III. THE CIRCUMSTELLAR GAS

OPTICAL EMISSION-LINE SPECTRA OF Be STARS
(Review Paper)

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Abstract. Recent observational work on spectra obtained at optical and near-infrared wavelengths is reviewed for "ordinary" (non-supergiant non-peculiar) Be and Be-shell stars, with particular emphasis on comparison between high-resolution spectral measurements and current Be star models. Emission-line profiles are interpreted in terms of geometry, dimensions and dynamics of a dense ($N \approx 10^{11}$ cm^{-3}), cool ($T \approx 10^4$ K) line-emitting region in the circumstellar envelope, separated from the thin, hot expanding stellar wind region. Present observations support a rotating-disk model for the cool, line-emitting region. Indications pointing towards structuring of cool circumstellar envelope regions are reported. Significant spectral variations are detected both on short (less than one day) and long time scales (months to years). Typical cycle times for large-amplitude V/R variations and intervals between shell episodes depend on spectral type, increasing with decreasing effective temperature of the central stars and ranging from a few years for early-Be type stars to a few decades for late Be stars.

1 INTRODUCTION

The Be phenomenon was discovered 120 years ago in Rome by Father Angelo Secchi (1866) who visually inspected spectra of bright stars and thereby found the Fraunhofer F (= Hβ) line to be bright in the spectra of both γ Cas and β Lyr. This was about the time when the first settlers came to the Boulder area.

Although large efforts have since been devoted to the study of Be stars, and notwithstanding the fact that several Be stars belong to the brightest stars in the sky (e.g., α Eri, γ Cas, δ Cen, η Cen), we are still far from understanding their properties.

Previous work performed prior to about 1980 on properties of Be stars in general and optical Be star spectra in particular has been reported and summarized in the proceedings of IAU Symposia no. 70 (Slettebak, 1976 a) and no. 98 (Jaschek and Groth, 1982). Fairly complete reviews of the subject were also published several times in recent years, although each time starting from different viewpoints and with various preferences of the authors for certain topics or for specific Be star models. A well-balanced account both of observations in all wavelength ranges and of then available models was presented by Slettebak (1979) and later supplemented by a review of spectroscopic observations in the photographic and visual regions between 1975 and 1981 (Slettebak, 1982 a). Doazan (1982), in her extensive survey of the Be phenomenon, points to the difficulties of existing model conceptions for Be stars and correctly emphasizes the need to incorporate Be star variations as a natural feature into realistic Be star models. Kogure and Hirata (1982) and Hirata and Kogure (1984) gave a bipartite account of Be star research, collecting arguments in favour of the disk model for the emission-line producing circumstellar envelope.

Be star variations were separately reviewed, with particular emphasis on correlations between photometric and spectroscopic variations, as well by Harmanec (1983) as by Kogure (1984).

The present review intends to give a progress report on recent studies of optical spectra for Be stars published after the 1981 IAU Symposium on Be stars, and to emphasize several hitherto neglected aspects of Be star research such as quantitative evaluation of envelope structure, statistics of envelope properties, and typical time scales for spectral variations of Be stars. We emphasize the difficulty or virtual impossibility of properly arranging and comparing scattered observations of strange astronomical objects such as Be stars without using a model as a guideline. As a basic model we shall frequently refer to a modified version of the approved rotating disk model for the emission-line producing envelope around Be stars.

For the purpose of this review, a Be star is defined as a non-supergiant early-type star whose spectrum shows, or has shown at some time, hydrogen lines in emission. This definition closely conforms to the recommendation of the IAU Working Group on Be stars (Jaschek et al., 1981) and is meant to include as well Oe and Ae-type stars as Be stars showing "shell" spectra characterized by narrow and usually deep absorption cores of hydrogen and sometimes also of metallic lines superimposed to a normal Be spectrum. The whole subgroup of early-type emission-line stars is sometimes also called the "ordinary" or "classical" Be stars. Because of space limitations, we generally exclude from our review the closely related types of peculiar B[e] stars characterized by forbidden emission lines in their spectra, the supergiant Be stars, and the Herbig Ae/Be stars believed to be associated with nebulosity, and to represent an early stage in stellar evolution although many similarities to the so-called "classical" Be stars exist. The latter two groups of emission-line stars were extensively discussed at the recent IAU Symposium no. 122 on Circumstellar Matter.

Since many Be stars do not permanently show the Be phenomenon or the shell phenomenon in their spectra, it is also common practice to use terms like Be phase, shell phase, shell episode, or mass loss episode to describe limited phases in the assumed cycles of variations for certain early-type stars. We avoid the term "shell" if the circumstellar region producing emission lines is meant. For this region, we prefer to use the word "envelope" instead in order to reduce confusion.

Today it is known that Be stars share the following general properties:

1. The underlying early-type stars are, on the average, rapid rotators, as first stated by Struve (1931) and later demonstrated quantitatively by Slettebak (1976 b, 1982 b).
2. Emission lines are present in their optical and infrared spectra, indicating the presence of cool dense circumstellar envelopes as also first noted by Struve (1931). Discussions of physical conditions in these line-emitting regions around Be stars point to typical electron temperatures of the order of 10^4 K, less than the photospheric temperatures of the stars, and to electron densities of the order of 10^{11} to 10^{12} electrons cm^{-3}; therefore these regions are often referred to as the cool circumstellar envelopes (CCE).
3. Profiles of the resonance absorption lines in ultraviolet spectra of early-Be type stars usually reveal variable stellar winds with typical velocities of outflow between about 500 and 1000 km s^{-1}, and electron temperatures well in excess of effective temperatures of the stars, as stated, e.g., by Snow (1981) and by Marlborough (1982).
4. Virtually all Be stars show strong irregular variations as well in their optical spectra as in their visual brightness and in the intensity and speed of their stellar winds, on various time scales, as noted, e.g., by Doazan (1982). Correlations between variations for these different phenomena are the object of active research and will be discussed in some detail at this colloquium.
5. Appearance of emission lines in the spectrum of an early-type star represents a transient phase in the life of the star; transitions from a normal B phase of a certain star showing a pure absorption-line spectrum to a Be phase of usually limited duration are a common phenomenon (cf., e.g., Jaschek et al., 1980).

Be stars represent the last class of strongly variable bright stars for which complete descriptions of light-curves and cycles of spectral variations are still lacking, and both the origin and the nature of variations are so far unknown. The disk model for the circumstellar emission-line region suggests the possibility to discuss both spectral and photometric variations of Be stars in terms of disk instability and disk interaction with the stellar wind.

Necessarily, this review can only be incomplete in view of the fact that about seven-hundred publications related to Be star research have appeared in the literature since about 1980, according to the meritorious and extremely useful listings in the Be Star Newsletter edited by Mercedes Jaschek at the Strasbourg Observatory. I apologize in advance for any omissions of important work in my paper.

