bright Be star β Canis Minoris, whose infrared excess can be fitted by an optically thin free-free shell. Infrared observations of Be stars since 1974 are discussed in the review paper by Lamers (1987).

"Classical" Be stars (as defined earlier in this review) have not been found to emit detectable amounts of radio emission (see the review by Purton 1976). However, a recent VLA survey by Taylor *et al.* (1987) for radio emission from a sample of Be stars having strong excess emission in the infrared (as measured by the *IRAS* satellite) has resulted in a detection from the shell star ψ Per. They state that the radio flux density, together with nearly simultaneous ultraviolet and near-infrared observations, favor equatorial disk models for the Be circumstellar envelope.

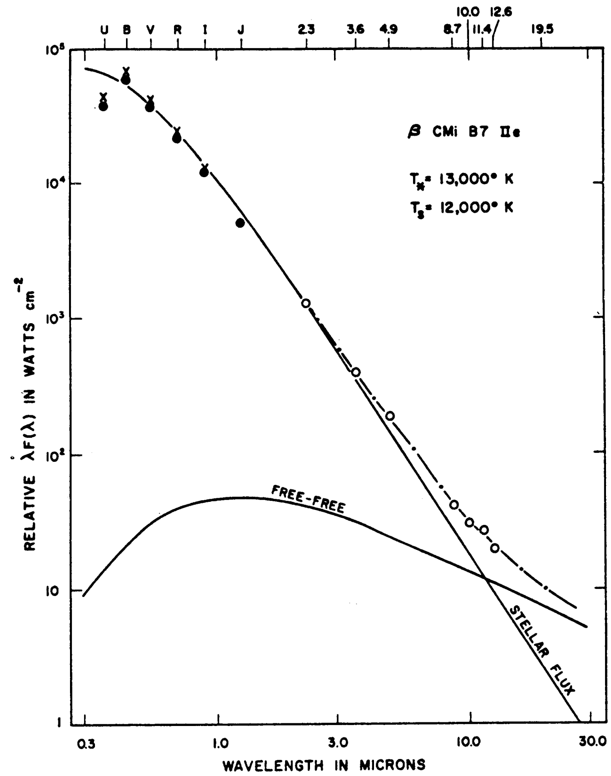

FIG. 3–The bright Be star, β CMi, is typical of Be stars whose infrared excess is well fitted by an optically thin free-free shell. The addition of the stellar and circumstellar continua (solid lines) is indicated by the dot-dash line, while the observations are shown by filled and open circles (Gehrz *et al.* 1974).

While support for the rotating, flattened disk model for Be stars came from optical spectroscopic, polarization, infrared, and radio observations, it was also clear that the simple model was not consistent with all of the observations. It is difficult to understand, for example, why the Be phenomenon is episodic on the basis solely of rotational instability—some kind of "trigger" mechanism must be present in addition to the presence of rapid rotation. Also, measured rotational velocities based on absorption-line profiles in the spectra of Be stars were found to be consistently lower than the computed critical rotational velocities at which centrifugal force equals gravity at the equator of the star (cf. Slettebak 1979), suggesting again that something in addition to rapid rotation must be acting to eject the circumstellar shell.

At the time of the first IAU Symposium on Be and Shell Stars in 1975, the *Copernicus* satellite had been operating for three years while the launch of *OAO-2* was still almost three years in the future. Those early ultraviolet observations included the discovery of stellar winds and mass loss from Be and shell stars (cf. Marlborough and Snow 1976), which was a strong influence on the models discussed at that conference. The stellar-wind models, both steady-state and time-dependent, were reviewed by Marlborough (1976), who suggested that while such models were supported by the ultraviolet observations, they could not account for the *V/R* variation in the Balmer emission lines. Marlborough (1976) reviewed also the elliptical-ring model, which attempts to explain the *V/R* variation. Originally suggested by Struve (1931) and developed further by McLaughlin (1961) and, especially, Huang (1973, 1975), this model proposes that the apsidal motion of an elliptical ring in which the emitting atoms revolve around the star according to Kepler's laws of motion causes the *V/R* variation. Although this model is able to explain the observational data for a number of Be stars, there are some drawbacks, as Marlborough (1976) has pointed out. The chief difficulty is the inability for the narrow ring required by the theory to produce the deep metallic-absorption lines observed in shell stars, but there are other difficulties as well (see the review article by Poeckert 1982).

The 1975 IAU Symposium on Be and Shell Stars also saw the introduction of the binary model for Be stars. While it has long been known that some Be stars are binary in nature, the suggestion was made by Harmanec and Křiž (1976) that most, if not all, Be stars are interacting binaries, the observed spectral changes being explained as a consequence of different modes of mass transfer between components. Figure 4 shows a schematic view of the possible distribution of circumstellar matter in a close binary, from their paper. As with other Be-star models, there are problems with the binary hypothesis, one being that more Be stars would be expected to be eclipsing binaries than are actually observed if most Be stars are indeed interacting binaries (Plavec 1976).

III. Observations from Space

A. *Ultraviolet Observations*

Struve's rotational model for Be stars, while explaining emission-line widths and the sharp absorption-line spectra of shell stars, runs into difficulties with respect to observed Be-star variability and the fact that Be stars rotate with less than the critical velocity, as was discussed above. Now ultraviolet observations, suggesting a hot, possibly global, component of the circumstellar gas in addition to the flattened cooler component in which the emission lines and infrared radiation arises, again point to the fact that the rotational model in itself is too simplistic.

In recent review papers, Snow (1987*a*) and Snow and Stalio (1987) discuss the phenomena of superionization and winds from Be stars. The term "superionization" refers to the presence of ionization stages higher than normally found in equilibrium at photospheric temperatures. Thus, in OB stars, ions such as O VI are found in the ultraviolet spectra of stars as late as B0 and N V in B1 or B2 stars, stars which are too cool to have such highly ionized species in their photospheres.

