IIA. THE UNDERLYING STARS: OBSERVATIONS

FUNDAMENTAL PARAMETERS OF THE UNDERLYING Be STARS

(Review Paper)

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Abstract. The various methods for determining masses, radii, luminosities, effective temperatures, spectral types, and rotational velocities of the underlying Be stars are reviewed, and representative values listed for each.

Introduction

The title of this review suggests that the paper should be a lengthy one, filling a good portion of the proceedings. Actually, we have very little direct information about the fundamental parameters of Be stars and this review will, in fact, be relatively short. The problem is that the underlying stars of Be-type objects are B stars, and most of these are too far away to permit accurate determinations of their fundamental parameters. Be stars do indeed occur in binary systems, but, as will be discussed in the following sections, accurate masses are not available for either visual or eclipsing binaries, nor have reliable radii been obtained. Indeed, since many Algol (semi-detached) systems show Hα emission (Plavec and Polidan 1976; Peters 1980), the question can be raised: are the B-type components of Algol systems which show Balmer emission the equivalent of "classical" (i.e., non-supergiant, non-peculiar B-type stars with Balmer emission) Be stars? Plavec (1976) has shown that many Algol systems resemble classical Be stars spectroscopically. On the other hand, most Be stars appear to be single stars and a mechanism other than mass transfer must be invoked to explain the Hα emission. In other words, even if masses and radii of Algol systems were accurately known, the relationship of these objects to the classical Be stars is still unknown. This matter will be discussed further by Mirek Plavec and Petr Harmanec during this Colloquium.

Despite the paucity of accurate data for Be stars, the underlying stars are often revealed essentially uncontaminated when the envelopes are optically thin or even disappear altogether, as happens for many objects. They then look spectroscopically like normal (although usually with greatly broadened lines) B stars. Spectral type and color determinations then allow us to place them in the framework of normal B stars and to estimate their fundamental parameters by comparison with normal B stars. It must be stressed, however, that the parameters obtained in this way are only as valid as the assumption that an emission-free Be star which looks spectroscopically identical to a normal B-type star is actually identical to that star. Rotation presents a problem here: we know that rapid rotation is a characteristic of Be stars, and there is

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evidence that rotation affects the colors and spectral types of stars (cf. Collins, 1974; Collins and Sonneborn 1977; Slettebak et al. 1980).

Masses

Although Be stars are found as components of visual binaries (cf. Slettebak 1963; Meisel 1968; Abt and Cardona 1984), none show sufficient orbital motion with sufficiently accurate parallaxes to yield reliable masses. Indeed, the same is true for B-type stars in general. Thus, the 41 systems selected by Harris et al. (1963) for a discussion of the mass-luminosity relation include no B-type stars, nor are any included in the critical discussion by Popper (1980).

Double-lined spectroscopic binaries that are also eclipsing binaries are another source of stellar masses but, unfortunately, no well-detached systems with Be-star components are known. I have already referred to the fact that the semi-detached (Algol) systems are spectroscopically similar to classical Be stars, but the mass transfer which occurs in these systems makes them unsuitable for mass determinations. We are left, therefore, with the observed masses of normal B-type stars, making the assumption that the underlying stars of Be-type objects are identical to B-type stars of similar spectral type. The data in Popper's (1980) critical review of stellar masses are extremely useful for this purpose. A total of 33 binary components of B-type (with spectral types from the Seventh Catalogue of the Orbital Elements of Spectroscopic Binary Systems [Batten et al. 1978] as well as from Popper's [1980] paper) are listed in his Tables 2, 4, and 7 (excluding the semi-detached systems in his Tables 11 and 12). The derived masses are of various accuracies, as Popper points out, but some rough averages from his data are presented in Table 1 to give an approximation to probable Be-star masses. These numbers are similar, though somewhat smaller, to those given by Underhill (1982) in her review of the B stars without emission lines and Schmidt-Kaler (1982) in the Landolt-Börnstein series.

