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The Be star phenomena I. General properties

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Abstract. General properties of Be stars including their variabilities are considered. The Be stars are first defined as non-supergiant B stars with emission-lines including non-emission shell stars. The percentage fraction of Be/B is deduced based on a homogeneous sample of Be and shell stars and a rather high fraction is found over the whole spectral range with a peak at B2. A statistical study of rotational velocities is made with the aid of Uesugi & Fukuda's catalogue transformed to the new Slettebak system. It is pointed out that the rotation properties of Be stars earlier than B2 are different from those of Be stars later than B3.

Statistics of Algol binaries are also examined in connection with the Be star phenomena. Although the Hα-emission survey is very incomplete at present, recent observations suggest a high fraction of Be and Ae stars among Algols, particularly for stars of longer orbital periods. Statistical grouping of Be binaries into short and long orbital periods is also suggested.

Hot plasma phenomena of Be stars appear in x-ray region, superionization in the UV spectral region, and in the mass-loss processes. A brief review is given with an attempt to find some properties depending on the spectral sequence or distinguished from normal OB stars. Mass loss rates from Be stars show no clear correlation with spectral sequence and rotational velocities.

Finally, a short review is given of the variabilities of Be stars, their general properties and some typical examples of the long-term variations (> 1 yr). The timescales of long-term variations are shorter in early-type Be stars than in late-type Be stars. Some characteristic features of E/C, V/R and brightness variations are also summarized.

Key words: Be stars—shell stars—stellar rotation—Algol binaries—x-ray sources—superionization—mass loss—spectral variations

1. Introduction

It is now generally accepted that the Be stars are the spectroscopic phenomena caused by the formation of envelopes around B type stars which are usually rapidly rotating.

The phenomena basically appear as the formation of emission lines in the Balmer lines or in some ionized metals; their intensities and profiles generally exhibit irregular variations with time scales from hours up to many decades. With the extension of observable spectral range to UV, x-ray, IR and radio wave regions by the development of ground-based as well as space observations, new facade of Be star phenomena has come to light, *e.g.* stellar winds, superionization, and x-ray emission.

Our knowledge on the Be star phenomena has been markedly improved in recent years through wide observational as well as theoretical works. We may refer to the *IAU Symposia No. 70* (1976) *and No. 98* (1982), a monograph of Underhill and Doazam (1982), and a review paper of Slettebak (1979) for recent developments.

In this article we present a review of the general properties of Be stars mainly from a statistical point of view. Main topics are the Be star frequency along the spectral sequence, rotational velocities, binary nature, hot-plasma phenomena, mass-loss processes and stellar winds. Finally we discuss the general trends in the variabilities along with some examples of long-term variations. Importance of quasi-periodic variation in a time scale of a day is also noticed. The interpretation of spectral features and the problems of structure and origin of the envelopes will be presented in another article.

2. What are Be stars ?

Be stars are in its broad sense B-type stars that show emission line(s) in H_α, H_β, and sometimes in the higher Balmer lines of hydrogen, in singly-ionized metals, and neutral helium lines in their optical spectra. Bidelman (1976) has classified Be stars in this broad sense; his definition of Be stars includes supergiants and quasi-planetary nebulae. Later, Jaschek *et al.* (1981) gave a more precise definition of Be stars confining them to stars of luminosity classes V–III. According to their definition, the Be stars principally include the following three types : (i) Be stars (non-supergiants); (ii) B-type shell stars; (iii) Pole-on stars. In this paper we also confine the Be stars to these three categories.

Figure 1 illustrates the schematic line profiles of lower and higher Balmer lines in B and Be stars.

Pole-on stars are characterized by single-peaked emission lines on broader photospheric absorption lines. They also show narrow He I absorption lines. *Be stars* (non-supergiants) show double-peaked emission lines whose central reversals are not deeper than the broad photospheric absorption lines. *B-type shell stars* are characterized by the sharp and usually deep absorption lines. The sharp absorption lines are called shell lines and they also appear in the lines of metals which arise from ground states or metastable levels. In strong shell stars, the shell lines appear in the Balmer series with *n* as high as 30 or even more, where *n* is the principal quantum number of the higher levels of Balmer series. The characteristics of shell lines are that, first, they are usually sharp, and second, their central depths are usually deeper than the centres of broad photospheric absorption lines.

The explanation of these spectral features interms of a flattened and extended envelope, around a rapidly rotating B star, is due to Struve (1931). The schematic structure of this envelope is illustrated in figure 2. Pole-on stars are, as their name suggests, Be stars seen from the direction of rotational axes or its vicinities. In

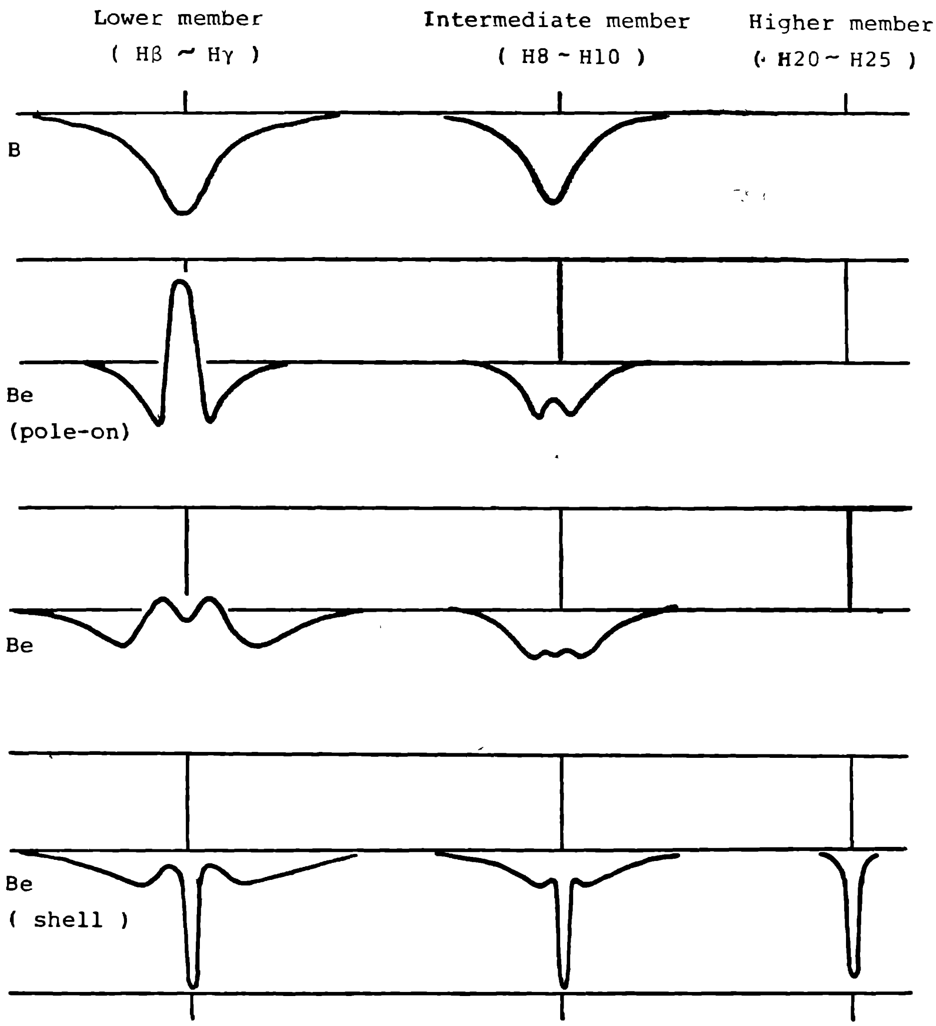

Figure 1. Schematic profiles of Balmer lines in B and Be stars.

contrast, shell stars are supposed as equator-on, *i.e.* they are seen from the direction of the equator or its vicinity.

Jaschek *et al.* (1980) have paid an attention to the strength of emission lines in addition to the profiles of emission lines for grouping Be stars.

Along with the definition of Be stars, their transient nature should be emphasized. That is, most of the Be stars are irregular spectral variables and often experience the transformation between Be and B stars. This infers that Be stars are a kind of phenomena occurring in B stars in their course of evolution from zero age main sequence (ZAMS) to the giant stage.