Several surveys based on *IUE* spectra (Marlborough and Peters 1982, 1986; Slettebak and Carpenter 1983;

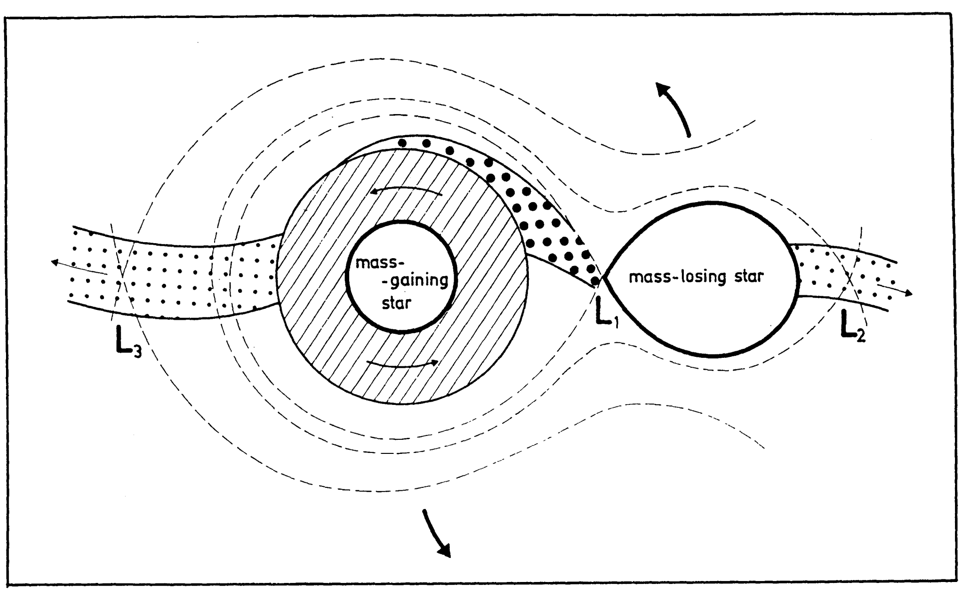

FIG. 4–A schematic view of the possible distribution of circumstellar matter in a close binary. The dashed lines correspond to Roche equipotentials. The heavy and light arrows denote the revolution of the components and the directions of gaseous flow, respectively (Křiž and Harmanec 1975).

Barker, Marlborough, and Landstreet 1984; Grady, Bjorkman, and Snow 1987) show that Be stars have a greater degree of superionization than normal main-sequence B-type stars: C IV and Si IV are observed in Be stars as late as B9, whereas they are seen in normal B stars only as late as about B2 and B5, respectively.

As Snow (1987*a*) points out, "There appears to be an intimate link between superionization and the presence of winds in Be stars. . . . examination of the profiles of the C IV and Si IV lines usually shows asymmetries or shifted absorption components having substantial outflow velocities, suggesting that most or all of the ion arises in circumstellar material that is expanding away from the stars".

Comparison of the asymmetrical line profiles with theoretical profiles based on stellar-wind theory leads to mass-loss rates in the range 10^{-11} to 10^{-9} solar masses per year, with wind-terminal velocities as high as 1000 km s^{-1} (Snow 1981).

The shortward-shifted discrete components were first detected in ultraviolet resonance lines of γ Cas (cf. Henrichs *et al.* 1983). They are generally observed in the lines of C IV and Si IV, with velocities which may exceed the rest velocity of the star by over 1000 km s^{-1} (see Fig. 5), and are highly variable, both in intensity and in velocity, on both long and short time scales (see also Henrichs 1984, 1986). An important result by Grady *et al.* (1987) is that, whereas shortward-shifted components are not ob-