TABLE 1

Masses and Radii of Main-Sequence B-type Stars
(Based on data listed by Popper 1980)

Spectral Type	$M/M_\odot$	$R/R_\odot$
B0	16	7
B2	9	4.5
B5	5	3.2
B8	3.5	2.7

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Radii

The problem in obtaining radii of Be stars from eclipsing spectroscopic binaries is identical to that of measuring masses in such systems: Be stars are not found as components in well-detached systems, while semi-detached systems yield values which are difficult to interpret. Resorting again to the assumption that the underlying Be star is identical to a B-type star of similar spectral type, Popper's data may again be used to approximate Be-star radii. Rough averages are listed in Table 1 for main-sequence B-type stars, but it must be remembered that many Be stars show spectroscopic evidence of being subgiants or giants. Underhill (1982) has presented a similar but more detailed table of stellar radii in her B-star review, based not only on the data from Popper (1980) but also on her own estimates of radii (Underhill et al. 1979). Her average values are systematically somewhat higher than those listed in Table 1, as are those of Schmidt-Kaler (1982) in the Landolt-Börnstein series.

Interferometric techniques have been used to determine angular diameters or upper limits to angular diameters for several Be stars. Using intensity interferometry at Narrabri Observatory in Australia, Hanbury Brown et al. (1974) measured angular diameters for the B4 Ve star α Eri and the 09.5 Ve star ζ Oph. Phase interferometry with the two-telescope interferometer at CERGA in France was used to obtain an upper limit to the angular diameter of the B0.5 IVe star γ Cas (Vakili et al. 1984) and upper limits to the angular diameters of the B7 IIIe star η Tau and the B1 IVe-shell star ζ Tau (Granes et al. 1985). Details of this work, including an Hα measurement of the angular diameter of the envelope of γ Cas, will be presented by Pierre Granes at this Colloquium. Table 2 lists radii based on angular diameters of Be stars obtained with interferometric techniques thus far. It is evident that longer base lines will be required before phase interferometry will yield Be-star radii.

Another technique for measuring stellar radii is speckle interferometry (cf. Labeyrie 1978). The limiting angular diameter for existing telescopes is about 0.″02, however, whereas the most favorable Be-star angular diameters are at least an order of magnitude smaller. The possibility of measuring angular diameters of Be-star envelopes by observing in Hα light exists, but this would be a marginal experiment and it has not been tried as yet.

Still another method for measuring stellar angular diameters is that of lunar occultations (cf. Nather and Evans 1970). Here the limiting angular diameter is about 0.″002, which would be marginal for Be-star photospheres. On the other hand, Be-star envelopes might be measured with this technique, using Hα filters, as was suggested by White and Slettebak (1980). Such an attempt was made by Schmidtke and Africano (1984) during an occultation of the B1 IVe star ζ Tau, but they were able only to obtain an upper limit to the size of the shell.

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TABLE 2

Radii Based on Angular Diameters of Be Stars

A. Intensity Interferometry (Hanbury Brown et al. 1974)

Star	HD	Sp. Type	θ	π	$R/R_\odot$
α Eri	10144	B4 Ve	0″00192	0″0333[1] 0.043[2]	6.2 4.8
ζ Oph	149757	O9.5 Ve	0″00051	0″0004[1] 0.004[3]	138 14

B. Two-Telescope Phase Interferometry (Vakili et al. 1984; Granes et al. 1985)

Star	HD	Sp. Type	θ	π	$R/R_\odot$
γ Cas	5394	B0.5 IVe	< 0″0009	0″0188[1] 0.004[4]	< 5.2 < 24
η Tau	23630	B7 IIIe	< 0″0044	0″0079[1] 0.0078[5]	< 60 < 61
ζ Tau	37202	B1 IVe	< 0″0044	0″0048[1] 0.004[6]	< 99 <119

Notes:
1) Trigonometric parallax (van Altena 1985).
2) Spectroscopic parallax with $M_v = -1.4$.
3) Spectroscopic parallax with $M_v = -4.5$.
4) Spectroscopic parallax with $M_v = -4.4$.
5) Based on Pleiades distance modulus $(V_o - M_v) = 5.55$ (Crawford and Perry 1976).
6) Spectroscopic parallax with $M_v = -4.0$.

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An interesting suggestion by Fresneau (1985) is to use the Fine Guidance Sensor of the Hubble Space Telescope to measure stellar angular diameters. The Fine Guidance Sensors consist of a system of photomultiplier tubes and amplitude interferometers (Koester's prisms). Since only two Sensors are required for guidance of the spacecraft, the third can be used for high precision astrometric observations. The analysis of the interference fringe visibility can give an indication of apparent diameters larger than 0$''$.003 - 0$''$.005. Fresneau has suggested that this technique could be used to measure diameters of Be star shells, but photospheric diameters are probably not possible.