2 SURVEYS AND CATALOGUES

For a total of 183 known Oe, Be, and A-F type shell stars brighter than visual magnitude $6\overset{m}{.}0$, a reliable catalogue of new MK types and rotational velocities, v sin i, in a homogeneous system has been prepared by Slettebak (1982 b). It also contains descriptions of the spectra and a detailed summary of previous observations of the stars. Analysis of the catalogue confirms the previously known results that the distribution of apparently bright Be stars shows a distinct maximum at spectral type B2, while rotational velocities peak between 200 and 300 km s^{-1}. A similar catalogue containing available data for more than 1100 Be stars including also many fainter objects has been compiled by M. Jaschek and Egret (1982) at the Strasbourg Stellar Data Center.

It is interesting to note that a recent investigation of spectral types and rotational velocities for a total of 57 Herbig Ae/Be stars by Finkenzeller (1985) yields average v sin i values in the range of 100 - 225 km s^{-1} and clearly points to a deficiency of slow rotators also among these objects.

The relative frequency of Be stars among B stars in the Bright Star Catalogue has been investigated according to existing Be star surveys by Jaschek and Jaschek (1983) confirming previous results that occurrence of Be stars peaks at spectral type B2 with 18% in order to fall to about 5% among late B-type stars (B8-9), and to less than 2% at A0-1.

As Hα is the strongest emission line in the spectra of Be stars, considerable effort is devoted to the study of Hα emission line profiles for as many Be stars as possible and to a surveillance of their Hα variations. Remarkable progress has been achieved during recent years by introducing improved instrumentation, modern detectors and new techniques for recording spectra in general and Hα emission lines in particular with high spectral resolution and good signal-to-noise ratio. Extensive surveys of Hα emission-line profiles in Be star spectra and of their temporal variations performed during the last decade were published by Slettebak and Reynolds (1978), Fontaine et al. (1982), Andrillat and Fehrenbach (1982), Andrillat (1983), and Barker (1983 a, b, c; 1984; 1986) for northern-hemisphere stars and by Dachs et al. (1981, 1986 a) and Hanuschik (1986 a) for southern-hemisphere stars. A few of these surveys also include Hβ and Hγ line profiles for the program stars.

Measurements of Hα line profiles for a representative sample of Ae and A-shell type stars by Andrillat et al. (1986) show Hα emission to be present at most weakly in the wings of photospheric Hα absorption lines. Emission was detected only for stars earlier than A5 and appears to always remain below continuum level for A0e to A5e stars.

A recent addition to the list of very bright early-type stars occasionally showing characteristics of a Be star was provided by Singh (1982) who detected faint central Hα emission to be present in the spectrum of the B7V-type star Regulus (α Leo) in February, 1981.

Finally, many faint new Be stars were detected during recent objective-prism surveys both in the northern and in the southern Milky Way, as reported by Vega et al. (1980), Vega (1982), by Mc Connell (1981) who covered a total of 4500 square degrees in the southern Milky Way finding altogether 731 new Hα emitting stellar objects, and by Pesch and Sanduleak (1983, 1986) and Sanduleak and Pesch (1984) who discovered a total of 252 mostly new emission-line stars in the northern hemisphere. In a survey covering 59% of the northern sky above 10° galactic longitude, Stephenson (1986) recently found 206 faint Hα emission-line stars of which a few might prove to be Be stars.

3 CLASSIFICATION OF EMISSION-LINE SPECTRA OF Be STARS

No general agreement has been reached so far about the proper way to describe, to compare and to classify the highly variable emission-line spectra observed for Be stars at optical wavelengths. Certainly, every description of a Be-type spectrum only refers to a certain Be star as measured at a fixed epoch. In order to allow comparison between different Be stars, any meaningful description of a Be star spectrum should contain at least the following information both about the underlying star and about the circumstellar envelope:

1. MK absorption-line spectral type of the underlying star,
2. Projected rotational velocity, v sin i, of the central star,
3. Intensities of line (and continuous) emission from the envelope for as many emission lines and wavelength regions as possible,
4. Accurately measured emission line profiles including radial velocities for important features and quantitative evaluation of line asymmetries.

Hitherto, three different groups attempted to classify gaseous envelopes around Be stars along these lines:

(a) Lesh (1968) divided bright northern Be stars into four different categories $e_1 \ldots e_4$ according to visibility and estimated strengths of emission in Hβ and higher-order Balmer emission lines on photographic spectrograms obtained for MK classification. Her system was subsequently applied also to bright southern Be stars by Hiltner et al. (1969). Unfortunately, no dates of observation were given for the spectra.

(b) Jaschek et al. (1980) worked out an intricate classification scheme for Be stars based upon prismatic spectrograms covering the wavelength range between λλ 3900 and 6700 Å. They assigned Be stars to five different groups using spectral characteristics such as appearance of Balmer line emission, FeII emission, presence of dark cores in emission lines and time scales of spectral variations recorded between 1953 and 1976 as parameters. In fact, the authors already suspected that the order of the groups is also an order of the intensity of the emissions. Quantitative comparison between group assignments by Jaschek et al. (1980) and average equivalent widths, W_e(Hα), of Hα emission lines measured for the same stars in 1975-81, in particular by Slettebak and Reynolds (1978), by Andrillat and Fehrenbach (1982) or by Dachs et al. (1981, 1986 a) clearly shows that the Jaschek et al. system essentially represents a classification according to equivalent width of Hα emission decreasing from group I to group V.

(c) Dachs et al. (1986 b) compared more than 700 Hα emission line profiles measured at different times for some 60 Be stars, mostly of early-Be type, with sufficiently high spectral resolution (of about 2 Å corresponding to 100 km s^{-1}), after arranging stars into six different groups of similar v sin i values. The authors interpret profile shapes by motions in the cool envelopes and conclude from their comparison that
   (1) gaseous envelopes around early-Be type stars, during most of the time, possess a fairly uniform and homogeneous structure,
   (2) motions in Be star envelopes are dominated by rotation,
   (3) Hα emission-line half-widths (FWHM) at given Hα equivalent width of emission increase as the projected rotational velocity of the central star (cf. Fig. 1). This was already stated first by Struve (1931) and later confirmed, e.g., by Slettebak and Reynolds (1978, Fig. 3) or by Andrillat (1983, Fig. 2),
   (4) Hα emission-line half-widths usually decrease with increasing equivalent width of Hα emission, since rotational velocity decreases with distance from the star in an envelope of increasing radius,
   (5) equivalent widths of Hα emission approximately scale with the projected visible area of circumstellar envelopes in units of the area of the stellar photospheric disk. The following mean relation between Hα emission equivalent widths, $W_e(H\alpha)$, and disk radii, R_d, in terms of stellar radii, R_*, was derived by the authors using available data for computed disk radii from various sources in the literature:

$$W_e(H\alpha) = -1.5\ \text{Å}\ (R_d/R_*)^2 \qquad (1)$$

These results strongly support the model of a quasi-stationary, differentially rotating Keplerian disk for cool gaseous envelopes around Be stars, similar to the model proposed by Struve (1931). Basically, the direct relation (1) between equivalent widths of Balmer line emission and disk radii was already predicted for rotating model disks by the results of Kogure (1969, Fig. 6) and of Poeckert and Marlborough (1978 a, Fig. 12). For clarity, it should be pointed out that the present version of the rotating disk model used for interpretation of emission line profiles does not include any specific assumption about the way of disk formation, and in particular does not necessarily imply disk formation by outflow at the equator of the star as a consequence of rotation at the critical limit of escape velocity, as originally suggested by Struve (1931).