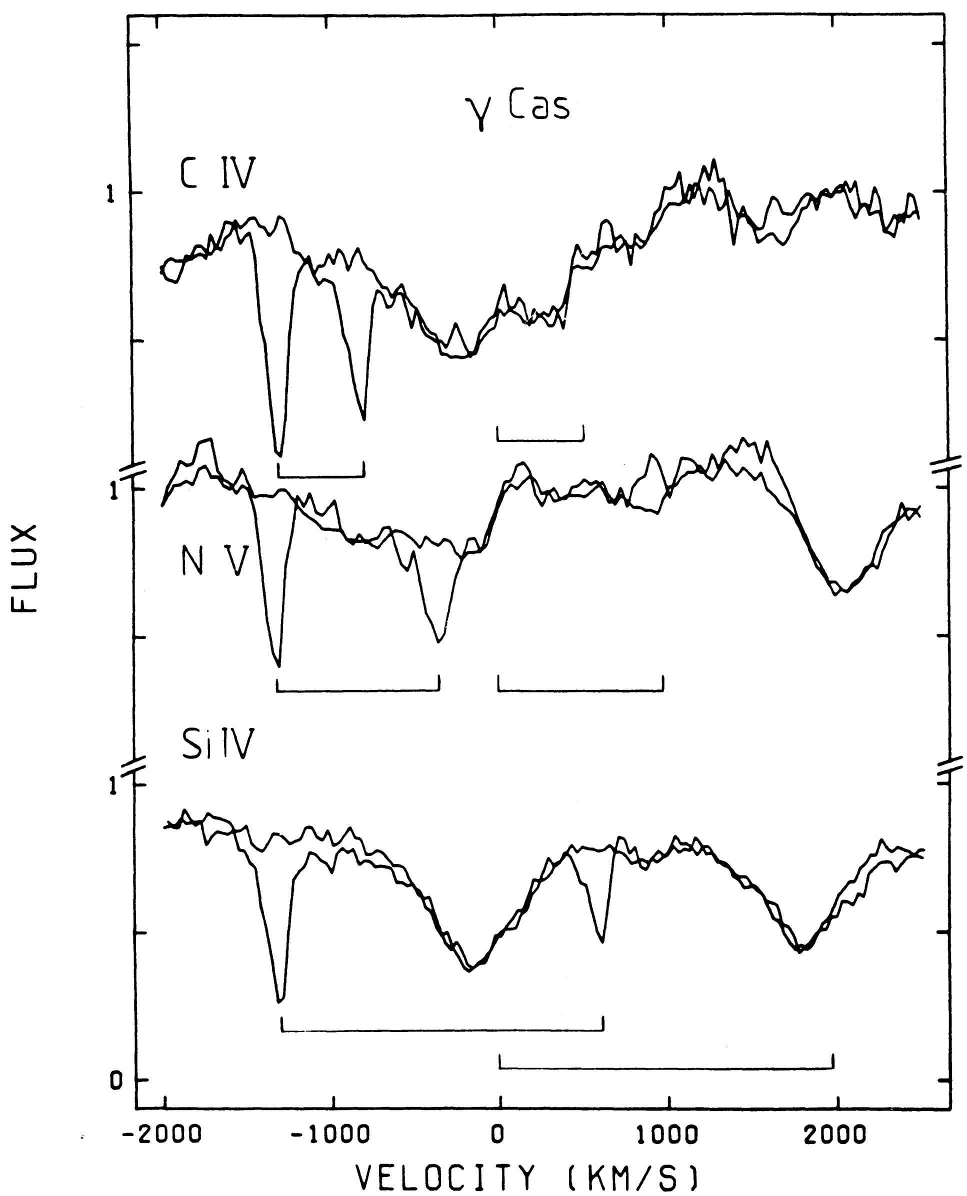

FIG. 5–Resonance lines in the ultraviolet spectra of γ Cas, illustrating the striking differences between a spectrum with and without the shortward-shifted (here, about −1300 km s^{-1}) discrete absorption components (Henrichs *et al.* 1983).

served in normal, nonsupergiant B-type stars, they occur in at least two-thirds of their sample of 62 Be stars observed. The presence of discrete absorption components thus seems to be a significant element in the Be phenomenon.

While optical and infrared observations provide evidence that the cool, circumstellar matter is concentrated in the equatorial plane, some of the ultraviolet data on the hot, high-velocity winds suggest that these are essentially global. Thus, both Snow (1981) and Slettebak and Carpenter (1983) found no strong correlation between mass-loss rates and $v \sin i$ for small samples of Be stars, while Peters (1982) and Dachs and Hanuschik (1984) found evidence for mass loss in several Be stars with relatively low $v \sin i$'s and therefore presumably being viewed nearly pole-on.

Grady *et al.* (1987), however, with a very large sample of Be stars, found evidence for a threshold in $v \sin i$ for the presence of the discrete absorption components: they are not observed in Be stars with $v \sin i$ less than about 150 km s^{-1}, which suggests either that a threshold rotational velocity for formation of the features exists or, more likely, that they are equatorially confined to some degree (assuming all Be stars to be rapid rotators). Shell stars, assumed to be viewed nearly equator-on, were found to show little or no evidence for high-velocity winds. As Snow (1987*a*) expresses it, "This combination of findings implies that there is indeed a disk in which high-velocity mass flow does not occur, and that the winds also do not reach very high latitudes". With regard to shell stars, however, Plavec (1987*c*) points out that the conditions for detecting high-velocity winds are worse for these objects because they are seen with their disks nearly edge-on. While the disk probably prevents high-velocity flows, there may be winds essentially perpendicular to the disk surfaces, which we cannot detect. Their emission would be too weak to compete with the full UV flux of the underlying B star, and the wind is not seen projected against any bright background if it goes to high latitudes, so that its absorption effects in the form of absorption lines canot be seen.

In a recent paper, Grady *et al.* (1988) extended their study of high-velocity absorption components in Be stars to the late-type (B6–B9.5e) Be stars. They again find a threshold value of $v \sin i$ for the appearance of the discrete components, but the threshold is higher ($\simeq$ 200 km s^{-1} for main-sequence stars) than for the earlier (B0.5–B5e) types. It is, as Snow (1987*b*) expresses it, ". . . as if the cooler stars require a little more 'oomph' from rotation in order to produce the high-velocity components".

The ultraviolet spectra of Be stars, like the observations made in other wavelength regions, are variable on many time scales. Short time-scale variability tends to be episodic, with periods of no variation followed by changes occurring in days or hours. The discrete absorption components in the broad, asymmetric resonance lines in Be stars may appear, become multiple, disappear, and/or show velocity shifts. Henrichs *et al.* (1983) have interpreted such behavior in terms of blobs of enhanced density moving outward through the wind, while Barker (1987*b*) suggests that the winds may contain shocks, with multiple shells ejected from the photosphere into the wind.

Long-term variability studies of Be stars in the ultraviolet are now possible with the continuing successful operation of the *IUE* satellite, and it has been possible to associate ultraviolet variability with variability observed in other wavelength regions. Thus, studies of 59 Cyg, θ Coronae Borealis, and γ Cas by Doazan and her associates (1985, 1986, 1987) show a correlated behavior between spectral features originating in the cool Hα-emitting envelope and features originating in the superionized regions. These observations suggest a definite relationship between the physically different components of the Be-star envelope.