A number of the aforementioned methods for measuring stellar diameters relate to a chord across the stellar disk for each measurement. Since the rapidly rotating Be stars are likely to suffer shape distortion, multiple measurements would be required to obtain both the size and the shape of the underlying star.

Luminosities

Early studies by Curtiss (1926) and Gerasimovic (1927) based on proper motion studies suggested that Be stars are somewhat more luminous (from half a magnitude to over two magnitudes) than absorption-line B stars of similar spectral type. Merrill and Burwell (1933) found Be stars to be about one magnitude more luminous than non-Be's, based on their galactic distribution. Wilson (1941), however, pointing out that the presence of supergiant B-stars in Gerasimovic's sample likely influenced his conclusions, showed from motion studies that when supergiants are excluded, most Be stars lie on the main sequence. This conclusion was supported on the basis of the appearance of their spectra by Morgan, who stated in the "Atlas of Stellar Spectra" (Morgan et al. 1943): "They (Be stars) show spectroscopic evidence of low luminosity and are probably no brighter than main sequence stars of the same classes".

More recent determinations of Be star luminosities, based largely on their membership in open clusters and double-star systems, are due, among others, to Abt and Levato (1977), Bidelman (1947), Bond (1973), Meisel (1968), Mendoza (1958), Mermilliod (1982), Schild (1965), Schild and Romanishin (1976), Schmidt-Kaler (1964), and Slettebak (1968, 1985a). The picture that emerges from all of this work is that Be stars, on the average, lie a magnitude or so above the main sequence, but may be found anywhere in a band from the zero age main sequence to the giant region, two magnitudes or more above the zero age main sequence. This conclusion is supported by spectroscopic evidence (Slettebak 1982): although many Be stars look spectroscopically like main-sequence objects, others show unmistakable evidence of somewhat higher luminosity (subgiants and giants, but never supergiants).

Unfortunately, the aforementioned conclusions are not simple to interpret. Thus, Collins and Sonneborn (1977) have shown that rapid rotation will move stars to the right, into the subgiant and giant regions, in a color-magnitude diagram, and concluded that "... the position of the Be stars above the main sequence could be interpreted as the result of rotation alone, without invoking evolutionary arguments". Nor is it possible to use spectral types to sort out such color effects, since spectral types also seem to be affected by rotation (Slettebak et al. 1980). There is also evidence (cf. Crawford et al. 1970; Schild 1978; Slettebak 1985a) that envelope reddening in Be stars may affect their positions in color-magnitude diagrams.

Finally, we must be careful, as George Collins has warned us at this Colloquium, to be clear what we mean by luminosity. Since a rapidly-rotating star will be distorted and emit different amounts of flux from different portions of its surface, the star's observed luminosity and color will depend upon the direction from which we see it. These effects must be taken into account in computing the total energy output of the star.

Effective Temperatures

Assuming an isotropic radiation field from a spherical star, the effective temperature of a star can be obtained from its measured angular diameter and its total absolute flux, integrated over the entire spectrum received from the star above the earth's atmosphere. Such empirical effective temperatures have been determined by Code et al. (1976), using intensity interferometry together with ultraviolet flux observations from OAO-2 plus ground-based photometry. Two Be stars are included among their 32 early-type stars, with the following results:

α Eri = HD 10144	B4 Ve	Te = 14,510 $\pm$ 390 $^{\circ}$K
ζ Oph = HD 149757	O9.5 Ve	Te = 31,910 $\pm$ 2040 $^{\circ}$K

A less direct method of estimating stellar effective temperatures is by comparing predictions from theoretically-derived model atmospheres with observations of continuous and line spectra. The effective temperature (and surface gravity) which define that model atmosphere which best fits the observations is then ascribed to the star. Unfortunately, the circumstellar envelopes which characterize Be stars may act to distort both their continuous and line spectra, and therefore yield inaccurate effective temperatures. Thus, Be stars commonly show an excess of flux in both the visible and infrared regions of the spectrum, exhibit a variety of Balmer jumps, and have been reported to show both flux deficiences and flux excesses in the ultraviolet (for a discussion and references to these observations, see Doazan 1982; Slettebak 1979, 1985a; Snow and Stalio 1987). On the other hand, Snow and Stalio (1987) write "It now appears safe (from UV data) to conclude that the underlying photospheric line spectra of Be stars are indistinguishable from normal B stars". If we now make the assumption that the underlying Be star is identical to a normal B-type star of similar spectral type, we are still faced with the fact that Be stars as a class are rapidly rotating and may therefore show gravity darkening effects. Under these circumstances, George Collins has warned us that the concept of a global effective temperature is meaningless. As an approximation to what we might expect for a kind of average temperature of the underlying Be star, Table 3 lists some values of effective temperatures of B-type stars from recent critical discussions by Böhm-Vitense (1981), Hayes (1978), Underhill (1982), and Schmidt-Kaler (1982).