Still unsolved problems of classification in Be star spectra include
- quantitative description and evaluation of asymmetries in emission lines which have to await a better understanding of the influence of radial motions through the envelope on emission line profiles, and

- quantitative description and evaluation of central depressions and absorption cores in emission line profiles. Such depressions are often loosely called "shell characteristics" (e.g., by Briot, 1986) without making a distinction between possible competing mechanisms contributing to central intensity minima in emission line profiles. Suggested mechanisms producing emission line doubling include: the velocity distribution of emitting atoms or ions in a disk (Struve, 1931), geometrical obscuration of the rear part of a disk-shaped envelope by the star (Huang, 1972), and internal self-absorption in an envelope of sufficiently large optical thickness for line radiation (Struve, 1942).

4 TYPICAL EMISSION LINE PROFILES

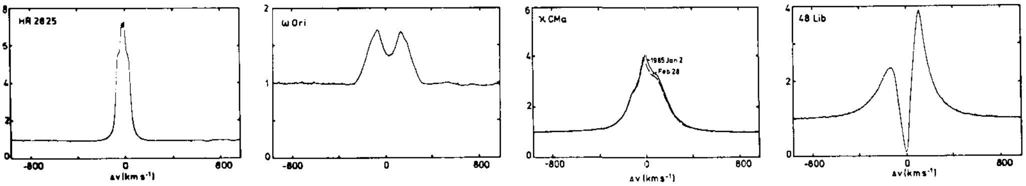
Surveys of Be star spectra reveal an embarrasing variety of emission line profiles. In the hydrogen (Balmer, Paschen etc.) and sometimes also the HeI lines, emission from the circumstellar envelope is superimposed to a normal stellar absorption-line spectrum, and separation of the envelope contribution from the stellar spectrum often is a difficult problem (Dachs et al., 1986 b).

In this section, a few typical emission-line profiles frequently observed in Be star spectra will be described, together with a report on attempts of their interpretation in terms of motions in the cool envelope regions.

4.1 Symmetric double-peak profiles

Fairly symmetric, double-peak emission-line profiles are the simplest case of relatively weak emission lines, frequently observed at high-order Balmer lines if emission there is detectable, and often also at Hα at least for v sin i $\gtrsim$ 100...150 km s^{-1} (Fig. 1 b). Nice examples for regular double-peak profiles are presented, e.g., for ζ Oph by

Fig. 1. Typical shapes of Hα emission-line profiles measured at resolution of 50000 and corrected for telluric H_2O absorption (Hanuschik, 1986 a). a) "Winebottle" profile (HR 2825, v sin i = 40 km s^{-1}), b) double-peak profile (ω Ori, v sin i = 160 km s^{-1}), c) asymmetric profile (κ CMa, v sin i = 220 km s^{-1}), d) shell profile (48 Lib, v sin i = 400 km s^{-1}).



Ebbets (1981), for 59 Cyg by Fontaine et al. (1982), for λ Eri by Barker (1983 a, b), for α Eri by Dachs et al. (1986 a), and for μ Cen both by Peters (1986) and by Dachs et al. (1986 b).

According to these examples, maximum peak separation occurs for the faintest emission lines and is always less than 2 v sin i of the star. For larger equivalent widths of the emission, peak separation rapidly decreases. These observations are in good agreement with predictions of the rotating disk model. In this model in its simplest version of an optically thin line-emitting disk, double-peak structure is already observed as a direct consequence of the velocity distribution of emitting atoms in the disk, leading to velocity crowding at the projected radial velocities of the outer edges of the disk. In the framework of the rotating disk model, distance of intensity peaks in the line profiles, v_p, therefore is a direct measure of outer envelope radius. e.g., for the case of angular momentum conservation in a disk of radius R_d (expressed as a multiple of the stellar radius R_*), peak separation is connected to projected rotational velocity of the star, v sin i, by the relation

$$v_p = 2\ v \sin i\ (R_*/R_d) \qquad (2)$$

as shown by Huang (1972) and by Hirata and Kogure (1984).

As far as this model is correct, central depressions in many double-peak profiles are not caused by self-absorption in the envelope and ought, in this case, not be called "shell" components of the emission lines.

4.2 "Winebottle-type" profiles

At sufficiently high spectral resolution, strong singly-peaked or doubly-peaked Balmer emission lines often exhibit clear structure in their flanks, usually in the form of inflexions (Fig. 1 a). We all are grateful to Paul Barker for having coined the memorable term "winebottle" for this type of profile (Barker, 1986), and certainly this term will contribute to a better understanding of the Be phenomenon. Fine examples for this type of profile were recorded first for pole-on Be stars (having small v sin i) at resolutions of about 20 km s^{-1}, e.g., by Kogure (1969) and by Andrillat and Fehrenbach (1982).

Both Kogure (1969) and Hanuschik (1986 a) interpret inflexions in the flanks of emission line profiles as a superposition of a faint narrow emission line upon a strong wider emission line, pointing to a composite structure of the envelope. Kogure (1969) successfully fitted a winebottle-type Hβ profile measured for 11 Cam to a theoretical profile calculated for a model envelope divided into two concentric, thin narrow gaseous rings surrounding the star in its equatorial plane and separated by a large gap.

The well-known broad emission-line wings observed in particular for Hα in the spectra of many Be stars are usually ascribed to the result of electron scattering of line photons in the envelope, as shown by

Poeckert and Marlborough (1979).

4.3 Asymmetric emission lines

Asymmetry in emission-line profiles is a common and strongly variable feature in Be star spectra. Study of asymmetries requires fairly high spectral resolution. At medium resolution, line asymmetries are often more easily visible in higher-order Balmer lines than in very strong singly-peaked Hα emission lines. According to Slettebak's (1982 b) description of Be star spectra,about 15% of his program stars at some time showed striking asymmetries in their emission lines, while in the collections of Balmer emission line profiles prepared by Andrillat and Fehrenbach (1982), Andrillat (1983) and Dachs et al. (1981, 1986 a), between 25 and 35% of the stars exhibit asymmetric line profiles at least at certain epochs (Fig. 1c).

Asymmetric double-peak emission lines are usually described by their V/R ratio, defined as the ratio of violet-side to red-side peak intensities above continuum in units of continuum intensity. For singly-peaked asymmetric emission lines, the corresponding designations may be "blue-dominated" if the short-wavelength part of the line is significantly more intense than the long-wavelength part, or "red-dominated" for the opposite case, following a recent suggestion by Mullan (1984). A useful measuring prescription how to determine V/R ratios as well as V and R peak intensities for singly-peaked asymmetric emission line profiles has also been devised by Doazan et al. (1984).

Existing surveys clearly show blue-dominated asymmetric emission-line profiles to occur with about equal frequency as red-dominated emission-line profiles.

In the framework of the rotating-disk model, asymmetry of an emission-line profile can be explained by radial motions superimposed upon rotation. Guided by the authority of Struve who considered expansion to be a natural feature of line-emitting envelopes around Be stars (Struve, 1931), most theoretical line profile calculations based on the disk model assume at least slow expanding motion through the disk in addition to rotation, with the result that only symmetric or red-dominated emission line profiles are obtained (e.g., Kogure, 1969; Poeckert and Marlborough, 1978 a, 1978 b, 1979).