B. *IRAS Observations*

Infrared observations of Be stars, especially with the *IRAS* satellite, are discussed in a recent review paper by Lamers (1987). In a statistical study of the IR excess of 101 Be stars, based on the IR fluxes at 12 μ, 25 μ, and 60 μ obtained with the *IRAS* satellite, Coté and Waters (1987) concluded that the observed IR excess in Be stars is caused by free-free radiation from circumstellar material. This conclusion is in agreement with the ground-based IR results of Gehrz *et al.* (1974) and Dachs and Wamsteker (1982). Coté and Waters (1987) also examined the correlation of the observed IR excess, expressed in terms of the color excess in (V − 12 μ), with the following stellar characteristics.

1. *(V − 12 μ) color excess vs. spectral type.* Their plot shows a large scatter for a given spectral type, indicating that the Be characteristics differ drastically in strength from star to star and that the presence of circumstellar material is not linked directly to the basic stellar parameters T_e and L (or some average of T_e and L, since Collins (1987) has pointed out that neither is directly observable for rapidly-rotating stars). An upper limit to the IR excess exists, which varies with spectral type: larger excesses are found for B0–4e stars than for B5–9e stars. The existence of an upper limit suggests that the Be mechanism, responsible for the presence of circumstellar material, cannot produce an arbitrarily large IR excess at a given spectral type.

2. *(V − 12 μ) color excess vs. v sin i.* In a study of all B-type main-sequence stars, Waters (1986) showed that a correlation between the (V − 12 μ) color excess and $v \sin i$ exists, in the sense that stars without IR excess tend to have small values of $v \sin i$, whereas stars with large IR excess tend to have large $v \sin i$ values. The latter group consists mainly of Be stars—among these, no clear corre-

lation between IR color excess and $v \sin i$ could be found, a result similar to that of Gehrz *et al.* (1974). As Waters states, this suggests that rotation facilitates the presence of a circumstellar shell but other mechanisms determine whether or not a star is a Be star. Once a shell exists there is no correlation between $v \sin i$ and IR color excess.

3. *(V − 12 μ) color excess vs. H α emission.* A correlation between the strength of Hα emission and IR emission was found, but with considerable scatter. Such a relation may suggest a common origin of the IR radiation and the Hα radiation from Be stars.

4. *(V − 12 μ) color excess vs. intrinsic polarization.* The intrinsic linear polarization of Be-star radiation is attributed to the scattering of the stellar radiation by free electrons in an equatorially-confined disk, as was discussed earlier in this review. On the other hand, IR emission is also due to free electrons in the circumstellar envelope. A correlation between IR excess and the degree of polarization might, therefore, be expected for Be stars, and this was found by Coté and Waters (1987) for 46 stars with polarization measurements (McLean and Brown 1978) in their *IRAS* sample. They found a well-defined upper limit in a plot of percentage of intrinsic polarization vs. the IR excess at 12 μ, showing that large polarization can only be reached with a large IR excess. The existence of such an upper limit is consistent with the IR excess being produced in a flattened envelope or disk.

Waters, Coté, and Lamers (1987) computed mass-loss rates for Be stars based on IR excesses from *IRAS* observations. Assuming a disk model with mass outflow, they found that the mass-loss rates from the IR are much higher than the rates derived from asymmetric UV resonance lines, typically by a factor $\simeq$ 100. They also found that the IR mass-loss rates depend only weakly on luminosity, indicating that radiation is not the only driving force—the mechanisms for the ejection of material observed in the UV and in the IR must be quite different.

C. *X-Ray Observations*

In a review of work done to 1981, Rappaport and van den Heuvel (1982) pointed out that Be-star binaries with neutron-star companions constitute a major class of X-ray sources. Data for the 12 Be/X-ray binary systems known at that time showed that they are systematically wider, with lower-mass primaries and significantly more transient behavior, than the more massive X-ray binaries such as Centaurus X-3 and SMC X-1. Rappaport and van den Heuvel also found that the Be star characteristics of the Be/X-ray systems are indistinguishable from those of other Be stars: the neutron star appears to have no influence on its companion. Thus, the Be characteristics need not arise from matter accreting onto the Be star. They also suggest, from evolutionary and statistical considerations, that thousands of Be/neutron star systems are expected to exist in our Galaxy.

In a later review, van den Heuvel and Rappaport (1987) find an increase from 12 to 20 X-ray sources associated with Be stars, making them the most abundant type of massive X-ray binary in the Galaxy. In a section entitled, "Why Be stars are good candidates for companions of X-ray sources", they write:

> To make an X-ray source out of a neutron star, the only required ingredient is: a nearby source of matter. This is most easily achieved when the neutron star is in a binary system and its companion is losing mass. The following general types of mass loss from stars are known: (a) strong stellar winds, as seen in blue and red supergiants; (b) overflow of Roche lobe in a binary system; (c) irregular outbursts of mass outflow from the equatorial regions of rapidly rotating B-stars, causing the 'Be-phenomenon'. Thus, if neutron stars can be born as companions to stars of any kind, one would expect to find X-ray binaries with companions of all the above-mentioned types. Indeed, this appears to be the case. . . . In the Be/X-ray binaries the companions are Be stars that are deep inside their Roche lobes, but from time to time undergo outbursts of equatorial mass ejection, upon which the neutron star appears as a strong 'transient' X-ray source.

Figure 6, from their paper, shows this behavior schematically.

Corbet (1984, 1986) has shown that the neutron star can be used as a probe with which to investigate the environment about the Be star in Be/X-ray binaries. (Janot-Pacheco, Ilovaisky, and Chevalier (1981) had suggested earlier that direct interaction of a compact object with a typical Be envelope may be important in the production of X-rays.) He finds densities and velocities which agree well with the typical parameters inferred from optical and infrared emission from circumstellar disks of Be stars. As van den Heuvel and Rappaport (1987) point out, the clear conclusion seems to be that the main source of the accretion in the Be/X-ray binaries is the relatively slowly expanding dense circumstellar disk around the Be star and not its weak high-velocity wind.