Then the question may be asked : what kind of B stars would experience such transformation to Be stars ? There are then several factors to be examined (Harmanec 1982) : (a) rotational velocity, relative to break-up velocity, (b) strength of radial flow (radiation pressure, stellar wind), (c) binary interaction, and (d) effect of stellar evolution. Massa (1975) has emphasized the combined effects of (a) and (b), whereas Harmanec & Kříž (1976) stress the importance of (c). The effect of stellar evolution (d) may appear in each of the factors (a)–(c), but it particularly relates to the distribution of Be stars on and above the main sequence on the HR diagram.

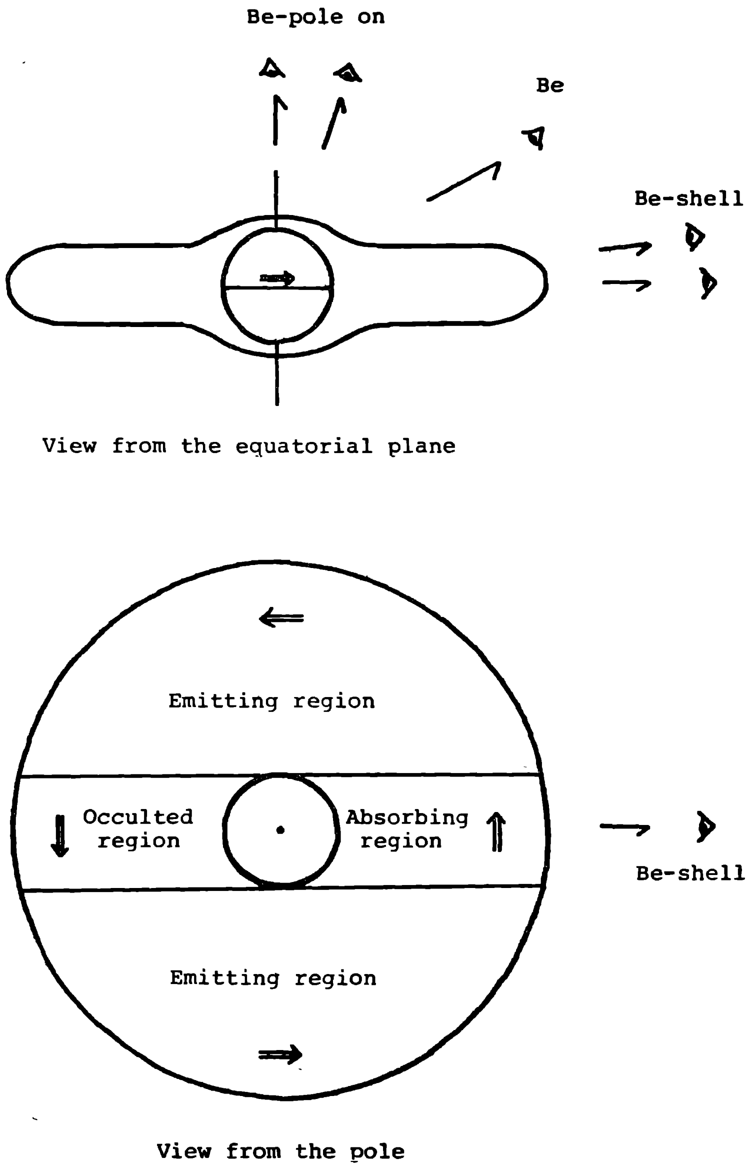

Figure 2. Schematic structure of an envelope of Be star. Extended envelope which is responsible for the formation of emission lines and shell absorption lines in the visual spectral region is illustrated.

Schild & Romanishin (1976) and Mermilliod (1982) have suggested a partial role for the evolutionary effects. At present it seems possible to say that different factors cited above are important in stars of different spectral classes. The examination of these problems is the main subject of the present article.

3. Frequency of Be stars

The fraction of Be to B stars was first estimated by Merrill (1933) who suggested a high fraction close to 15–20 per cent for the early B stars. This fraction has been examined recently by many investigators for various data sets (Meadows 1960; Massa 1975; Henize 1976; Andrillat & Houziaux 1975). These results are summarized by Briot & Zorec (1981).

We present here the fraction Be/B based on the Bright Star Catalogue (Hoffleit 1964). A great effort has been made recently to discover bright Be stars after the compilation of Wackerling's (1970) catalogue (*e.g.* Kucewicz 1975; Irvine 1975; Hirata & Asada 1976; Doazan *et al.* 1977; Irvine & Irvine 1979). Thus, we can expect that survey of Be stars is fairly complete for stars brighter than 6.5 mag, *i.e.* for stars contained in the Bright Star Catalogue. The spectral types are taken from the same source except when they are not given there, in which case we take them from Jaschek (1978). Table 1 gives the numbers of B and Be stars, and the fraction of Be/B along the spectral sequence. For comparison, Slettebak's (1982) values for the Be stars brighter than 6.0 mag are also shown. The frequency distributions along the spectral type are not very different in the two cases [Slettebak (1982) and ours] except for the fluctuation in the neighbouring subclass. This fluctuation probably comes from different systems adopted in spectral classification.

In figure 3 the percentage fraction of Be/B is plotted from the present work and from Merrill (1933), Massa (1975), Henize (1976), and Andrillat & Houziaux (1975). It is seen that our result well agrees with that of Massa (1975), which is essentially based on the rotational velocity catalogue of Uesugi & Fukuda (1970). The results of Henize (1976) and Andrillat & Houziaux (1975) yield definitely

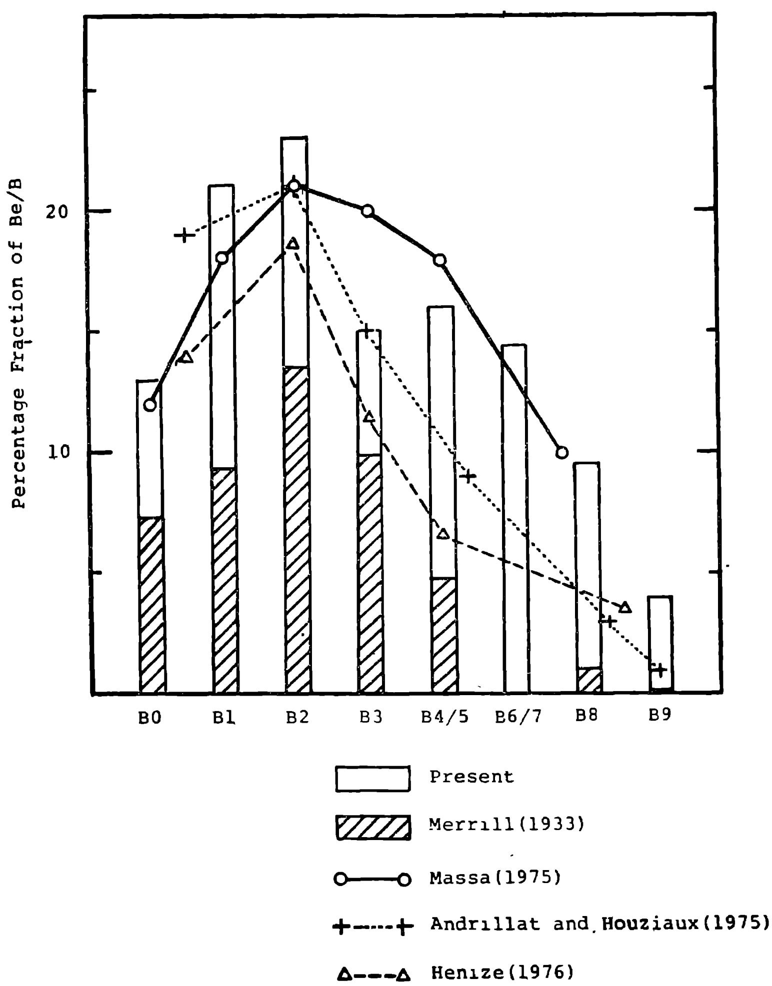

Figure 3. The percentage fraction of Be/B along the spectral sequence.

lower values than ours in later spectral types. These authors' statistics are based on the fainter stars, like stars contained in the Henry Draper catalogue. From the fact that emission-line intensity decreases towards later spectral type (Briot 1971; Briot & Zorec 1981), while the photospheric absorption strength increases, we can suppose that many Be stars with faint emission intensity are left undiscovered in later spectral types in the case of low-dispersion spectral survey.

We conclude from our results that the fraction of Be/B has a maximum in B2 (~ 20 per cent) and gradually decreases towards later spectral type (10 per cent in B8). Table 1 contains 193 Be stars and 1580 B stars in total, giving an overall mean of 12 per cent in the spectral range B0–B9, V–III.