Observations of blue-dominated asymmetric emission-line profiles seem to force us to accept the hypothesis that inflow through the line-emitting envelope can occur as well as outflow at least intermittently. This has been also noted, e.g., by Delplace (1970 a) and by Hubert-Delplace et al. (1983). Temporary inward motion through a disk-shaped circumstellar envelope may be thought to be part of a large-scale circulation system including the stellar wind region, as suggested by Dachs et al. (1986 a).

4.4 Shell lines and shell components (Fig. 1d)

Starting from the original definition of a shell spectrum as suggested by Merrill (1949), emission lines with central shell components can be taken to be distinguished from central depressions in ordinary double peak emission lines mentioned earlier by the following two related properties (Kogure and Hirata, 1982):

(a) Measured at sufficiently high spectral resolution, central cores of shell lines are distinctly deeper than the centres of rotationally broadened photospheric absorption lines would be for absorption-line B-type stars of the same spectral class while the centres of normal double-peak emission lines always remain above the level of the stellar absorption lines.

(b) Cores of shell absorption lines are V-shaped, i.e. possess sharp minima, while central depressions in ordinary doubly-peaked emission lines are U-shaped.

Evidently both these two properties are to be explained by the assumption that shell line cores are produced by self-absorption of line radiation at and near the velocity of the core. Recent calculations of theoretical line profiles by Rybicki and Hummer (1983) and by Horne and Marsh (1986) nicely demonstrate the expected transition from U-shaped line centres in double-peak emission lines produced in optically thin rotating disks to V-shaped line cores (or M-shaped line profiles) obtained for emission from optically thick disks.

On the basis of the disk model, analysis of shell line profiles in shell spectra and of their central depths and strengths provides an important, well established method to derive physical properties for the absorbing region of the envelope around Be (-shell) stars (Hirata and Kogure, 1984). For typical Be-shell stars showing strong Hα emission, results obtained for excitation temperature in the disk range from 8000 to 13000 K, for electron density from 10^{10} to 10^{11} electrons cm^{-3} and for the disk radii from 3 to 7 stellar radii, depending on the assumptions about the velocity-radius law for the rotating gas (Kogure et al., 1978; Hirata and Kogure, 1984).

4.5 Indications for composite envelope structure

Structure and breaks in the flanks of emission-line profiles can be taken to indicate a multi-component structure of cool circumstellar envelopes, as mentioned above (Section 4.2). Another line of evidence for envelope structuring comes from comparing profiles for different emission lines in the same spectrum which may be supposed to originate from separate regions of different density in the envelope.

In this connection, Slettebak (1982 b) notes that seven of his program stars showed different V/R ratios for the Balmer emission components than for the FeII emission components, thereby suggesting a difference in the velocity characteristics and/or density of the material producing the Balmer emission and self-absorption, relative to the gas giving rise to the FeII lines.

As another example for differences between emission-line profiles, Chalabaev and Maillard (1985) compared near-infrared line profiles obtained in November, 1982, for γ Cas and found the strong Paschen-β (λ 1.28 µm) emission line to be distinctly asymmetric and red-dominated, while the fainter Brackett-γ (λ 2.17 µm) line was nearly symmetrical. This implies that the inner parts of the envelope where Br-γ is likely to be produced are essentially in rotational motion with only a small outward velocity component while the outer regions of the envelope emitting Pa-β show predominantly radial (expanding) motion in excess of 100 km s^{-1}, partly because velocity of rotation decreases with distance from the star. According to the authors, the decelerated mass-flux model of Doazan and Thomas (Doazan, 1982) can explain these data only if one speculates that strong variations of the stellar wind had occurred shortly before the observations.

The opposite case of strong asymmetry in emission lines presumably produced near the star and of little asymmetry in emission lines produced at large distances from the central star has been observed by Hanuschik (1986 b) who compared FeII and Hα emission lines, e.g. for δ Cen and for HD 68980 (= HR 3237).

5 VARIATIONS

Variability is an inherent property of apparently all Be stars. Variations are found to occur in the line spectra as well as in the continua, and are observed in all spectral ranges from ultraviolet to infrared wavelengths and on various time-scales extending from hours to decades. Observed spectral or photometric variations can be both periodic and non-periodic; sometimes also quasi-cyclic variations have been described. Be star variability in general is sometimes also called activity (Barker, 1983 a).

In spite of large efforts by many investigators, no complete descriptions are available for typical Be star light-curves or their related spectral variations, even for the best-studied objects. This continuing lack of information is due to the irregularity of the Be phenomenon, to inevitable seasonal gaps of surveillance, and to the difficulties associated with typical cycle lengths of several decades. Another unsolved fundamental problem of Be star research is the study of correlations and phase differences between variations observed in different spectral regions, in particular between phenomena related to the hot and to the cool circumstellar parts of envelopes, respectively. Both the study of light-curves and the study of these correlations will remain a challenge to observers for a long time.

5.1 Periodic variations

To date, strictly periodic components of variations have been clearly established only for a limited number of well-observed Be stars. Evidence for periodic variations in Be star spectra and possible inferences towards explanation of the Be phenomenon is adequately treated by other review papers (Baade, Harmanec, Percy) during this colloquium and will therefore be omitted from discussion here.

5.2 Rapid irregular variations

Irregular variations in Be star spectra on time scales of hours to days were already discussed in previous reviews (Slettebak, 1982 a; Harmanec, 1983) and continue to be reported by numerous investigators.

Variations of Hα equivalent width are usually of the order of a few percent per day as observed for γ Cas by Slettebak and Reynolds (1978) and by Chalabaev and Maillard (1983) who compared measurements one night apart, or for ω Ori by Guinan and Hayes (1984) and by Dachs et al. (1986 a) who followed slow drifts of increasing or decreasing emission-line strength for about 20 to 30 days. As a maximum value on record, Fontaine et al. (1982) measured a 20% increase of Hα emission equivalent width from -34 to -42 Å within one day for HD 208682 (B2Ve).

Irregular V/R variations of double-peak Hα emission lines can amount to as much as 20...25% per day as observed for α Eri by Dachs et al. (1981) or for 59 Cyg by Barker (1983 c).

5.3 B - Be phase transitions

B - Be phase transitions and vice-versa were recorded for a considerable number of Be stars during recent years. Examples collected by Jaschek et al. (1980) according to their observations of northern-hemisphere stars between 1953 and 1976 are called group V Be stars in their lists. Other very bright Be stars detected during recent years to fall into this category include the southern sky objects ζ Oph (Ebbets, 1981), η Cen (Baade, 1983; Dachs et al., 1986 a), μ Cen (Peters, 1979, 1984, 1986; Dachs et al., 1981, 1986 a), α Eri (Dachs et al., 1981, 1986 a), and λ Eri (Barker, 1983 a, b).