IV. Later Models of Be Stars

As Plavec (1987*b*) stated in his "Reflections on Be Stars and the Be Phenomenon" at the conclusion of the Proceedings of IAU Colloquium 92,

> I believe that the realization of the inherent complexity of the Be phenomenon is one of the fundamental conclusions one has to draw from three recent meetings on Be stars. This is a strikingly different situation compared to the idyllic times that still prevailed some 20

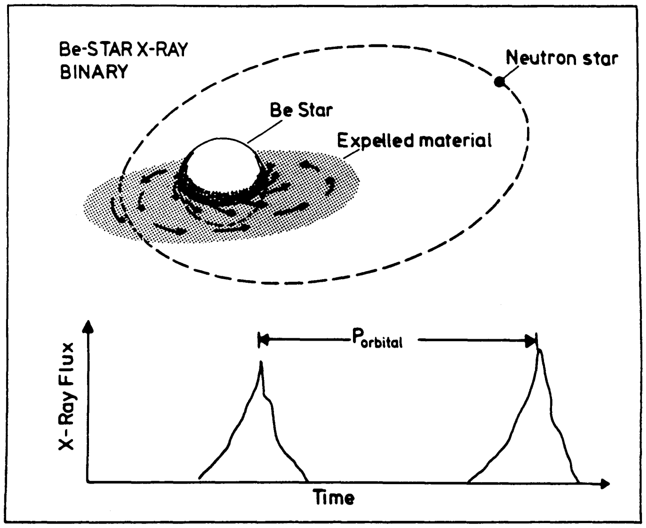

FIG. 6–Schematic model of a Be-star/X-ray binary system such as A0538−66 and V0332+53. The neutron star moves in a moderately eccentric orbit around the Be star, which is much smaller than its own critical equipotential lobe. The rapidly-rotating Be star is temporarily surrounded by matter expelled in its equatorial plane. Near its periastron passage the neutron star enters this circumstellar matter and the resultant accretion produces an X-ray outburst lasting several days to weeks (van den Heuvel and Rappaport 1987, adapted from *Los Alamos Science*, Spring 1986).

> years ago. Then, the model outlined by Otto Struve in 1931 was almost generally accepted as *the* explanation, and was only being modified from time to time in order to accommodate new findings.

By 1986, at the time of IAU Colloquium 92, there were five competing models. These will be summarized briefly in this section.

A. *Rotationally-Enhanced Stellar-Wind Models*

These models are summarized in a review paper by Marlborough (1987). He reviews the earlier stellar-wind models (see also the review paper by Poeckert 1982) and discusses radiation-driven stellar winds, including the role of rotation and magnetic fields. Marlborough presents his conclusions at the end of his article as follows:

> New data (. . . especially the Hα line profile studies of Dachs *et al.* 1986 and the interpretation of *IRAS* data by Waters 1986*b*) strongly support the idea that optical and infrared emission comes from a cool, disklike region concentrated to and extending a few radii from the surface in the equatorial plane. Inclusion of rotation (Marlborough and Zamir 1984) and both the finite angular size of the star and rotation (Friend and Abbott 1986; Poe and Friend 1986) yield radiation-driven winds with larger densities near the equatorial regions than near the poles, thus providing dynamical support for the ad hoc wind models. Mass loss from polar regions may account for displaced UV lines in stars of smaller $v \sin i$. Mass loss driven by nonradial pulsation changes will add to the background wind in stars hotter than B2; in cooler ones the entire circumstellar envelope may arise in this way. Whether the part of the circumstellar envelope outside the cool, disklike zone is hot or cool is still in doubt (i.e., the observed superionization could be a non-LTE effect in a cool wind).

A meridional plane section showing the possible arrangement of matter consistent with these ideas is shown in Figure 7.

B. *The Spheroidal/Ellipsoidal, Variable Mass-Loss, Decelerated Be-Star Model*

This model was proposed by Doazan and Thomas (see Doazan 1982) and discussed further in a review paper by Doazan (1987). The radial sequence of atmospheric regions in this model has a chromosphere just above the photosphere, surrounded by a corona, a postcorona, in which the outward flow begins to cool, and finally a low-velocity, cool, extended, Hα-emitting envelope which is formed after a shock in the postcorona. The Be phenomenon is associated with variable mass outflow produced by nonthermal subatmospheric modes. The deceleration of the mass outflow is assumed to be produced by interaction of mass flows of different velocities which occur at different epochs or between the mass outflow and the local stellar environment. Figure 8 shows a schematic view of this model, labeled "Scenario 4" in the review paper by Poeckert (1982). The original model consisted of a spherical system which, as has been pointed out in this review, is contradicted by optical spectroscopic and polarization data as well as infrared and radio observations. In the most recent summary (Doazan 1987), however, the suggestion is made that, due to the coupling of the rotation of the star with the expanding flow, the shape of the Be-star atmosphere is ellipsoidal, with a time-dependent degree of flattening.