Table 1. The frequency of B and Be stars

	B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	Total
Slettebak (1982)											
N (Be)	4	15	34	27	14	17	15	13	16	12	167
Present work											
N (B)	39	66	157	260	24	177	65	81	313	398	1580
N (Be)	5	14	36	39	2	30	6	15	30	16	193
Be/B (per cent)	13	21	23	15	8	17	9	19	10	4	12

4. Rotational velocities

Recently Uesugi & Fukuda (1982) have published the revised catalogue of rotational velocities. This catalogue is based on Slettebak's old system. The new system (Slettebak *et al.* 1975) which is more refined is not adopted because a sufficiently large number of stars are not available to calibrate the system. The transformation factor from old to new system is estimated to be 0.81 in B stars from figures of Sletteback *et al.* (1975) and Uesugi (1976). It may be sufficient to adopt this value for the purpose of global statistics of Be stars. In the following, multiplying by this factor to the values of $V \sin i$ in Fukuda (1982), we examine some statistical properties of rotational velocities. Notice also that spectral types adopted by Fukuda (1982) are from Jaschek (1978).

4.1. *Mean rotational velocities*

The mean observed rotational velocities $\langle V \sin i \rangle$ are given in table 2 for normal stars of O7–A9 averaged in suitable spectral ranges and in every luminosity class. Emission-line stars (Oe, Be and Ae) are averaged for the stars of luminosity classes V–III. The number of stars, N, in each group is also given in table 2. It is seen from table 2 that the mean rotational velocities of emission-line stars are apparently

Table 2. Average rotational velocities*

Spectral range	N	V $\langle V \sin i \rangle$	N	IV $\langle V \sin i \rangle$	N	III $\langle V \sin i \rangle$	Em. line stars	N	$\langle V \sin i \rangle$
O 7–9.5	59	128	9	103	21	122	Oe + Oef	12	221
B 0–2.5	297	124	148	95	162	87	Be	132	179
B 3–6.5	275	127	69	93	56	87	Be	65	227
B 7–9.5	349	143	41	131	98	79	Be	42	232
A 0–2.5	628	105	49	68	22	72			
A 3–6.5	279	116	54	99	37	76	Ae, A-shell	8	140
A 7–9.5	114	130	35	103	38	92			

*The values of $\langle V \sin i \rangle$ are transformed to the new system of Slettebak.

much higher than those of normal stars in the respective spectral types, as is well known. The mean rotational velocity has a maximum in the late B-type stars both for normal stars (except stars of luminosity class III) and emission-line stars.

4.2. *Relationship with the break-up velocities*

The distribution function $f(u)$, where $u \equiv V/\langle V \rangle$, has been considered by Fukuda (1982) in detail, assuming a simple step function of u. That is, he assumes that the variable u is distributed uniformly over a range between $(1 - p)$ and $(1 + p)$, where p is a constant $(0 \leqslant p \leqslant 1)$, called the width parameter. Fukuda (1982) has derived the value of p by comparing the model calculation with the observed histogram of rotational velocity u. The result converted to the Slettebak's new system is shown in figure 4, where the length of vertical stripe corresponds to the value of $2p$ around the mean velocity $\langle V \rangle$. The hatched and empty stripes denote the normal main sequence (luminosity class V) and the emission-line stars, respectively. The curve of break-up velocity calculated by Collins (1974) for the field main-sequence stars is also shown. Inclusion of stars with luminosity classes IV and III in normal stars will make the empty stripe shift downward because of lower rotational velocity in luminosity classes IV and III. But its effect may be small because the number of sample stars in IV and III is relatively small.

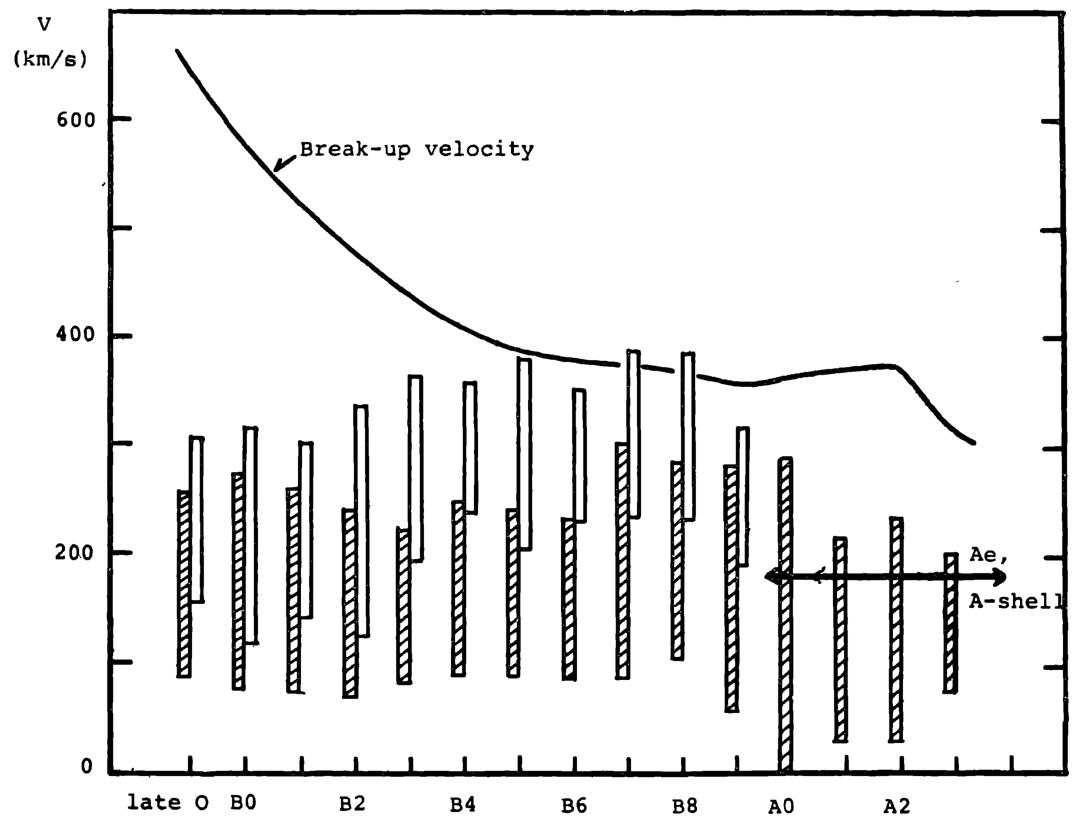

Figure 4. The ranges of distribution of rotational velocity V in km s^{-1} are shown along the spectral sequence. The hatched and empty stripes denote the normal main sequence stars (luminosity class V) and emission-ine stars, respectively. The curve of break-up velocity by Collins (1974) for the field main sequence stars is also shown.

Figure 4 shows that B and Be stars are distributed well below the curve of break-up velocity as a whole, except for the late-type Be stars whose rotational velocities near their upper boundaries apparently overtake the break-up velocity.

The second point concerns the relative position of vertical stripes for B and Be stars : the stripes are mostly overlapping for stars earlier than B3, whereas the stripes of Be stars are definitely higher than those of B stars in the spectral range B3-B9. This behavior implies the existence of a kind of transition spectral-type in B2–B3 in the sense that Be stars earlier than this transition type are not distinguished from B stars in their rotation property, in contrast to later type Be stars which are essentially rapid rotators.

Figure 4 suggests the necessity of some strong trigger mechanism in early-type Be stars. Radiation pressure proposed by Massa (1975) may not play an important role in B0–B2, since there are also many normal B stars with the same rotational velocities as Be stars. Fukuda (1982) alternatively suggested that the role of radiation may become important for stars earlier than or equal to B2, which is the spectral type with the maximum relative fraction of Be/B, in the sense that radiation pressure prevents the formation of permanent cool equatorial envelope (see Massa 1975). It may be expected that the radiation pressure acts as an acceleration mechanism in the hot, high-speed expansion region of Be stars.

5. Binary nature

It is well known that a number of Be stars are spectroscopic binaries and their spectroscopic behaviour is deeply related to their binary nature. Křiž & Harmanec (1975) and Harmanec & Křiž (1976) have presented as an extension of this evidence a general hypothesis that *all* Be stars are mass-exchanging binaries. Harmanec (1982) argued for the binary models of Be stars based on the recent observational results. Plavec & Polidan (1976) and Plavec (1976b), opposing such a generalization, have argued that Be stars involve two categories, of single Be stars and mass-exchanging binaries. At the same time Plavec & Polidan (1976) have drawn attention to a close relationship between Algols and Be binaries in the sense that they are both semi-detached systems. In this section, we first consider the relationship between Algol binaries and Be stars, and then, the binary nature of Be stars.