In all of these examples, first traces of faint emission appearing in spectra of Be stars after B-type phases become visible at Hα and always assume the form of a double-peak emission line profile with peak separation $v_p \lesssim 2\ v \sin i$, superimposed to the photospheric absorption-line profile. This wide double-peak profile points to a narrow rotating circumstellar ring closely surrounding the stellar equator as the most likely model for a newly forming Be star envelope.

In the case of μ Cen, Peters (1986) observed appearance of newly developed Hα line emission with emission equivalent width as large as about -2 Å within less than two days after a B phase of the star; she estimates that a total energy of the order of 10^{37} ergs had to be released within two days in order to lift circumstellar gas of total mass of order 10^{22} g into a distance of about one stellar radius from the surface of the star.

Other examples of beginning faint double-peak Hα emission studied during recent years include 88 Her (Doazan et al., 1982 a), o And (Gulliver et al., 1980; Fontaine et al., 1982), 59 Cyg (Fontaine et al., 1982), and θ CrB (Doazan et al., 1986).

Sometimes, very weak emission at Hα is already accompanied by genuine deep shell absorption cores in the Balmer lines, pointing to large optical depths for Balmer line radiation within the envelope in front of the star occurring already at very small intensity of Hα emission. This was noted in the spectrum of the rapidly rotating (v sin i = 350 km s^{-1}) B2IV(e) star η Cen by Baade (1983) and by Dachs et al. (1986 a), and in the spectrum of θ CrB (B6III, v sin i = 320 km s^{-1}) by Doazan et al. (1986).

5.4 Cyclic radial velocity and V/R variations

Certain well-observed Be stars with v sin i $\geqq$ 200 km s^{-1} and double-peak or shell-type Balmer emission lines are known to display at times cyclic variations in their Balmer emission line profiles of both radial velocities of central absorption cores and V/R intensity ratios. Cycle times are of the order of years to decades and can vary from one cycle to the next for individual stars. For a total of 28 Be stars, cycle times of long-term V/R variations were determined by Hirata and Hubert-Delplace (1981) who found a mean cycle length of seven years for their sample.

An incomplete list of Be stars having shown these quasi-cyclic spectral variations according to recent investigations is given in Table 1. Stars are arranged in order of decreasing effective temperatures in this Table which also contains the epochs during which cyclic variations were observed, and typical cycle lengths.

Inspection of Table 1 immediately shows that average cycle times for envelope variations increase with decreasing effective temperature of the central stars, from typical values of a few years for B0.5-1 e-type stars to several decades for B6-8 e-type stars. This result is probably related to the fact noted by Jaschek et al. (1980) that also average time scales for cycles of B → Be → B transitions are generally shorter for early-Be type stars than for late-Be type stars. One may therefore also speculate that time scales for cycles of long-term envelope variations are inversely related to luminosities of the central Be stars.

Future models for envelopes around Be stars and for their variations will have to explain these quantitative relations observed between cycle lengths and stellar properties, and also the fact that cyclic radial velocity and V/R variations can develop in certain stars for extended periods of time and then are switched off again.

5.5 Shell episodes

If the spectra of certain Be stars, ever since their discovery, permanently show the presence of narrow shell absorption cores in their Balmer emission lines and in addition also in numerous metallic lines, then these stars often are properly called "shell stars". Well-known examples are ϕ Per, ζ Tau, and 48 Lib.

For many other Be stars, shell absorption cores are observed in their emission-line spectra only during relatively short transient phases of their spectral variations. Following Merrill (1952), it has become customary to call such phases "shell episodes".

New shell episodes were detected and studied in some detail during recent years for the following Be stars: 59 Cyg (B1Ve; Hubert-Delplace and Hubert, 1981; Barker, 1982), o And (B6III; Gulliver et al., 1980), 88 Her (B6IV-V; Doazan, 1973; Doazan et al., 1982 a, b), and Pleione (= 28 Tau, B8(V:)e-shell; Kogure and Hirata, 1982).

From these investigations, the following general conclusions are tentatively drawn:

1. Typical duration of shell episodes is less than one year for B1e stars and about five years for B6-8 stars, as first noted by Barker (1982).

Table 1. Cycle times for recurrent V/R variations

Star	MK	Epoch of variations	Quasi-cycle (years)	Authority
γ Cas	B0.5IVe	1932-40 1969-81	3 4	Baldwin (1939), Edwards (1956) Doazan et al. (1983, 1984)
π Aqr	B1Ve	1925-43	2-6	Mc Laughlin (1962)
ζ Tau	B1IVe	1960-75	4-7	Delplace (1970 a, b) Hubert-Delplace et al. (1982)
59 Cyg	B1Ve	1972-83	2	Barker (1982) Doazan et al. (1985)
25 Ori	B1Ve	1915-33	3-5	Dodson (1936) Mc Laughlin (1937)
105 Tau	B3Ve	1930-65	10-12	Mc Laughlin (1966)
48 Lib	B3:IV:e	1935-81	7-12	Aydin and Faraggiana (1978) Hubert-Delplace et al. (1983)
β^1 Mon	B4Ve	1930-65	12.5	Cowley and Gugula (1973)
88 Her	B6IV-V	1955-81	15	Doazan et al. (1982 a, b)
28 Tau	B8(V:)e	1930-80	34:	Gulliver (1977) Kogure and Hirata (1982)

2. For early-Be stars, shell episodes are embedded into cycles of V/R variations of their Balmer emission lines.
3. For late-Be stars, maxima of shell line strength are connected with minima of photometric light-curves which are of the type of an "inverted nova" (Kogure and Hirata, 1982; Harmanec, 1983).
4. There is a tendency for shell episodes to repeat at least twice. Typical length of an individual shell episode is about one quarter of separations between subsequent episodes.

Barker (1982) estimates that during the 1974 shell episode of 59 Cyg, about 10^{-7} solar masses of envelope gas had to be lifted to a distance of order 10 stellar radii from the star in less than two years.

Detailed spectroscopic observations of the shell episode of o And resulted in a two-phase model for envelope dissipation during the declining phase of a shell episode, with gas density first decreasing in the inner region of the envelope and subsequently decreasing also in the outer envelope regions (Poeckert et al., 1982).

The onset of V/R variations was studied in the spectrum of the well-known B3:IV:e-shell star EW Lac by Kogure and Suzuki (1984). After having shown a strong, but relatively quiet shell spectrum from 1928 to 1975 for about 47 years, apparently without any indication of major V/R variations of emission components, the star entered a phase of beginning V/R variations in 1975 (Hubert-Delplace et al., 1982), V/R asymmetry starting to become visible as V < R (expansion) at high-order Balmer emission lines (H8) produced in the inner regions of the envelope, and then progressively migrating towards lower-order Balmer lines until finally reaching Hα emitted in the outermost layers of the envelope, about four years later. A whole first cycle of V/R variations was completed in the inner regions of the envelope after six years by the end of 1981, and two years later also in the Hα producing outer regions of the envelope.

In order to explain shell episodes in the framework of the rotating disk model for Be star envelopes, one has to assume that during shell episodes, the optical density in the disk for line radiation or the scale height of the disk or both increase for some time in such a way that the mean optical density of the line of sight to the star becomes sufficiently large in the line centre to produce shell absorption cores, as discussed by Hirata and Kogure (1984).