C. *The Nonradial Pulsation Model*

In recent review papers Percy (1987) and Baade (1987) summarize the observational evidence for rapid variability in Be stars, especially the moving patterns detected in the line profiles. These may be interpreted, according to two competing hypotheses, either in terms of nonradial pulsations or rotational modulation of a feature or features on the surface of the Be star. (The latter interpretation is suggested by Balona and Engelbrecht (1986) to explain periodic photometric variations of Be stars in the cluster NGC 3766.) In his review paper, "Be Stars as Nonradial

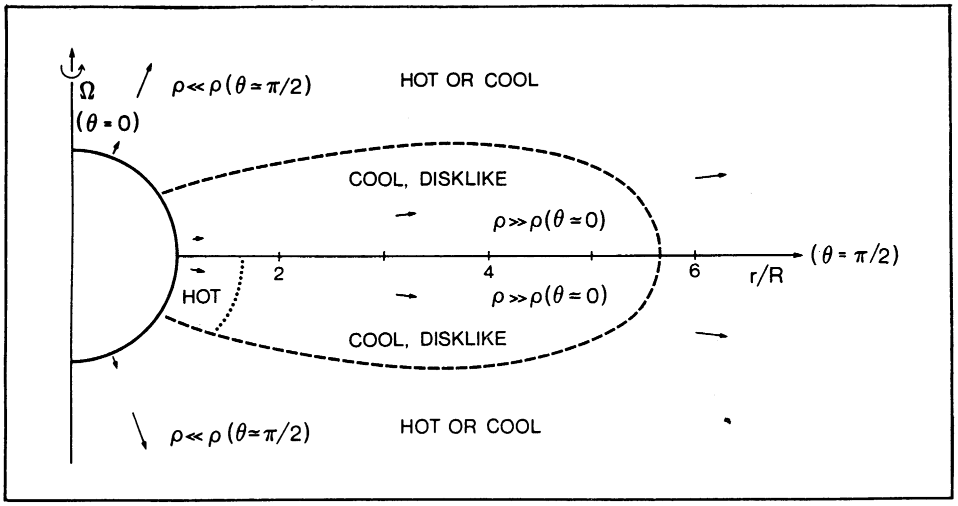

FIG. 7–Schematic meridional plane structure of the circumstellar envelope, according to Marlborough (1987). The extent and shape of the cool, disklike region is unknown. Two possibilities are shown: in the upper the disklike cool region extends to the stellar surface; in the lower a dotted line separates the cool region from a hot zone at the surface. The background wind may be hot or cool with shocks to give superionized ions throughout the wind.

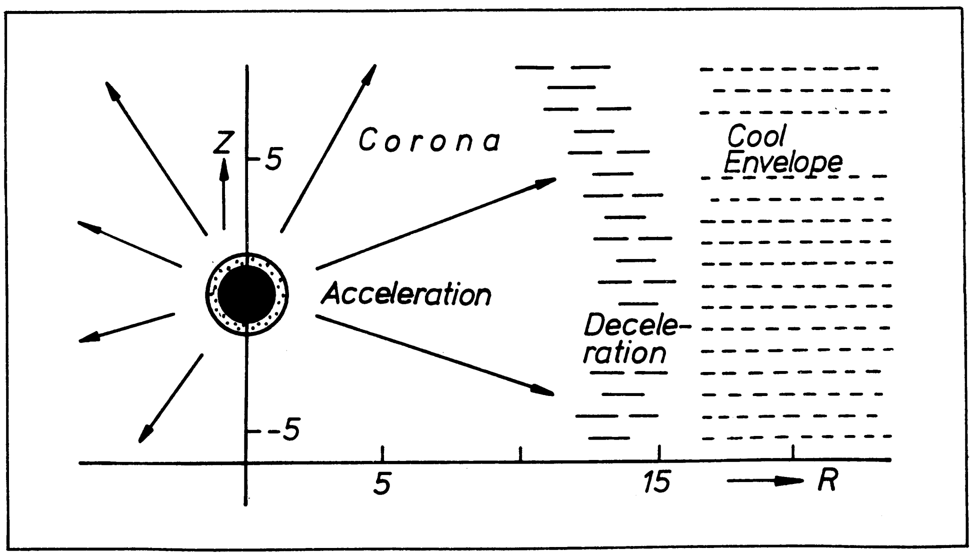

FIG. 8–A schematic view of the spheroidal/ellipsoidal, variable mass-loss, decelerated Be star model, as illustrated by Poeckert (1982).

Pulsators", Baade (1987) examines the evidence for nonradial pulsation, which has been suggested as the underlying cause of the Be phenomenon (Vogt and Penrod 1983; Penrod 1986, 1987). Figure 9, from the paper by Vogt and Penrod (1983), illustrates the formation of distortions in the line profiles of a rapidly-rotating, nonradially-oscillating star. The mode shown has ℓ (which determines the degree of concentration of the oscillations toward the stellar equator) = 8, and m (which describes the number of wave crests along the equator) = −8. The sign of m describes the direction in which the running waves are moving, with negative values applying to waves moving in the same direction as the rotation of the star.

Vogt and Penrod (1983) found a correlation between the apparent amplitude of the oscillations and episodes of outburst for the hot Be star ζ Ophiuchi and suggested that the outbursts in this and other Be stars may be driven by the occasional release of this energy during episodes of mode-switching. Later, Penrod (1987) found all but two of 25 rapidly-rotating Bn and Be stars to show obvious line-profile variations, which he attributes to nonradial oscillations. The Be stars in his sample pulsate in a long-period $\ell = 2$ mode in all cases, and often in a short-period high-ℓ mode as well. The amplitude of the pulsations was found to be correlated with the occurrence of Be outbursts in four of his Be stars. Penrod states: "The correspondence between the presence of a long-period $\ell = 2$ mode and Hα emission in rapidly-rotating B stars strongly suggests