5.1. Algols and Be binaries

Let us consider the statistical properties of Algols based on the general catalogue of variable stars (GCVS, Kukarkin *et al.* 1969, 1970).

In GCVS, Algols are defined by the shape of light curves and designated by EA, as distinguished from β Lyr type (EB), W UMa type (EW) and elliptical eclipsing binaries (Ell). If we suppose that Algols are mass-exchanging semi-detached systems, then they are also found in EB. The class EW may be excluded from the category of Algols, since their spectral types are usually later than F.

The period distribution of EA, EB and EW are shown in figure 5. The total number of stars with known orbital periods and the mean periods are given in table 3.

The spectral distribution of EA, EB and EW, for which the HD spectral types of the primary components are known, are illustrated in figure 6. Sharp concentration

Table 3. Total number of eclipsing binaries and mean period in GCVS

Type of eclipsing binaries	Total number	Mean period (days)
EA	2101	2.81
EB	460	1.22
EW	381	0.557

of EA in early A type and broad concentration of EB in early B—middle A is remarkable. The former was already pointed out by Plavec & Polidan (1976).

The survey of Hα emission for Algols is very incomplete at present. This is because EA and EB in GCVS are generally fainter than 10th mag and also the appearance of Hα emission usually depends on the phase of orbital motions. Plavec & Polidan (1976) have made a spectral survey for 46 Algols. Their results are summarized in table 4, from which one may see that (a) the Hα emission has been detected for more than 50 per cent of Algols in their light maximum, minimum, or in both, (b) the Hα emission tends to appear in Algols with longer orbital periods. Actually, Peters (1980) found Hα emission in almost all Algols with orbital period longer than 6 days.

Although it is not certain whether Algols with longer periods are continuously connected to Be/Ae stars or not, it is certain that there is no sharp boundary between them. Then if we include the emission-line Algols to the category of Be/Ae stars,

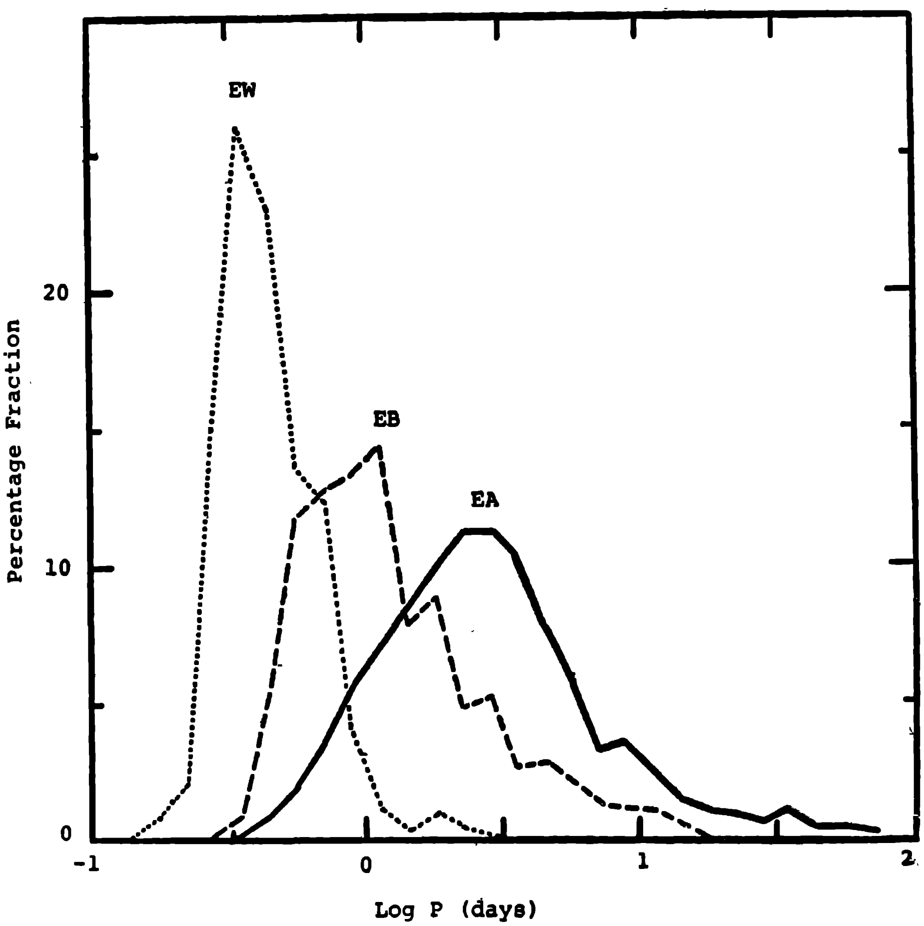

Figure 5. The period distributions of eclipsing binaries in EA, EB and EW classes in GCVS.

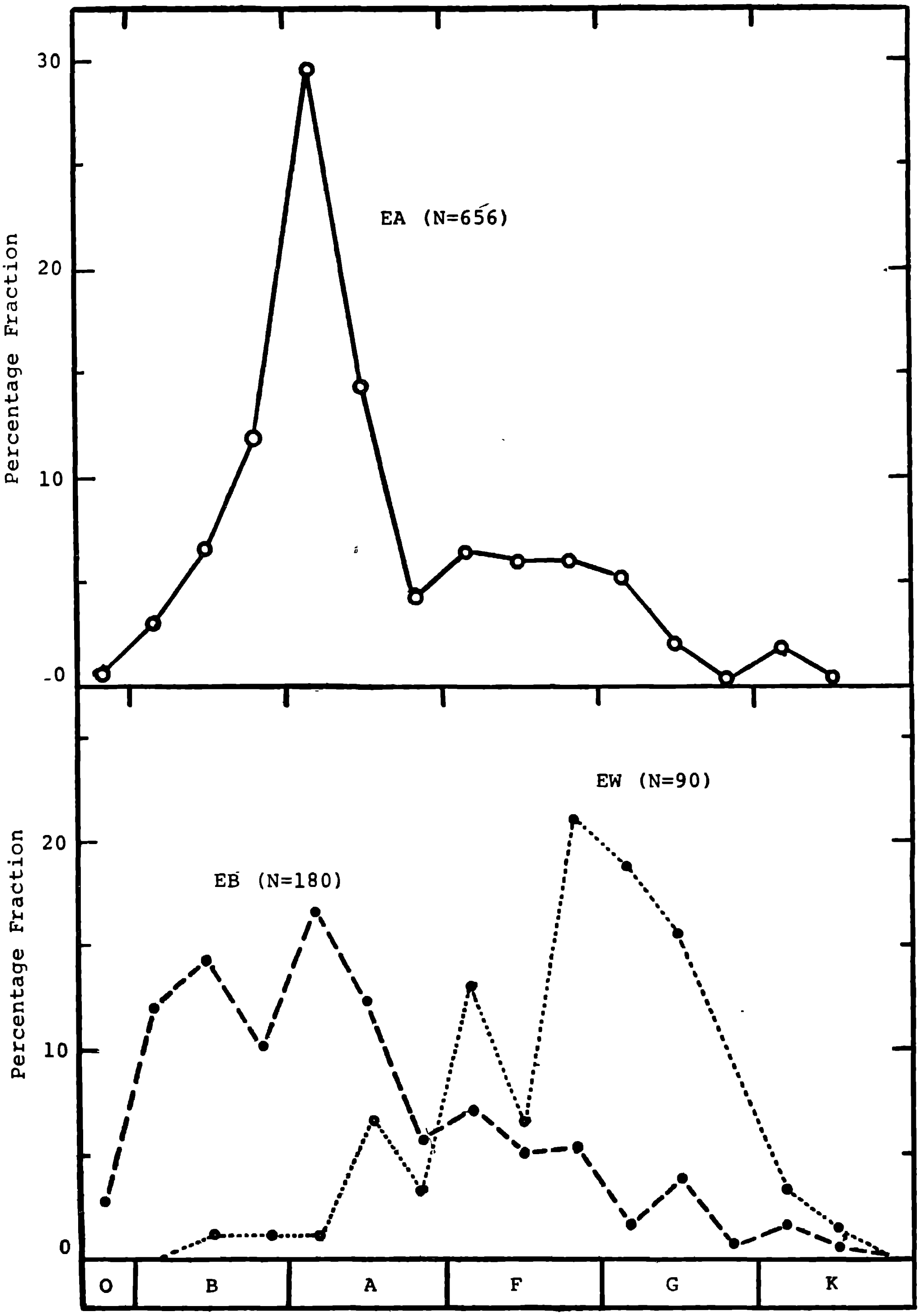

Figure 6. The spectral distribution of eclipsing binaries in EA, EB and EW classes in GCVS. The upper panel exhibits EA ($N = 656$), the lower panel gives EB ($N = 180$) and EW ($N = 90$).

the percentage fraction of Be/B in the late-type tail in A stars will be increased appreciably. In GCVS, the number of Be and Ae stars found in EA and EB classes is very limited and makes any statistical study difficult. Effective survey of faint emission-line stars is desirable.