The statistical correlation between occurrence of shell characteristics and rotational velocities of Be stars was investigated by Briot (1986) with the result that shell spectra are preferentially observed for Be stars with the largest average v sin i's.

6 FAINT EMISSION LINES

Several of the Hα emission-line surveys mentioned in Section 2 also contain some similar, although less extensive, data for Hβ and Hγ emission lines which are much fainter than Hα emission lines. Generally, surveys of higher-order Balmer line emission and of faint emission produced by elements other than hydrogen from Be star envelopes are less complete than surveys of Hα emission, and usually are also limited to Be stars showing very strong Hα emission.

Both the peak separations of double-peak Balmer emission-line profiles and their half-intensity widths increase with increasing quantum number of the upper level of transition as noted by Hutchings (1970) and by Dachs et al. (1986 a), and they attain maximum values eventually approaching 2 v sin i for faint FeII and HeI emission lines. These progressions of peak separations and of half-widths are easily explained by the assumption of Hutchings (1970) that Hα emission is produced in the outermost slowly rotating layers of Be star envelopes, while broader emission lines are emitted from the more rapidly rotating, inner envelope regions.

6.1 High-order Balmer lines

Intensity ratios of Balmer emission lines, called Balmer decrements, are usually measured relative to Hβ. For Hα/Hβ = D_{34} and Hγ/Hβ = D_{54}, mean values for different spectral types of Be stars were determined from intensity-calibrated photographic spectrograms by Briot (1971); she found mean Balmer decrements to increase from "flat" decrements at spectral type B0 (with mean values $D_{34} \simeq 1.5$, $D_{54} \simeq 0.8$) to "steep" decrements for Be stars later than about B5 (average $D_{34} \simeq 5$, $D_{54} \simeq 0.3$).

A slightly different result was obtained in a still unpublished study by Dachs, Loose, and Rohe (in preparation) based on data of Dachs et al. (1981, 1986 a). Omitting shell spectra from their discussion, these authors find that Balmer decrements, independently of spectral type, are relatively close to the theoretical value for a low-density Baker-Menzel case B nebula of electron temperature T_e = 10000 K (D_{34} = 2.85, D_{54} = 0.47). Only for very few Be stars, Balmer decrements are relatively flat, presumably because mean electron density in their envelopes is particularly high. Steep Balmer decrements are only obtained for Be stars exhibiting shell-type absorption cores in their Balmer lines.

Occasionally, relatively strong emission is observed in high-order Balmer emission lines, pointing to an extremely flat Balmer decrement extending to Balmer lines of order as high as H15 to H25 or even more. This occurs most easily in "pole-on" stars for which v sin i $\lesssim$ 150 km·s^{-1}, and can be used to determine an average value of electron density in the emission-line forming envelope from a consideration of competing mechanisms causing population of different hydrogen levels, as demonstrated by Dachs and Hanuschik (1984).

6.2 FeII emission

According to Slettebak (1982 b), about one quarter of strongly widened Be spectra investigated at a dispersion of 40 Å mm^{-1} display noticeable FeII emission. Remarkably enough, FeII emission has been observed by Walborn (1980) even in stars as early as O7.5Ve.

A recent survey of FeII emission in the spectra of bright southern Be stars by Hanuschik (1986 b) shows equivalent widths of emission for the strongest FeII lines to be of the order of one percent of Hα emission equivalent widths for the same stars (Table 2). This paper also nicely demonstrates the advantage of using FeII emission line profiles to study physics in the inner regions of Be star envelopes, since FeII emission lines are not disturbed by underlying photospheric absorption line profiles of the stars, as are high-order Balmer or helium emission lines, and thermal - or turbulent - broadening is small.

6.3 HeI and other faint emission lines

Only scattered reports exist in the literature about HeI emission and emission lines of heavier ions in Be star spectra. Stars reported to have shown HeI emission during recent years include ζ Oph (O9.5(e); Ebbets, 1981), γ Cas (B0.5IVe; Chalabaev and Maillard, 1985; Lowe et al., 1985), 59 Cyg (B1Ve; Hubert-Delplace and Hubert, 1981), o Pup (B1IVe; Meisel et al., 1982; Hanuschik, 1986 b) and ϕ Per (B1.5(V:)e; Meisel et al., 1982). From a review of these reports, the

Table 2. Typical values for relative intensities of emission lines in B1V/IIIe-type spectra

Line	emission equivalent width (Å)	relative envelope flux	References
Hγ 4340	0.8	17	Dachs et al. (1981, 1986 a)
Hβ 4861	2.3	35	
Hα 6563	20	100	
Pa14 8598	1.5	3.0	Chalabaev and Maillard (1985) Lowe et al. (1985) Hanuschik (1986 b)
Paγ 10938	4.5	3.7	
Paβ 12818	8	3.3	
HeI 5875	0.7	5	
HeI 6678	0.4	2	
HeI 10830	8	6.5	
OI 8446	1.5	4	Kitchin and Meadows (1970) Briot (1981)
FeII 4584	0.16	3.0	Hanuschik (1986 b)
FeII 5169	0.3	3.5	
FeII 5317	0.25	2.8	
Integrated stellar flux (T_{eff} = 25000 K, log g = 4)		6.8×10^{5}	Kurucz (1979)

following preliminary conclusions are drawn:

1. HeI emission is more often observed in the spectra of Be stars earlier than B1 than in the spectra of stars later than about B2.
2. HeI emission is more easily detected in the red and infrared regions of Be star spectra (at λλ 5875, 6678, 10830) than in the photographic region (at λλ 4026 or 4471).
3. Intensity of HeI emission in the spectrum of a certain Be star is correlated to the actual strength of variable Hα emission, as stated for γ Cas by Hubert-Delplace and Hubert (1979).
4. During onsets of Be phases, faint emission is frequently visible in the wings of photospheric HeI emission lines, as detected in the spectra of α Eri (B2III(e)p) in 1983 by Penrod (1986) and of μ Cen (B2IV-Ve) in 1984 by Peters (1986).
5. Occasionally, HeI emission has been found to appear for short times also in the spectra of Be stars as late as ε Cap (B3IIIe; Buscombe, 1970) and p Car (B4Ve; Jaschek and Jaschek, 1965).

Surveys of OI λ 8446 Å emission from Be stars were performed by Kitchin and Meadows (1970) and by Briot (1981); surveys of MgII λλ 2795/2802 Å emission are reported by Dachs (1980), by Bruhweiler et al. (1982), and by Slettebak and Carpenter (1983).

Typical values for relative equivalent widths of important emission lines in early-Be spectra according to different sources are collected in Table 2 together with corresponding relative intensities of line emission as computed for the spectral energy distribution of an early-Be star atmosphere with T_{eff} = 25000 K, log g = 4 according to the tables of Kurucz (1979). It turns out that a typical Be star with equivalent width of Hα emission of -20 Å emits a fraction of order $1.5 \cdot 10^{-4}$ of its total luminosity in Hα, the strongest emission line in its optical spectrum.