TABLE 3

Effective Temperatures of B-type Stars

Spectral Type	Böhm-Vitense (1981) Lum. Class V	Hayes (1978) Lum. Class V	Underhill (1982) Lum. Classes IV, V	Schmidt-Kaler (1982) Lum. Class V
B0	29,500 ^{o}K	30,300 ^{o}K	30,780 ^{o}K	30,000 ^{o}K
B2	21,500	23,100	22,820	22,000
B5	15,400	15,300	15,170	15,400
B8	12,000	11,500	11,900	11,900

Spectral Types

Spectral classification of Be stars is difficult and rather uncertain, as has been discussed in several review papers (cf. Slettebak 1979, Doazan 1982). On the one hand, emission and/or absorption from the circumstellar envelope can distort absorption lines from the underlying star which are used for estimating spectral types or luminosity classes. In addition, the rapid rotation which is characteristic of Be stars has two detrimental effects: (1) it causes very large line broadening, which makes faint lines difficult to see and generally makes line intensities difficult to estimate; (2) it may cause distortion of the star with consequent changes in temperature and pressure over the stellar surface, thereby affecting the spectral classification. The latter effects have been discussed by Slettebak et al. (1980), who found that rapidly-rotating B-type models viewed equatorially will tend to be classified somewhat later in spectral type and somewhat more luminous than non-rotating models of the same mass.

MK classifications of Be stars may be found in the papers by Morgan et al. (1955), Mendoza (1958), Lesh (1968), Hiltner et al. (1969), Garrison et al. (1977), Jaschek et al. (1980), and Slettebak (1975, 1982, 1985a), as well as in many papers treating individual Be stars. Also, Divan (1979) has developed a quantitative system of spectral classification of Be stars, based on measurements of the Balmer discontinuity.

If we extend the definition of Be stars to include all objects which show the "Be phenomenon", the distribution of spectral types extends from about O8 to the A- and F-type shell stars, with a maximum in the frequency distribution near B2 (see discussions by Slettebak 1979, 1982; and Jaschek and Jaschek 1983).

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Rotational Velocities

A discussion of the determination of stellar rotational velocities, including methods and accuracies, may be found in the review paper by Slettebak (1985b). Struve (1931) first pointed out that the majority of Be stars have extremely broad, "dish-shaped" absorption lines, indicating very rapid rotation, and proposed a rotational model to explain the Be phenomenon. Although attempts to measure Be star rotations have been made by searching for modulation of starlight due to an uneven distribution of flux from the star or shell, our primary source of Be star rotational velocities continues to be the analysis of line profiles.

The rapid rotation which is characteristic of Be stars again causes several problems. On the observational side, the broad and shallow line profiles are difficult to measure accurately (and may also be distorted by both absorption and emission contributions from the circumstellar envelope). In addition, shape distortion and gravity darkening will affect the line profiles, as shown by the work of Collins (1974). When applied to the most rapidly rotating stars (Slettebak et al. 1975), a considerable uncertainty was found to exist in assigning rotational velocities. This is due to a basic ambiguity in that the half-intensity widths of lines used to measure rotational broadening do not uniquely specify a rotational velocity for large v sin i's. Uncertainties up to 15-20 percent of the assigned v sin i may result from this effect.

Mean values of the estimated rotational velocities, v sin i, range between about 200 and 250 km/sec for both main-sequence and luminosity class III and IV Be stars (Slettebak 1982). Thus, although Be stars as a class are very rapid rotators, their rotation characteristics seem not to be a strong function of either spectral type or luminosity class.