Table 4. Algols at Hα (Plavec & Polidan 1976)

E/A^* \ Period (d)	<5	5–10	10–20	20–	Total
E	8	5	11	2	26
A	13	3	0	1	17
Total	21	8	11	3	43

*E : Hα emission is detected in the light maximum or minimum, or in both.
A : Hα emission is not detected.

5.2. Statistical grouping of Be binaries

Kogure (1981) has shown, based on Batten's catalogue of spectroscopic binaries (Batten *et al.* 1978), that the non-supergiant Be stars can be statistically separated into two groups of short-period ($P < 30$ d) and long-period ($P > 30$ d) binaries. The grouping can be seen in the rotational-velocity *vs* orbital-period relation shown in figure 7. The short-period group is well mixed in distribution with non-emission line stars and they are closely related to the Algol binaries. In contrast, the long-period group occupies the highest part of $V \sin i$ in figure 7, where the rapid rotation plays an important role in the formation of envelopes.

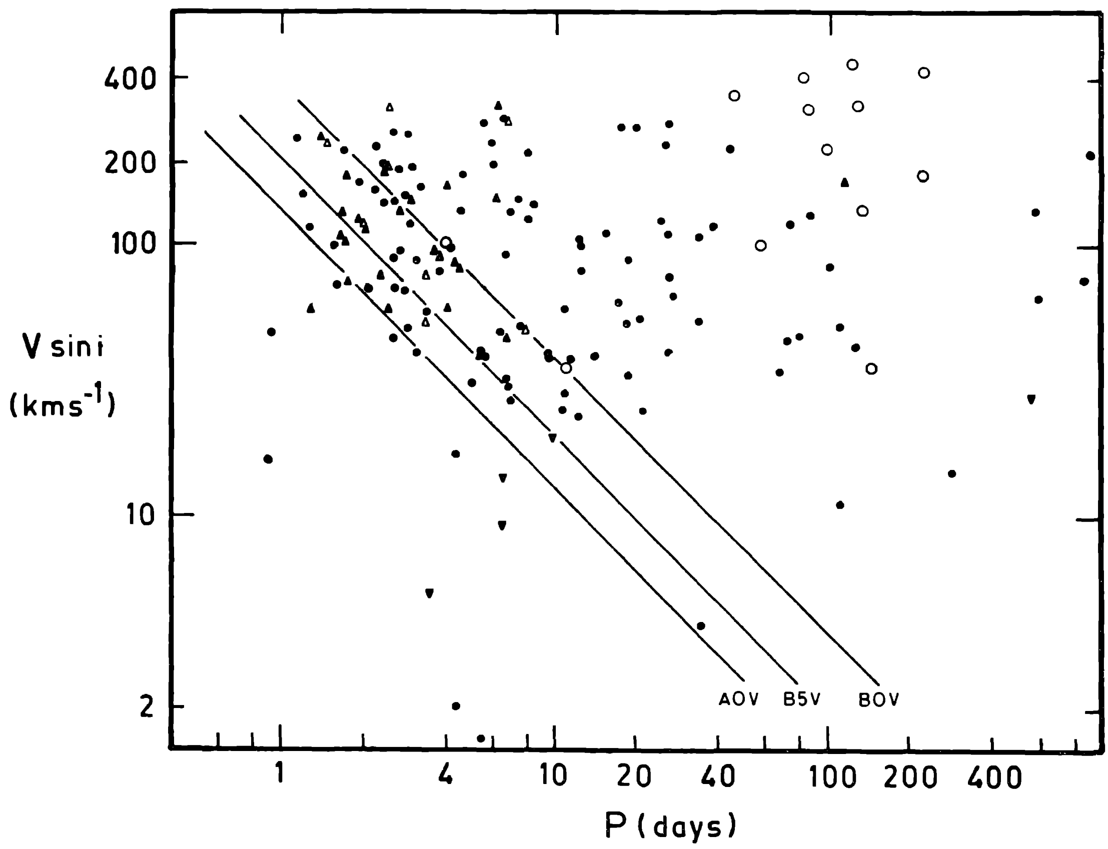

Figure 7. The period-rotational velocity relation for the spectroscopic binaries of B0–B9, V–III. Circles and triangles indicate the noneclipsing and eclipsing binaries, respectively. The inverted triangles denote B_p stars. The emission-line stars are designated by open marks in each case. The lines of synchronization between axial rotation and orbital motion are also shown. (Reproduced from Kogure 1981).

In this way Kogure (1981) has suggested that Be stars in the short-period group are essentially the Algol binaries and may belong to a typical case of interacting binary systems, whereas Be stars in the long-period group are in its essence included in the category of rapidly rotating single Be stars. This conclusion supports the argument of Plavec (1976b) on the two possible categories of single and binary Be stars.

Harmanec (1982) has criticized the above conclusion on two counts, *viz.* : (a) the selection effect in the statistics, and (b) the exclusion of supergiant stars. As for point (a), the survey of Hα-emission stars in spectroscopic binaries may be actually very incomplete at present. However, if we consider the period distribution of spectroscopic binaries with sharp maximum in $\log P$ (d) $\sim$ 0.5, the detection of Be stars in this period range will not affect the conclusion of Kogure (1981). As for point (b), we again emphasize the categorical difference between supergiants and non-supergiants in Be stars in accordance with the definition of Jaschek *et al.* (1981).

5.3. Binary nature of Be stars

In his review article Harmanec (1982) has convincingly argued for the binary models of Be stars. The essential point of binary models is that Be envelopes are formed by the matter transferred to the B stars from the other components of the binary system. According to this picture the ruling parameters of the Be star phenomena are (i) the orbital period, which determines the size of the Roche lobe, and (ii) the strength of mass transfer which depends on the masses and the mass-ratio of the binary system. Stellar rotational velocity becomes a secondary feature as a consequence of angular momentum transfer. Harmanec (1982) has also shown that many Be star phenomena, such as long-term RV (radial velocity) and V/R variations (asymmetry of violet and red components in emission lines), can well be interpreted as the results of binary interaction. Also, interacting binaries in the sense of binary hypothesis do exist in stars which were thought to be *classical Be stars, e.g.*, HR2142 (Peters 1976). The problem is then whether *all* Be phenomena including the statistical nature presented in this article can be attributed to such binary interaction or not.

From the opposite point of view, the problem can be stated as whether most B stars, if not all, can form their envelopes as a result of internal causes, usually aided by rapid stellar rotation. In order to answer this question one has to confirm one of the following pieces of evidence : (i) the existence of single Be stars, (ii) the existence of binary systems in which the Be star is the mass-losing component, and (iii) the direct evidence of mass supply from B star.

Among these, the confirmation of evidence (i) is difficult, since, unless we can get a close approach to the candidate star, there always remains the possibility of duplicity. As for evidence (ii), we can point out some examples of mass-losing Be stars in Be/x-ray binaries (Rappaport & van den Heuvel 1982, section 6), though they may not be typical Be stars. Concerning evidence (iii), spectroscopic observation at the time of envelope formation might give a new evidence on the single star or binary hypothesis.

If there are two categories—single and binary—of Be stars, the origin and structure of their envelopes should not be the same : one is formed by the process of mass outflow, and the other by the opposite process of mass accretion. In spite of this difference, the Be star phenomena look very similar in all cases. At least we could not sharply separate these two kinds of phenomena from spectroscopic observations (Plavec 1976a). The relationship between the two kinds of phenomena merits study.

6. Hot plasma phenomena

With the development of space observations it has become evident that Be stars often reveal some hot plasma phenomena through x-ray emission and UV spectra. The phenomena imply the existence of a hot region, with a temperature much higher than that of the photosphere and of the extended cool equatorial envelope, the latter being responsible for the formation of Balmer emission lines or the shell absorption lines. The structural relationship between hot region and cool envelope constitutes a basic problem in the study of Be stars. We shall take a brief look at these phenomena.