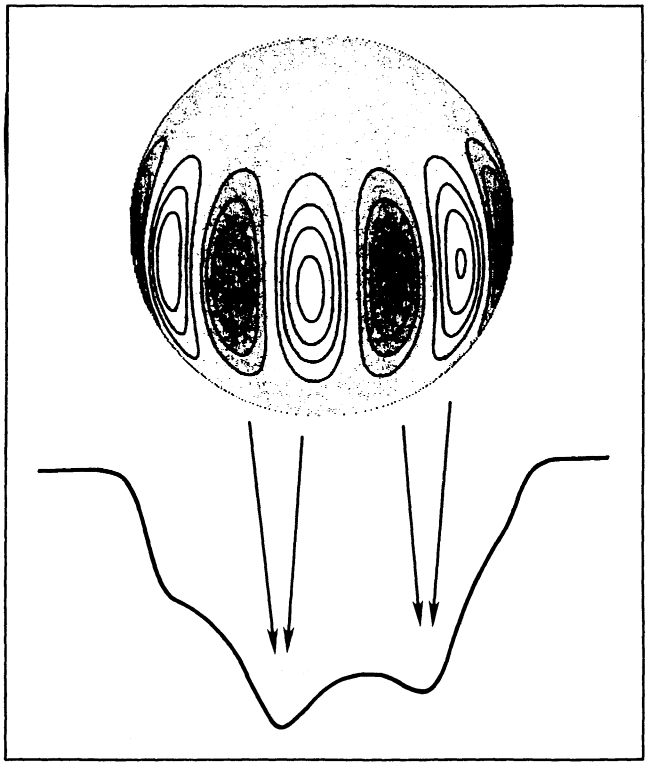

FIG. 9–Illustration of the formation of distortions in the line profiles of a rapidly-rotating nonradially-oscillating star. This is a velocity map of the star with the resultant line profile shown below. The darkest shaded regions correspond to material moving away from the observer, while the lightest regions represent material moving toward the observer (Vogt and Penrod 1983).

that nonradial pulsation and rapid rotation are the essential components which enable single early B stars to become Be stars. The time scale between Be outbursts probably reflects the relaxation oscillation cycle of the $\ell = 2$ mode excitation and damping".

Although nonradial pulsation offers an exciting prospect of explaining the Be phenomenon, there are some reservations. Thus, Balona (1987) at IAU Colloquium 92 stated, "The main weakness of nonradial pulsations as an explanation of line profile variations in Be stars is that it explains too much, i.e., there are too many free parameters so that *any* line profile may be fitted by suitably choosing a combination of parameters. This makes the theory practically impossible to disprove". Also, as Baade (1987) points out, low pulsation amplitudes in stars cooler than B6 make it likely that the Be phenomenon extends to lower temperatures than significant nonradial pulsations do. M. A. Smith (1988) suggests that nonradial pulsation, even combined with rotation, is unlikely to be the sole causative process for Be outbursts because it does not exhibit the necessary strong correlations, nor can it release enough energy over short time scales to match the observations. He favors magnetic instabilities in addition to nonradial pulsation to explain the Be phenomenon. Obviously, more work needs to be done, both observationally and theoretically, but nonradial pulsations are important in that they offer a physical mechanism for getting material out of the equatorial regions of a rapidly-rotating star into the circumstellar disk.

D. *The Interacting Binary Model*

This model was discussed briefly in Section II (see Fig. 4) and is summarized in the review articles by Harmanec (1982, 1987). In the latter paper, he gives the following brief outline of the binary model:

> The binary model assumes that the formation of the Be envelope is a result of evolutionary processes and interactions in a binary system. In most cases, the Be envelope is simply an accretion disk/envelope structure around the mass-gaining components of interacting systems. Computer modelling of mass transfer in binaries has demonstrated that most systems should be observed in later phases of mass transfer when the mass-gaining component is already much more massive, and also more luminous in the optical region, than its counterpart.

As has been mentioned, the binary model as the explanation of the Be phenomenon in general has been criticized on the basis of an observed scarcity of Be-star close binaries (Abt 1987, for example, concludes from statistical studies that while most Be stars are in binaries, the bulk of the periods are decades or more in length and are unlikely to be interacting systems) and, in particular, a much smaller number than expected of Be-star eclipsing systems (Plavec 1976). Harmanec (1987) responds:

> The available data are insufficient to test possible duplicity for the majority of even bright Be stars. The binary model seems to offer a consistent interpretation of those emission-line stars which have already been known as binaries but to what extent it can be considered as a general model of the emission-line phenomenon remains an open question.

Plavec (1987*a*) points out that semidetached close binary stars of the Algol type often have primary components of spectral type A0 or earlier and display emission at Hα. Binaries of this type which are not eclipsing will look like ordinary Be stars and there must be many of them.

E. *The Magnetic-Loop Model*

Underhill (1983, 1987) describes a model for Be stars consisting of a low-density wind and a disk generated by the magnetohydrodynamic interactions which may occur as a star with extruding, magnetically-supported plumes rotates rapidly. Her model consists of arcades of magnetic loops which form helmet-type structures in the equatorial band of the star, and of coronal-hole-type structures, emanating from weak unipolar magnetic regions which are chiefly distributed at polar latitudes. The shortward-displaced discrete components of resonance lines (see Section III.A and Fig. 5) are explained as due to magnetic reconnection near the tops of some of the arcades, releasing parcels of plasma from particular spots above the photosphere.

Snow (1987*b*) points out that the magnetic-loop model should probably predict substantial X-ray fluxes from Be stars; yet these objects tend to be X-ray sources only when compact companions are present (see Section III.C above) and do not yield strong observed soft X-ray fluxes. He is pursuing this subject further.

Observational evidence for the magnetic-loop model would be difficult to obtain. While no mean longitudinal or torroidal magnetic fields have yet been detected on any classical Be star (see the review paper by Barker 1987*a*), the tangled, disordered fields (analogous to those on the solar surface) implied in this model would produce only very small mean field components when averaged over the entire stellar surface and would, therefore, be difficult to detect with present techniques.