The aforementioned difficulties in estimating large rotational velocities of Be stars make it very difficult to answer the interesting and important question: do Be stars rotate at the critical velocity at which centrifugal force balances gravitational attraction? The best evidence we have at present suggests that the answer to this question is: no. The largest v sin i's measured from line profiles are in the neighborhood of 400 km/sec (Slettebak 1982), whereas computed equatorial critical velocities for main sequence models (Collins 1974) are generally larger than this, especially for the models earlier than B5. This result receives support from the work of Stalio et al. (1987) on flux distributions of Be stars in the far-UV, which is reported at this Colloquium: they find a comparison of their observations with model results to be consistent with Be stars rotating at less than 0.85 of critical velocity.

On the other hand, while rapid rotation may not be the trigger for the Be phenomenon, there is strong evidence that it must play a crucial role. Frequency distributions of observed rotational velocities tend

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toward the monotonically-increasing functions predicted by the rotational model for Be stars (Struve 1931), with a maximum near (but not as large as) the critical velocity (cf. Slettebak 1979, 1982).

Morton et al. (1972) observed several ultraviolet absorption lines in the rapidly rotating Be star ζ Oph to be unusually narrow and suggested that they form predominately in the more slowly rotating polar regions or that they may originate in a shell that has a lower rotational velocity than the visual photosphere. Not long after, Heap (1976) found several ultraviolet lines in the spectrum of the Be shell star ζ Tau to be relatively narrow, corresponding to a considerably lower rotational velocity than is estimated from visual line profiles. Hutchings (1976) and Sonneborn and Collins (1977) analyzed the problem quantitatively in terms of gravity darkening of a rapidly-rotating star, and predicted a variation in line broadening in the sense reported by Morton and Heap.

Carpenter et al. (1984) compared observed ultraviolet and visual line profiles in late-B and A-type stars with theoretical line profiles based on shape-distorted, gravity-darkened models and found good agreement, suggesting that the models are reasonable. The effect is interesting because, in principle, it can be used to separate v from i. In practice, however, the many uncertainties inherent in the analysis make the results questionable.

Recent Be star rotational velocity determinations may be found in papers by Gao and Cao (1984), Slettebak (1982, 1985a), Ruusalepp (1986), and the Revised Catalogue of Stellar Rotational Velocities by Uesugi and Fukuda (1982).

Conclusions

Little direct information about the fundamental parameters of the underlying Be stars is presently available, and that information which can be obtained is not always easy to interpret because of envelope effects and the shape distortion and non-isotropic radiation fields which are probably characteristic of rapidly-rotating stars. Often the best that can be done is to assume that the underlying Be star has the same physical characteristics as a non-emission B-type star of similar spectral type, but we should be clear that envelope and rotation effects in the former may result in systematic differences in the fundamental parameters.

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References

Abt, H. A. & Cardona, O. (1984). Ap. J., 285, 190.

Abt, H. A. & Levato, H. (1977). Publ. Astron. Soc. Pacific, 89, 797.

Batten, A. H., Fletcher, J. M., & Mann, P. J. (1978). Publ. Dominion Astrophys. Obs., 15, 121.

Bidelman, W. P. (1947), A.J., 52, 121.

Böhm-Vitense, E. (1981), Ann. Rev. Astron. Astrophys., 19, 295.

Bond, H. E. (1973), Publ. Astron. Soc. Pacific, 85, 405.

Carpenter, K. G., Slettebak, A., & Sonneborn, G. (1984), Ap. J. 286, 741.

Code, A. D., Davis, J., Bless, R. C., & Hanbury Brown, R. (1976). Ap. J., 203, 417.

Collins, G. W., II (1974). Ap. J., 191, 157.

Collins, G. W., II & Sonneborn, G. H. (1977). Ap. J. Suppl., 34, 41.

Crawford, D. L., Glaspey, J. W., & Perry, C. L. (1970), A.J., 75, 822.

Crawford, D. L. & Perry, C. L. (1976). A.J., 81, 419.

Curtiss, R. H. (1926). J. Astron. Soc. Canada, 20, 19.

Divan, L. (1979). In Spectral Classification of the Future, IAU Colloq. 47, ed. M. F. McCarthy, A. G. D. Philip & G. V. Coyne, Specola Vaticana Ricerche Astronomiche, 9, 247.

Doazan, V. (1982). In B Stars With and Without Emission Lines, ed. A. Underhill and V. Doazan, Monograph Series on Non-thermal Phenomena in Stellar Atmospheres, NASA-CNRS.