6.1. X-ray emission

The CGS catalogue (Bradt *et al.* 1979) compiles x-ray and optical data of various kinds of strong x-ray sources which have been observed by Uhuru, Copernicus and other satellites and rockets. Einstein satellite has extended survey observations to weaker x-ray sources (Vaiana *et al.* 1981; Long & White 1980). These and later observations have revealed that there are many galactic x-ray sources associated with B and Be stars. Among them, we pay special attention to the B and Be stars of luminosity classes V–III, which may be closely connected with the Be star phenomena we are considering here.

In order to get an overall view of the x-ray sources, we have prepared the log L_x versus spectral-type relation from available data sources, where L_x denotes the x-ray luminosity. The relative luminosity L_x/L_{op}, where L_{op} denotes the optical luminosity calculated by Allen (1973), is also derived. Figure 8 exhibits the relation for B and Be stars. The main sources of x-ray luminosity and the observed energy ranges are as follows : CGS (Bradt *et al.* 1979) in 2–11 keV; Vaiana *et al.* (1981) in 0.3–3.5 keV; Long & White (1980) in 0.15–4.5 keV; Peters (1982b) in 2–6 keV, and Rappaport & van den Heuvel (1982) in 2–10 keV. We include the possible x-ray sources of Peters (1982b).

Since the energy range is different for different observers as seen above, the deduced values of L_x are not uniform. The methods of reduction are also varied. Taking these inhomogeneities into account, we make only some qualitative arguments from figure 8.

(i) There are in principle two classes of strong and weak x-ray sources, the boundary being $L_x \sim 10^{34}$ erg s^{-1}. As has long been known, strong sources should be x-ray binaries containing neutron stars or blackholes. The presence of an x-ray pulse, which is a direct evidence of the presence of a neutron star is also the prevailing feature for the strong sources in figure 8. From the viewpoint of B and Be stars, one may notice that these stars are the mass-losing components in the binary systems, implying that the Be star phenomena in these systems are different from the Algol-type binary interaction. Moreover, according to Rappaport & van den Heuvel (1982), most of Be/x-ray binaries are the detached system with primary masses of less than 20 $M_\odot$.

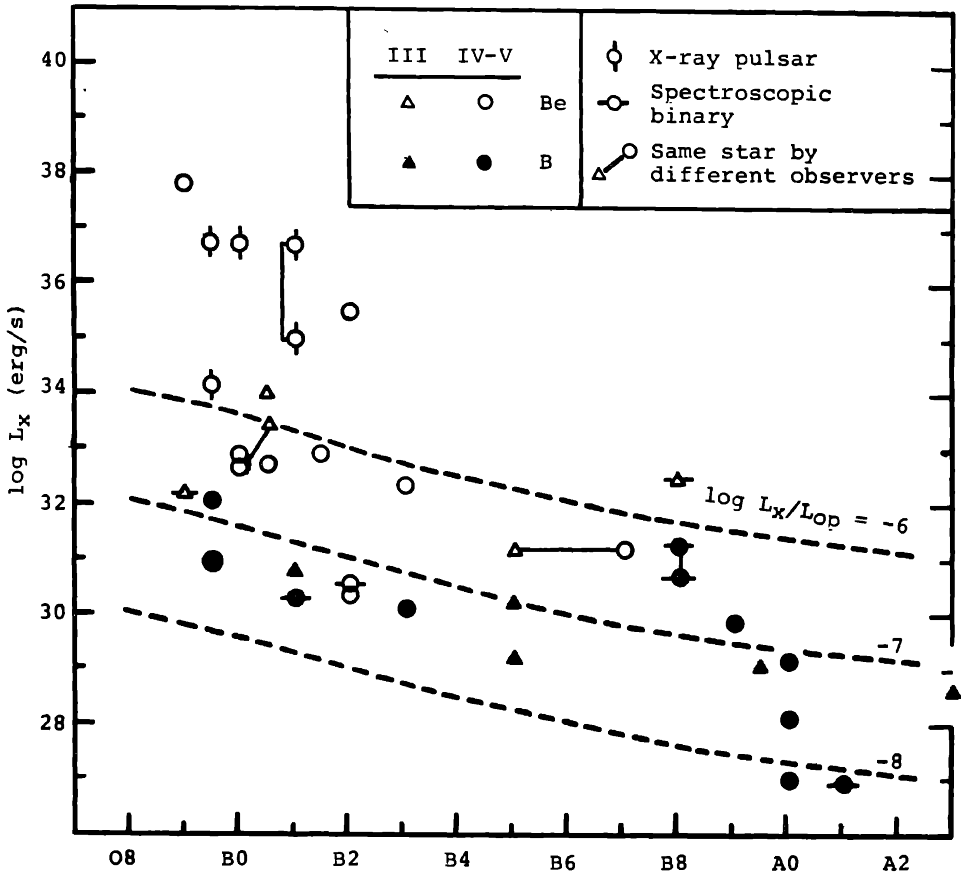

Figure 8. Spectral dependence of x-ray luminosities in B and Be stars of the luminosity classes V, IV and III. The curves of constant relative luminosity log (L_x/L_{op}) are also shown.

(ii) For the weak x-ray sources one has first to mention that most of Be stars may belong to this class, and that they radiate the x-ray energy below the present detector limit. For example, the number of Be stars which showed detectable x-ray luminosities is only 7 out of 32 stars listed by Peters (1982b). In figure 8, the normal B stars are distributed in a range of log $L_x/L_{op} = 10^{-6} \sim 10^{-8}$ with an approximate average of 10^{-7}, in accordance with the relation of Vaiana (1981) and Pallavicini *et al.* (1981). In contrast, Be stars seem to have somewhat higher values of L_x/L_{op} than normal B stars. This conclusion, however, is only a tentative one, because of the inhomogeneity of the data sets.

(iii) The Be stars with detectable x-ray luminosities are mostly concentrated toward spectral types earlier than B3, independent of strong and weak x-ray sources. Exceptions are κ Dra (B7 IVe or B5 IIIe) and HD 187399 (B8 IIIe). As against this, in the case of normal B stars x-ray sources are rather concentrated towards late-type B stars. For the stronger Be/x-ray binaries, this evidence might be attributed to some evolutionary scenario of binary formation which leads to the formation of compact components as a result of some suitable initial conditions.

(iv) As for the relationship between x-ray luminosity and the stellar rotational velocity or the binary nature, the present data seen in figure 8 are very insufficient and future study will be highly appreciated, the spectral type dependence mentioned above also deserves further study.

6.2. *Superionization in the UV region*

UV observations of OB stars brighter than $M_{bol} = -6$ have revealed the existence of resonance lines due to ions in high stages, such as Si IV, C IV, N V and O VI, which are not produced in the photospheres of these stars. This phenomenon, which is called 'superionization', can also be seen in Be stars. In both cases, the superionization phenomena are closely connected with the high-speed expansion of ions concerned.

Marlborough (1982) has given a nice review on the present state of ultraviolet observations of Be stars. In this article we pay our attention to the strong parallelism of superionization between Ia-supergiants and Be stars, which is shown in figure 9 (Cassinelli & Abbot 1981, Marlborough 1982).

Apparent parallelism may suggest the common origin of superionization phenomena for rather different types of stars such as supergiants and Be stars.

In connection with the interpretation of superionization phenomena of OB stars brighter than $M_{bol} = -6$, a number of models have so far been proposed (*cf.* Cassinelli *et al.* 1978; Conti & de Loore 1979). However, none of these models in their original forms can explain the x-ray emission detected by the Einstein satellite (Harnden *et al.* 1979; Vaiana *et al.* 1981). In the case of thin corona + cold wind model (Cassinelli & Olson 1979), the absorption in the soft x-ray region is too strong (Nordsiek *et al.* 1981; Cassinelli *et al.* 1981). To overcome this difficulty, some modification has been introduced, such as clumpiness (Stewart & Fabian 1981), and warm regions (Waldron 1982). The other models proposed recently are the magnetically confined corona analogous to solar corona (Rosner & Vaiana 1980; Vaiana 1981), and shock or turbulence heating due to wind instability (Lucy & White 1980; Lucy 1982; Kahn 1981). In Be stars, there are also cool envelopes around the equator, which make the problem complicated. The geometrical as well as physical structure of those cool-hot regions of Be stars deserve further examinations which will be given in part II of this article.

7. Mass loss phenomena

Mass loss process in stellar surface is a prevailing phenomenon over a wide spectral range from the earliest down to the latest types. Be stars are also not exceptional.