7 CONCLUSIONS

Considerable progress has been achieved for the physics of Be stars in recent years by investigating optical and near-infrared Be star spectra, and by comparing these spectra to the results of measurements obtained for the same stars in other wavelength ranges. Evidence from optical spectra has accumulated that the basic picture for emission-line formation is emission from a rotating circumstellar disk, that radial motions in either direction, outward or inward, can be superimposed to rotation in the line-emitting disks, and that these disks possess a complicated structure consisting of several components and subject to important variations.

We note that the study of related classes of non-classical Be stars in recent years also led to suggest the rotating disk model for their circumstellar envelopes, for example for the class of peculiar emission-line (B[e]) stars (Swings, 1974) and for the class of peculiar Be supergiant stars (Zickgraf et al., 1985).

Unsolved problems of Be star research include in particular:

1. Explanation of disk formation;
2. Understanding both the irregular and quasi-regular variations of disk structure giving rise to frequently recorded variations of emission-line profiles;
3. The relations between the circumstellar disk and the properties of the star, such as luminosity, modes and amplitudes of pulsation and stellar wind characteristics.

Large amounts of observing time at medium-sized and large telescopes and hard work for many engaged observers will be needed to finally solve these fascinating problems.

REFERENCES

Andrillat, Y. (1983). Astron. Astrophys. Suppl. 53, 319.
Andrillat, Y., Fehrenbach, Ch. (1982). Astron. Astrophys. Suppl. 48, 93.
Andrillat, Y., Jaschek, M., Jaschek, C. (1986). Astron. Astrophys. Suppl. 65, 1.
Aydin, C., Faraggiana, R. (1978). Astron. Astrophys. Suppl. 34, 51.
Baade, D. (1983). Astron. Astrophys. 124, 283.
Baldwin, R.B. (1939). Astrophys. J. 89, 255.
Barker, P.K. (1982). Astrophys. J. Suppl. 49, 89.
——— (1983a). Publ. Astron. Soc. Pacific 95, 996.
——— (1983b). Be Star Newsl. (Obs. Strasbourg) 7, 10.
——— (1983c). Astron. J. 88, 72
——— (1984). Be Star Newsl. (Obs. Strasbourg) 9, 20.
——— (1986). Publ. Astron. Soc. Pacific 98, 44.
Briot, D. (1971). Astron. Astrophys. 11, 57.
——— (1981). Astron. Astrophys. 103, 1+5.
——— (1986). Astron. Astrophys. 163, 67.
Bruhweiler, F.C., Morgan, T.H., van der Hucht, K.A. (1982). Astrophys. J. 262, 675.
Buscombe, W. (1970). Monthly Not. Royal Astr. Soc. 148, 79.
Chalabaev, A.A., Maillard, J.P. (1983). Astron. Astrophys. 127, 279.
——— (1985). Astrophys. J. 294, 640.
Cowley, A., Gugula, E. (1973). Astron. Astrophys. 22, 203.
Dachs, J. (1980). Proc. Second IUE Conference, ESA Special Publ. 157, 139.
Dachs, J., Eichendorf, W., Schleicher, H., Schmidt-Kaler, Th., Stift, M., Tüg, H. (1981). Astron. Astrophys. Suppl. 43, 427.
Dachs, J., Hanuschik, R. (1984). Astron. Astrophys. 138, 140.
Dachs, J., Hanuschik, R., Kaiser, D., Ballereau, D., Bouchet, P., Kiehling, R., Kozok, J., Rudolph, R., Schlosser, W. (1986a). Astron. Astrophys. Suppl. 63, 87.
Dachs, J., Hanuschik, R., Kaiser, D., Rohe, D. (1986b). Astron. Astrophys. 159, 276.
Delplace, A.M. (1970a). Astron. Astrophys. 7, 459.
——— (1970b). Astron. Astrophys. 7, 68.
Doazan, V. (1973). Astron. Astrophys. 27, 395.
——— (1982). In: B stars with and without emission lines (eds.: A.

Underhill, V. Doazan), NASA SP-456, p. 277.

Doazan, V., Briot, D., Bourdonneau, B. (1975). Astron. Astrophys. 42, 161.

Doazan, V., Franco, M., Rusconi, L., Sedmak, G., Stalio, R. (1983). Astron. Astrophys. 128, 171.

——— (1984). Astron. Astrophys. Suppl. 55, 1.

Doazan, V., Grady, C.A., Snow, T.P., Peters, G.J., Marlborough, J.M., Barker, P.K., et al. (1985). Astron. Astrophys. 152, 182.

Doazan, V., Harmanec, P., Koubsky, P., Krpata, J., Zdarsky, F. (1982a). Astron. Astrophys. 115, 138.

——— (1982b). Astron. Astrophys. Suppl. 50, 481.

Doazan, V., Marlborough, J.M., Morossi, C., Peters, G.J., Rusconi, L., Sedmak, G., Stalio, R., Thomas, R.N., Willis, A. (1986). Astron. Astrophys. 158, 1.

Dodson, H. (1936). Astrophys. J. 84, 180.

Ebbets, D. (1981). Publ. Astr. Soc. Pacific 93, 119.

Edwards, D.L. (1956). Vistas in Astronomy 2, 1470.

Finkenzeller, U. (1985). Astron. Astrophys. 151, 340.

Fontaine, G., Villeneuve, B., Landstreet, J.D., Taylor, R.H. (1982). Astrophys. J. Suppl. 49, 259.

Guinan, E.F., Hayes, D.P. (1984). Astrophys. J. Letters 287, L39.

Gulliver, A.F. (1977). Astrophys. J. Suppl. 35, 441.

Gulliver, A.F., Bolton, C.T., Poeckert, R. (1980). Publ. Astr. Soc. Pacific 92, 774.

Hanuschik, R. (1986a). Astron. Astrophys. (in press).

——— (1986b). Astron. Astrophys. (submitted).

Harmanec, P. (1983). Hvar Obs. Bull. 7, no. 1, p. 55 (Zagreb).

Hiltner, W.A., Garrison, R.F., Schild, R.E. (1969). Astrophys. J. 157, 313.

Hirata, R., Hubert-Delplace, A.M. (1981). Proc. Workshop on Pulsating B Stars, Nice Observatory, p. 217.

Hirata, R., Kogure, T. (1984). Bull. Astr. Soc. India 12, 109.

Horne, K., Marsh, T.R. (1986). Monthly Not. Royal astron. Soc. 218, 761.

Huang, S.-S. (1972). Astrophys. J. 171, 549.

Hubert-Delplace, A.M., Hubert, H. (1979). Atlas of Be Stars, Observatoire, Paris.

——— (1981). Astron. Astrophys. Suppl. 44, 109.

Hubert-Delplace, A.M., Jaschek, M., Hubert, H., Chambon, M.Th. (1982). Internat. Astr. Union Symp. 98 (ed. M. Jaschek, H.-G. Groth), p. 125.

Hubert-Delplace, A.M., Mon, M., Ungerer, V., Hirata, R., Paterson-Beeckmanns, F., Hubert, H., Baade, D. (1983). Astron. Astrophys. 121, 174.

Hutchings, J.B. (1970). Monthly Not. Roy. Astr. Soc. 150, 55.

Jaschek, C., Jaschek, M. (1965). Publ. Astr. Soc. Pacific 77, 376.