Fresneau, A. (1985). Fine Guidance Sensor Instrument Handbook, NASA-ESA Edwin P. Hubble Space Telescope, Oct. 1985.

Gao, W. & Cao, H. (1984). In Proc. Workshop on Stellar Activity and Obs. Techniques: Sino-Japan. Publ. Beijing Astron. Obs., 6, 33.

Gerasimovic, B. P. (1927). Harvard College Obs. Bull., No. 849, 8.

Garrison, R. F., Hiltner, W. A., & Schild, R. E. (1977), Ap. J. Suppl., 35, 111.

Granes, P., Thom, C., & Vakili, F. (1985). Work reported at I.A.U. General Assembly, New Delhi, India, Nov. 1985.

Hanbury Brown, R., Davis, J., & Allen, L. R. (1974). M.N.R.A.S., 167, 121.

Harris, D. L., III, Strand, K. Aa., & Worley, C. E. (1963), In Basic Astronomical Data, ed. K. Aa. Strand, p. 273. Chicago: University of Chicago Press.

Hayes, D. S. (1978). In The HR Diagram, IAU Symp. 80, ed. A. G. D. Philip & D. S. Hayes, p. 65. Dordrecht: Reidel.

Heap, S. R. (1976). In Be and Shell Stars, IAU Symp. 70, ed. A. Slettebak, p. 165. Dordrecht: Reidel.

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

Hutchings, J. B. (1976). Publ. Astron. Soc. Pacific, 88, 5.

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

Jaschek, M., Hubert-Delplace, A.-M., Hubert, H., & Jaschek, C. (1980). Astron. Astrophys. Suppl., 42, 103.
Labeyrie, A. (1978). Ann. Rev. Astron. and Astrophys., 16, 77.
Lesh, J. R. (1968). Ap. J. Suppl., 17, 371.
Meisel, D. D. (1968). A.J., 73, 350.
Mendoza, E. E., V. (1958). Ap. J., 128, 207.
Mermilloid, J.-C. (1982). Astron. Astrophys., 109, 48.
Merrill, P. W. & Burwell, C. G. (1933). Ap. J., 78, 87.
Morgan, W. W., Code, A. D., & Whitford, A. E. (1955). Ap. J. Suppl., 2, 41.
Morgan, W. W., Keenan, P. C., & Kellman, E. (1943). An Atlas of Stellar Spectra. Chicago: University of Chicago Press.
Morton, D. C., Jenkins, E. B., Matilsky, T. A., & York, D. G. (1972). Ap. J., 177, 219.
Nather, R. E. & Evans, D. S. (1970). A.J., 75, 575.
Peters, G. J. (1980). In Close Binary Stars: Observations and Interpretation, IAU Symp. 88, ed. M. J. Plavec, D. M. Popper, and R. K. Ulrich, p. 287. Dordrecht: Reidel.
Plavec, M. (1976). In Be and Shell Stars, IAU Symp. 70, ed. A. Slettebak, p. 1. Dordrecht: Reidel.
Plavec, M. & Polidan, R. S. (1976). In Structure and Evolution of Close Binary Systems, IAU Symp. 73, ed. P. Eggleton, S. Mitton, and J. Whelan, p. 289. Dordrecht: Reidel.
Popper, D. M. (1980). Ann. Rev. Astron. Astrophys., 18, 115.
Ruusalepp, M. (1986). Publ. Tartu Astrophys. Obs., 51, 84.
Schild, R. E. (1965). Ap. J., 142, 979.
Schild, R. E. (1978). Ap. J. Suppl., 37, 77.
Schild, R. & Romanischin, W. (1976). Ap. J., 204, 493.
Schmidt-Kaler, Th. (1964). Z. Astrophys., 58, 217.
Schmidt-Kaler, Th. (1982). In Landolt-Börnstein, New Series, Group VI, Volume 2b. Berlin-Heidelberg-New York: Springer-Verlag.
Schmidtke, P. C. and Africano, J. L. (1984). A.J., 89, 663.
Slettebak, A. (1963). Ap. J., 138, 118.
Slettebak, A. (1968). Ap. J., 154, 933.
Slettebak, A. (1979). Space Science Rev., 23, 541.
Slettebak, A. (1982). Ap. J. Suppl., 50, 55.
Slettebak, A. (1985a). Ap. J. Suppl., 59, 769.
Slettebak, A. (1985b). In Calibration of Fundamental Stellar Quantities, IAU Symp. 111, ed. D. S. Hayes, L. E. Pasinetti, and A. G. D. Philip, p. 163. Dordrecht: Reidel.
Slettebak, A., Collins, G. W., II, Boyce, P. B., White, N. M., & Parkinson, T. D. (1975). Ap. J. Suppl., 29, 137.
Slettebak, A., Kuzma, T. J., & Collins, G. W., II (1980). Ap. J., 242, 171.
Snow, T. P. & Stalio, R. (1987). In Scientific Accomplishments of the IUE, ed. Y. Kondo et al. Dordrecht: Reidel.
Sonneborn, G. H. & Collins, G. W., II. (1977). Ap. J., 213, 787.
Stalio, R., Polidan, R. S., & Peters, G. J. (1987). This Colloquium.