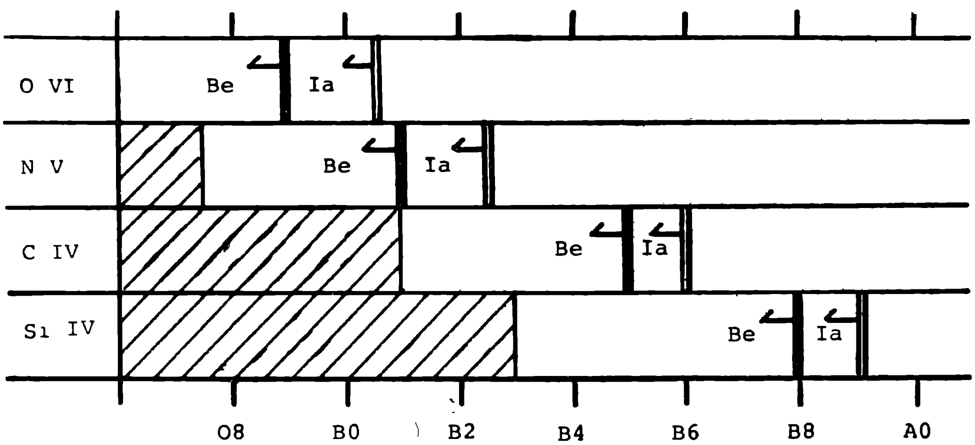

Figure 9. Superionization phenomenon in Be stars and Ia supergiants. Each ion is detected in earlier than or equal to the spectral type designated by arrow. These ions are present in the photosphere in the hatched area of the figure.

We can observe a number of mass loss phenomena, like line-shift and line-asymmetry, in Be stars, but their actual processes are not well known at present.

Before discussing the problems of Be stars, we shall comment on the observations of Furenlid & Young (1980) for normal B stars. They have observed the line profiles of Hα in 60 normal dwarfs of B0–B3. According to them, rapidly rotating stars ($V \sin i > 200$ km s^{-1}) always disclose the blue-winged asymmetric profiles, and the stars with $V \sin i < 100$ km s^{-1} do not show any noticeable line asymmetry. This evidence suggests that the mass-loss process in B0–B3 dwarfs is restricted to stars rotating faster than $V = 200$ km s^{-1}, and that mass loss process occurs in the direction of equational plane. Snow (1981) has detected in UV spectral region asymmetric profiles in Si III and/or Si IV lines for three normal B dwarfs with $V \sin i \simeq 150$ km s^{-1} (new Slettebak system) in the same spectral range.

The value of $V \sin i = 200$ km s^{-1} in Furenlid & Young (1980) corresponds to $V \sin i = 165$ km s^{-1} in the new Slettebak system. It may be interesting to see again the distribution of rotational velocities in figure 4. One may notice that the lower boundary of rotational velocities V of Be stars in the spectral range B0–B3 ranges in $130 \sim 200$ km s^{-1}, which is nearly the same as 165 km s^{-1} given above. This coincidence is very suggestive, and one may imagine that all main sequence stars of spectral types B0–B3 lose mass if the rotational velocity exceeds 150 km s^{-1} or so, and that such stars have a possibility to become Be stars when some other suitable conditions are fulfilled. The extension of Furenlid & Young's (1980) observation to stars later than spectral type B3 and the UV observation of normal B stars are highly desirable.

We now proceed to the mass loss rate $\dot{M}$ from Be stars. In Be stars, the circumstellar gas, which emits radiation in lines, continuum and in polarized light in the visual and infrared spectral region, seems to form cool, disk-like envelope around the stellar equator. Since the velocity field in these envelopes is usually dominated by rotation component, the estimation of mass loss rate $\dot{M}$ from the direct measurement of radial motion is generally difficult. One possible way to estimate mass loss rate $\dot{M}$ is the model fitting of line profiles under the single star hypothesis. The mass loss rate thus found lies in a range of 10^{-7} to 10^{-9} $M_\odot$ yr^{-1} (Marlborough 1976). The estimation of envelope mass in the course of the time development of Be envelope is another possible way. The mass loss rate thus found, or more precisely the mass accumulation rate is $\sim 5 \times 10^{-11}$ $M_\odot$ yr^{-1} for the recent shell phase of Pleione (Higurashi & Hirata 1978; Hirata *et al.* 1982a), or $\sim 5 \times 10^{-9}$ $M_\odot$ yr^{-1} for EW Lac (Kogure *et al.* 1982). It is also to be mentioned that the mass loss process in Be stars is rather intermittent and highly variable.

In the UV spectral region, the asymmetric resonance lines also indicate the mass loss which may be different from those derived from optical spectra, since the UV spectral lines correspond to some hot region accompanying high velocity winds. Snow (1981, 1982) has made a systematic survey of mass loss rate of B and Be stars with the aid of UV resonance lines (Si III, Si IV). His results are illustrated in figure 10, together with those for 0B stars of $M_{\rm bol} < -6.0$ (Lamers 1981a; Abbot *et al.* 1981; Garmany *et al.* 1981).

For luminous OB stars brighter than $M_{\rm bol} = -6$, the mass loss rates are strongly dependent on their luminosity and show a tendency to increase with stellar evolutions

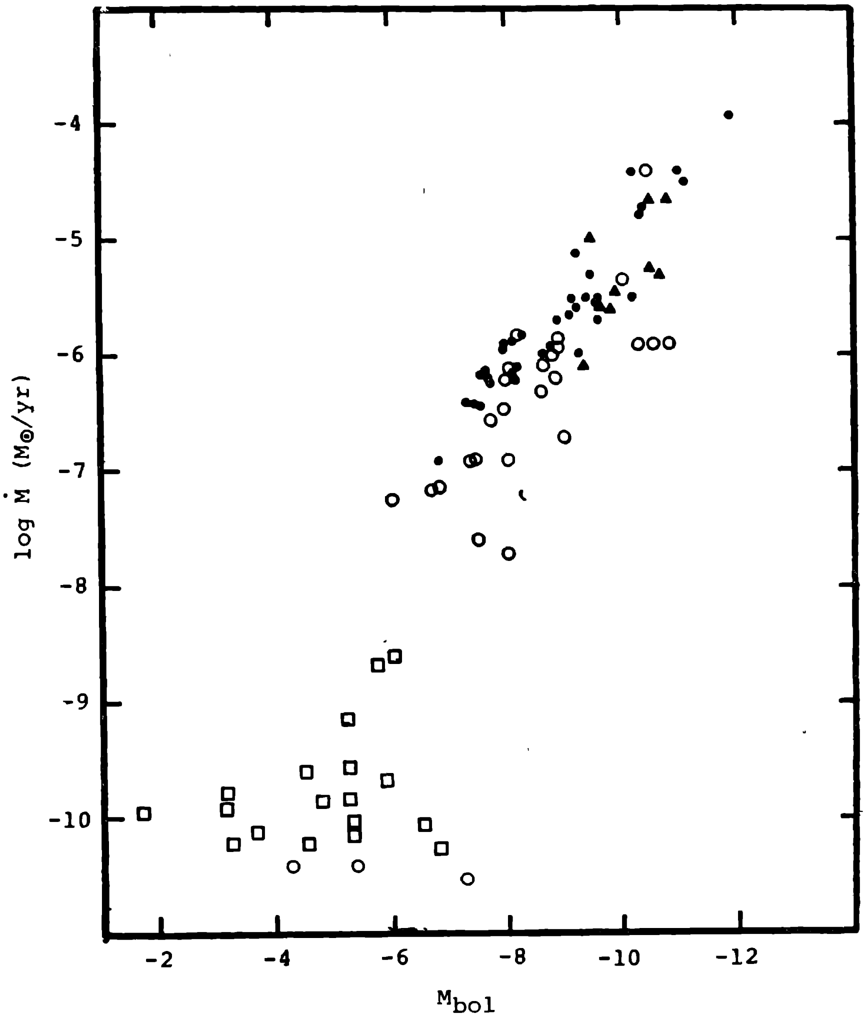

Figure 10. Mass loss rate in OB stars. Symbols: ●, supergiant (I ~ II); ○, giant, dwarf (III ~ V); ▲, Of star without luminosity designation; □, Be star.