Jaschek, C., Jaschek, M. (1983). Astron. Astrophys. 117, 357.

Jaschek, M., Egret, D. (1982). A catalogue of Be stars, Microfiche 3067, Centre de Données Stellaires, Observatoire,Strasbourg.

Jaschek, M., Groth, H.G. (eds.) (1982). Int. Astron. Union Symp. 98, Reidel, Dordrecht.

Jaschek, M., Hubert-Delplace, A.M., Hubert, H. Jaschek, C. (1980). Astron. Astrophys. Suppl. 42, 103.

Jaschek, M., Slettebak, A., Jaschek, C. (1981). Be Star Newsletter (Obs. Strasbourg) 4, 9.
Kitchin, C.R., Meadows, A.J. (1970). Astrophys. Space Sci. 8, 463.
Kogure, T. (1969). Astron. Astrophys. 1, 253.
——— (1975). Publ. Astr. Soc. Japan 27, 165.
——— (1984). Publ. Beijing Astr. Obs. 6, 1.
Kogure, T., Hirata, R., Asada, Y. (1978). Publ. Astr. Soc. Japan 30, 385.
Kogure, T., Hirata, R. (1982). Bull. Astr. Soc. India 10, 281.
Kogure, T., Suzuki, M. (1984). Publ. Astr. Soc. Japan 36, 191.
Kurucz, R.L. (1979). Astrophys. J. Suppl. 40, 1.
Lesh, J.R. (1968). Astrophys. J. Suppl. 17, 371.
Lowe, R.P., Moorhead, J.M., Wehlau, W.H., Barker, P.K., Marlborough, J.M. (1985). Astrophys. J. 290, 325.
McLaughlin, D.B. (1937). Astrophys. J. 85, 181.
——— (1962). Astrophys. J. Suppl. 7, 65.
——— (1966). Astrophys. J. 143, 285.
Marlborough, J.M. (1982). P. 361 in: IAU Symp. 98, eds. M. Jaschek, H.-G. Groth, Reidel, Dordrecht.
McConnell, D.J. (1981). Astron. Astrophys. Suppl. 44, 387.
Meisel, D.D., Saunders, B.A., Frank, Z.A., Packard, M.L. (1982). Astrophys. J. 263, 759.
Merrill, P.W. (1949). Publ. Astron. Soc. Pacific 61, 38.
——— (1952). Astrophys. J. 115, 145.
Mullan, D.J. (1984). Astrophys. J. 284, 769.
Penrod, G.D. (1986). Publ. Astron. Soc. Pacific 98, 35.
Pesch, P., Sanduleak, N. (1983). Astrophys. J. Suppl. 51, 171.
——— (1986). Astrophys. J. Suppl. 60, 543.
Peters, G.J. (1979). Astrophys. J. Suppl. 39, 175.
——— (1984). Publ. Astr. Soc. Pacific 96, 960.
——— (1986). Astrophys. J. Letters 301, L61.
Poeckert, R., Gulliver, A.F., Marlborough, J.M. (1982). Publ. Astron. Soc. Pacific 94, 87.
Poeckert, R., Marlborough, J.M. (1978a). Astrophys. J. 220, 940.
——— (1978b). Astrophys. J. Suppl. 38, 229.
——— (1979). Astrophys. J. 233, 259.
Rybicki, G.B., Hummer, D.G. (1983). Astrophys. J. 274, 380.
Sanduleak, N., Pesch, P. (1984). Astrophys. J. Suppl. 55, 517.
Secchi, P. (1866). Comptes rendus Acad. Sciences Paris 63, 621.
Singh, M. (1982). Be Star Newsl. (Obs. Strasbourg) 6, 27.
——— (1982). Inf. Bull. Var. Stars (Budapest) 2188.
Slettebak, A. (ed.) (1976a). Int. Astron. Union Symp. 70, Reidel, Dordrecht.
——— (1976b). In: Be and shell stars, IAU Symp. 70 (ed.: A. Slettebak), Reidel, Dordrecht, p. 123.
——— (1979). Space Science Rev. 23, 541.
——— (1982a). Int. Astr. Union Symp. 98 (eds.: M. Jaschek, H.-G. Groth), Reidel, Dordrecht, p. 109.
——— (1982b), Astrophys. J. Suppl. 50, 55.
Slettebak, A., Carpenter, K.G. (1983). Astrophys. J. Suppl. 53, 869.
Slettebak, A., Reynolds, R.C. (1978). Astrophys. J. Suppl. 38, 205.

Snow, T.P. jr. (1981). Astrophys. J. 251, 139.
Stephenson, C.B. (1986). Astrophys. J. 300, 779.
Struve, O. (1931). Astrophys. J. 73, 94.
——— (1942). Astrophys. J. 95, 134.
Swings, J.-P. (1974). Astron. Astrophys. 26, 443.
Vega, E.I. (1982). Astron. J. 87, 794.
Vega, E.I., Rabolli, M., Muzzio, J.C., Feinstein, A. (1980). Astron. J. 85, 1207.
Walborn, N.R. (1980). Astrophys. J. Suppl. 44, 535.
Zickgraf, F.-J., Wolf, B., Stahl, O. Leitherer, C., Klare, G. (1985). Astron. Astrophys. 143, 421.

DISCUSSION FOLLOWING DACHS

Buscombe:

The published MK classifications for fainter Be stars (which had only been observed under lower resolution) are usually much too late, due to the influence of the sharper shell components of the absorption-line spectrum. The Hα emission strength is related to the ultraviolet flux of the underlying star.

Dachs:

Correct.

Hirata:

You suggested the Keplerian disk. In such a case, the inner edge of the envelope rotates with critical velocity v_c, not with v_e in the definition of Dr. Collins. Then, one should use $v_c$sini in place of vsini.

Dachs:

Observation indicates that the maximum peak separation in double-peaked emission-line profiles is $2v_e$sini. Adopting the velocity law of Keplerian rotation for the emitting disk, this observation would imply that the inner edge of the rotating disk has to be located at a certain distance above the stellar surface at the equator.

Peters:

A parameter usually quoted for Be emission line profiles is V/R. In fact in many examples the profile is quite triangular in shape and it is not clear how to measure V/R: one emission line does *not* exist. But many observers publish values V/R for such stars and subsequently models are developed for the stars in question which attempt to explain the quoted numbers! Could you comment on measurements of V/R?

Dachs:

This seems to be an unsolved problem. A method for defining V/R for a singly-peaked emission-line profile of asymmetric, quasi-triangular shape has recently been suggested by Doazan et al. (1984) in a paper on γ Cas.

Tarafdar:

What kind of relation do you find between the strength of emission of Hα and the spectral type? One expects to find stronger Hα emission in early type stars thsn later types. But is there a good relation?

Dachs:

This is an unsolved question. Maximum Hα equivalent widths appear to occur near B1, but statistics of Hα observations both for hotter and for cooler emission-line stars are still poor, at least in my sample.

Doazan:

I would like to simply mention that when one observes a given Be star over a long interval of time - several decades - the emission lines exhibit large changes in widths (cf. γ Cas, 59 Cyg, μ Cen, etc.).