What can be said at this stage in Be-star research about the cause of the Be phenomenon? As Corbet (1984) expressed it, "Although there is an enormous body of observational data on the Be phenomenon this is not matched by the degree of understanding". Yet, there has been progress. While it seems unlikely that any one of the above models can explain all of the observed features of Be stars, combinations of one or more are more successful. Thus, Marlborough (1987) has suggested that the concept of a radiation-driven wind combined with the variable nature of nonradial pulsations may provide a basic outline for an explanation of the Be phenomenon. Then, too, it is clear that *some* Be stars are interacting binaries and that the interaction of the components must play an important role in the Be characteristics of those objects, even if the evidence seems to be against *all* Be stars as close binaries. Local magnetic fields, perhaps in combination with one or more of the above models, may well also play an important role.

Plavec (1987*b*) has also pointed out another trend:

> . . . the growing realization that the Be stars are not an isolated group of objects, as they appeared to be at the time of the early models. In the stellar wind model, the Be stars are a continuation of the Oe stars; the strong radiative push provided by the high-luminosity OB supergiants is believed to be partly provided by the rapid rotation in the less luminous Be stars. The binary star model implies that in the wide sea of various types of interacting binaries, there are cases that by chance the mass gainer happens to be a B star, that is, provides enough ionizing photons to create Balmer emission lines radiated from the accretion disk. The hypothesis of nonradial pulsations stresses the affinity of the Be stars to their other neighbors in the HR diagram, namely to the pulsating β Cep stars. And the model of the chromosphere-corona complex dominated by the non-radiative energy flux from the deeper layers of the star, as advocated by Thomas, Doazan, Cannon, and others, stresses explicitly that the Be phenomenon is only an enhancement of a structural complex which should exist in all stars.

V. Evolutionary Status of Be Stars

One of the most interesting and important questions about Be stars is their evolutionary status. Unfortunately, it is also one of the most perplexing questions and is still basically unanswered.

Spectroscopic studies by Merrill, Struve and his collaborators, and Morgan in the 1930s and 1940s (see Slettebak (1979) for these and other references in this section) showed that Be stars are close to the main sequence. Later work by many investigators, especially studies of Be stars in clusters, confirmed this result, suggesting that, on the average, Be stars are located one-half to one magnitude above the main sequence.

Meanwhile, statistical studies from the time of Merrill and Burwell to the present show that Be stars are not exotic objects but a rather common type of star representing up to 20% of the B-star population. Most recently, Abt (1987; see also Jaschek and Jaschek 1983) found Be stars to comprise 18% of the B0–B7 stars in a volume-limited sample of field stars, with a maximum at B3–B4 and lower frequencies for the early- and late-B types. Abt (1987) also studied the galactic distribution of Be stars and found this to be similar to that of the early B-type stars in the Gould Belt. He suggests that this result implies that Be stars have roughly the same ages and the same origin as the B stars of the same type.

The aforementioned results suggest that Be stars may represent a stage in the normal evolution of B-type stars. Thus Crampin and Hoyle (1960) proposed that the shell star Pleione is in the secondary contraction phase following hydrogen exhaustion in the core: conservation of angular momentum would cause the shrinking star to spin faster and a shell might be produced when the critical rotational velocity was reached. Schmidt-Kaler (1964) then suggested that *all* Be stars might be in this evolutionary phase, but statistical and theoretical studies as well as observations of Be stars in clusters do not support this suggestion (see Slettebak 1979 for references).

Studies of Be stars in clusters have yielded some information about evolutionary effects but are limited by rotational effects on colors and spectral types as well as by internal reddening effects. Schild and Romanishin (1976) found for a sample of 41 Be stars in 29 young galactic clusters that the fraction of Be stars varies little during most of their post-main-sequence evolution but increases sharply at the onset of the secondary contraction phase. In a study of 14 galactic clusters, Abt (1979) found no dependence of the frequency of Be stars on cluster age in the range $10^{5.7}$ to $10^{8.1}$ years. These investigators suggest that Be stars form early in the cluster histories, with a possible formation spurt at the onset of the secondary contraction phase. On the other hand, Mermilliod (1982) found the distribution of the Be stars as a function of age of the parent cluster not to be uniform. His results show the frequency of Be stars to have a strong maximum in the youngest clusters and then to decrease with increasing age, becoming very rare in clusters older than 10^8 years.

Color-magnitude and H-R diagrams of galactic clusters containing Be stars show that Be stars may be found anywhere between the zero-age main sequence and the giant region (Mermilliod 1982; Slettebak 1985). If the position of the Be stars in these diagrams is attributed to evolution alone, the conclusion would be that they may exist in various evolutionary states. Other effects may enter to move Be stars off the main sequence in such diagrams, however. Thus, many Be stars in clusters show an intrinsic reddening (Crawford, Glaspey, and Perry 1970; Schild 1978; Mermilliod 1982; Slettebak 1985), presumably due to the Be envelopes. Also, Collins and Sonneborn (1977) predicted that rapid rotation in B-type stars will cause gravity-darkening effects which will move a star off the zero-age main sequence regardless of the inclination of the rotation axis, while Slettebak, Kuzma, and Collins (1980) found a similar effect on the spectral types and luminosity classes due to rapid rotation.

What can be said, finally, about the evolutionary status of Be stars? The existence of Be stars close to the zero-age main sequence suggests that some, at least, are relatively unevolved. The majority of Be stars, on the other hand, are located off the main sequence, which may be due to evolution but may be due in part also to circumstellar reddening and, probably to a lesser degree, gravity darkening of the underlying rapidly-rotating star. It does not follow that most Be stars are in the secondary contraction stage, as has been maintained by some authors. Unfortunately, the evolutionary status of Be stars still seems quite uncertain.

It is a pleasure to express my thanks to my friends and Be-star colleagues Paul Barker, George Collins, Carlos Jaschek, Mike Marlborough, Mirek Plavec, and Ted Snow for reading the manuscript and making valuable suggestions to improve this paper. Of course, any errors or misconceptions which remain are all mine.

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