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Struve, O. (1931). Ap. J., 73, 94.
Uesugi, A. & Fukuda, I. (1982). Revised Cat. of Stellar Rotational Velocities, Kyoto University.
Underhill, A. (1982). In B Stars With and Without Emission Lines, ed. A. Underhill and V. Doazan, Monograph Series on Nonthermal Phenomena in Stellar Atmospheres, NASA-CNRS.
Underhill, A. B., Divan, L., Prevot-Burnichon, M.-L., & Doazan, V. (1979). M.N.R.A.S., 189, 601 and Microfiche MN 189/1.
Vakili, F., Granes, P., Bonneau, D., Noguchi, M., & Hirata, R. (1984). Publ. Astron. Soc. Japan, 36, 231.
van Altena, W. F. (1985). Revised Catalog of Trigonometric Parallaxes.
White, N. M. & Slettebak, A. (1980). A.J., 85, 44.
Wilson, R. E. (1941). Ap. J., 94, 12.

DISCUSSION FOLLOWING SLETTEBAK

Thomas:

Who is correct, you or Anne Underhill, on the radii of main- sequence B-type stars, since your values are a factor two less than Anne's?

Slettebak:

My numbers are based entirely on the data in Popper's (1980) critical review, whereas Anne used Popper's data plus angular diameters for additional stars derived using the method of Blackwell and Shallis (1977).

Thomas:

What do I use for γ Cas - Anne's 15 solar radii or your 7?

Underhill:

10 solar radii.

Garmany:

When you said that Be stars occur between the ZAMS and 2 magnitudes above the ZAMS, was this based on spectroscopic and photometric properties or on luminosities derived from cluster members?

Slettebak:

It was based on color-magnitude diagrams of open clusters having Be star members.

Sareyan:

As there are still questions about line broadening versus rotation, I would like to know: (1) If there are B stars showing line broadening (vsini?) near the "critical velocity", without any emission feature; (2) On the other hand, could you comment about the Be stars with sharpest ("vsini"=0?) lines?

Slettebak:

B-type stars with large line broadening which have never been observed to have emission do indeed exist: ψ^2Aqr and α Leo come to mind. I might remind you that ζ Oph was an MKK standard and did not show emission (quite weak) until relatively recently. The stars with the largest line broadening are all Be stars, however, and even these seem not to be rotating as fast as the critical velocity.

The Be stars with sharpest lines still have broader lines than the sharpest-lined absorption B-type stars, such as γ Peg, possibly due to electron scattering in the polar regions, as was suggested many years ago by Burbidge and Burbidge.

Chkhikvadze:

What are the general differences between normal Be stars (post main sequence) and the Herbig Be/Ae stars (pre main sequence)?

Slettebak:

Usually, the difference is based on the environment - Herbig Be/Ae stars are located inside interstellar gas and dust clouds. Spectroscopically, I believe that they may look rather similar, although I have never taken spectra of Herbig Be/Ae stars.

Underhill:

The Herbig Ae/Be stars, located in well-defined environments, have *strong* Hα emission components at all times observed. They may be called "extreme" Be stars, with apologies to Collins.

Peters:

Considering the observed variability in both the visual and far-UV light in Be stars, I wonder to what extent we can believe calibrations of luminosity. Such attempts are yet in their infancy. Of course, once the full amplitudes for the light variations are known, we can proceed with a meaningful calibration. Also, there are several stars in Popper's (1980) article on stellar masses which, according to the definition of a Be star stated by George Collins, qualify as a Be star (RY Per, TT Hya, and others)! Their masses are generally consistent with what one would expect from their given spectral types.