(see figure 10). B and Be dwarfs exhibit the mass loss rates in the range of $10^{-11} \sim 3 \times 10^{-9}\ M_\odot\ yr^{-1}$, and these values fall on the smooth extrapolation of the O-type dwarfs in the order of magnitude, though the scatter is large. No correlation is found between $\dot{M}$ and M_{bol}, T_{eff} or $V \sin i$ (Snow 1981, 1982). Highly variable nature of Be stars in the UV region probably prevents one from finding any correlation between the mass loss rate and stellar parameters. In deriving the mass loss rate, Snow (1981) has postulated the spherical symmetry of mass flow, which may often give rise severe effect on the estimation of $\dot{M}$ in Be stars. Geometry of the formation region of UV resonance lines should be fully considered for the next step.

Remarks should also be made on the expansion velocities in Be stars. Dachs (1980) has measured the blue edge velocity of the C IV and Si IV resonance lines for eight Be stars and obtained the expansion velocity ranging from 600 to 1100 km s^{-1}. Other values from the UV observations are summarized by Marlborough (1982), according to which the range is from a few hundred up to one thousand km s^{-1}. Snow (1981) has also derived the terminal velocity V_∞ in the range of 550 ~ 1100 km s^{-1} for most Be and B stars examined.

The ratio $\alpha = V_\infty/V_{esc}$, where V_{esc} denotes the escape velocity from the stellar photosphere, has so far been deduced in various types of stars. In B and Be dwarfs, α takes the value ranging from 0.7 to 1.8, with appreciable concentration at unity, but without showing any dependence on stellar parameters (Snow 1981, 1982). This is compared with the case of OB stars brighter than $M_{bol} = -6$, for which variation in α depends on the spectral sequence. That is, the value decreases from $\alpha = 3$ for O stars down to $\alpha \sim 0.5$ for A-type supergiants (Lamers 1981b; Cassinelli & Abbot 1981; Garmany *et al.* 1981). These figures show that the values of α in Be and B dwarfs are rather moderate ones.

The values of $\alpha \sim 1$ derived from UV resonance lines are still remarkably high in Be stars as compared with optical observations. The expansion velocities deduced from the optical lines of Be stars seldom exceed 100 km s^{-1} even in some very active phases of spectral variations. In contrast, expansion velocities of normal B dwarfs are rather high even in optical region: Furenlid & Young (1980), using the Hα profile, have derived the expansion velocities in a range from 150 to 600 km s^{-1} for rapidly rotating B stars. They have attributed the Hα expansion region to the bottom of the high-speed stellar wind.

In connection with the structure of stellar winds, it may be worthwhile to mention the relationship between the expansion velocity and the ionization structure of envelopes in B and Be stars. In normal B dwarfs, inspite of x-ray source phenomena which can be seen throughout the range B0–B9 (figure 8), the superionization phenomenon is restricted to the subclass of B1 or earlier (Marlborough 1982). Besides, the high-speed expansion is detectable down to B3 among rapidly rotating stars (Furenlid & Younng 1980, Snow 1981). In this way, the stellar winds of B dwarfs later than B1 in rapid rotation may be characterized by the existence of high-speed hot regions which are undetectable in the UV region.

In case of Be stars, the expanding velocities are high in hot regions and low or absent in cool regions. The high-speed expansion is not restricted to the equator-on Be stars, but is also seen in the pole-on Be stars (Peters 1982c). And, the superionization phenomenon is detectable down to B8e (figure 9).

8. Variability

The key to the nature of Be-star phenomena lies in its variabilities. A large amount of observational data has so far been accumulated on the variable nature of line, continuum and polarization in a wide spectral range including x-ray and IR radiations.

We begin with defining the two terms E/C-variation and V/R-variation, which we often encounter when we speak of Be star variabilities. *E/C variation* is the time variation of emission-line intensities relative to the adjacent continuum. There are two possible cases of E/C-variation, one the true variation of emission-line radiation, and the other the variation of continuum level (*i.e.* the brightness variation). The so-called *veiling effect*, which occasionally appears in early type Be stars, is a direct spectroscopic consequence of the latter case (*e.g.* Hubert-Delplace *et al.* 1982a). *V/R-variation* is the time variation of relative intensities of violet (V) and red (R) components in double-peaked emission-line profiles. V/R-variation is expressed in such ways as the ratio of emission equivalent widths of respective components, or the ratio of respective emission-peak intensities relative to the adjacent continuum.

The variability of Be star phenomena generally takes place in an irregular manner which lacks strict periodicities. Exceptions are the orbital periods of Be binaries and the short-term variations on a time scale of a day which are observable in some Be stars (see later). In many Be stars, we can also follow several kinds of variabilities in various forms and on various time scales even for a particular star. A typical case is γ Cas, the brightest northern Be star, for which time scales and their corresponding phenomena are summarized in table 5.

Among the variations on various time scales, no general tendency has been yet established for the variation on time scales shorter than months or a year. So, we mainly focus our attention to long-term variations.

Table 5. Timescales and phenomena observed in γ Cas

Timescale	Year observed	Phenomena	Source of reference
$\sim$ hour	1973	H_β, H_γ-profiles	Doazan (1976)
a few hours	1973, 1977	*UBV*-polarization degree	Piirola (1979)
a few hours	1977	Sudden increase of emission intensities of H_α, UV–Mg II, Si IV	Stettebak & Snow (1978)
hours $\sim$ days	1974	H_β-profile	Clarke *et al.* (1975)
$\sim$ 0.7 days	1969	H_γ-profile	Hutchings (1970)
$\lesssim$ day	1966	H_β-profile	Slettebak (1969)
hours $\sim$ months	1975–1976	H_α-intensity	Slettebak & Reynolds (1978)
a week $\sim$ a month	1980	UV-shell expansion	Henrichs (1982)
< 1 year (?)	1971–1973	Variable x-ray intensity	Peters (1982b)
3.0–3.5 years	1927–1935	Fluctuation of E/C (H_β)	Kitchin (1970)
4 years	1972–1975	α, β photometric indices	Baliunas & Guinan (1976)
4 $\sim$ 6 years	1967–1980	V/R variation	Hubert-Delplace *et al.* (1982 a)
$\sim$ 5 years	1936-1941	Active phase including two shell phases (E/C, V mag)	Edwards (1956)
5 years	1950–1960	Spectrophotometric gradient	Ivanova *et al.* (1969)
> 30 years	1866–1980	Slow E/C variation	Kitchin (1970), Doazan *et al.* (1980)

8.1. Examples of long-term variations

We first discuss the long-term variations of 59 Cyg and 28 Tau (Pleione) as examples of most spectacular variations in early and late type Be stars, respectively.

59 Cyg (BlVe, $V \sin i$ = 260 km s^{-1} in Slettebak 1982)

Since the first discovery of emission lines in 1904, this star has shown emission components with variable intensities all throughout except in 1912 and 1916 (Doazan *et al.* 1980; Barker 1982a). V/R variations are reported in 1926–1929, 1941–1942 and in 1946–1948 (McLaughlin 1932; Merrill & Burwell 1943, 1949).

Recently this star has shown a remarkable spectral variation (Doazan *et al.* 1980, 1982; Hubert-Delplace & Hubert 1979, 1981; Barker 1982a). After showing a gradual strengthening of emission lines in 1971–1972, 59 Cyg came up with rich shell lines in 1973 June, which constituted the first shell phase, in which strong shell absorption lines were detected in the Balmer lines (up to H30), He I, Mg II, and in some singly ionized metals (Doazan *et al.* 1975; Hubert-Delplace & Hubert 1981). In the period 1973 December–1974 July shell lines changed to strong emissions with *apparently* single peak. With the declining of emission components and the appearance of double emission peaks, 59 Cyg proceeded to the second shell phase in 1974 October, which lasted till 1975 March. In figure 11 are illustrated the variations of *E/C*, *A/C*, *V/R*, and peak separation of double emission components of Hβ, and the radial velocity of shell lines in and near the second shell phase, based on Hubert-Delplace & Hubert (1981) and Barker (1982a). In figure 11, *E/C* denotes the peak intensity of Hβ when it has apparently single peak profile, or the average peak intensity of violet and red components when it has double peak profile, both relative to the adjacent continuum. *A/C* denotes the intensity of central dip which gives a measure of shell line strength in the shell phase. Stellar velocity ($v_* = -23$ km s^{-1}) is adopted from Barker (1982a).

As seen in figure 11, the shell absorption feature becomes apparent when v, the radial velocity of the central dip, takes its minimum value (~ -100 km s^{-1}). The shell phase reached its maximum state in 1974 December when v was back to the value of v_*. In 1974 October-December, the lines showed the P Cyg profiles in general. Later on, the emission components once weakened, double-peaked, and

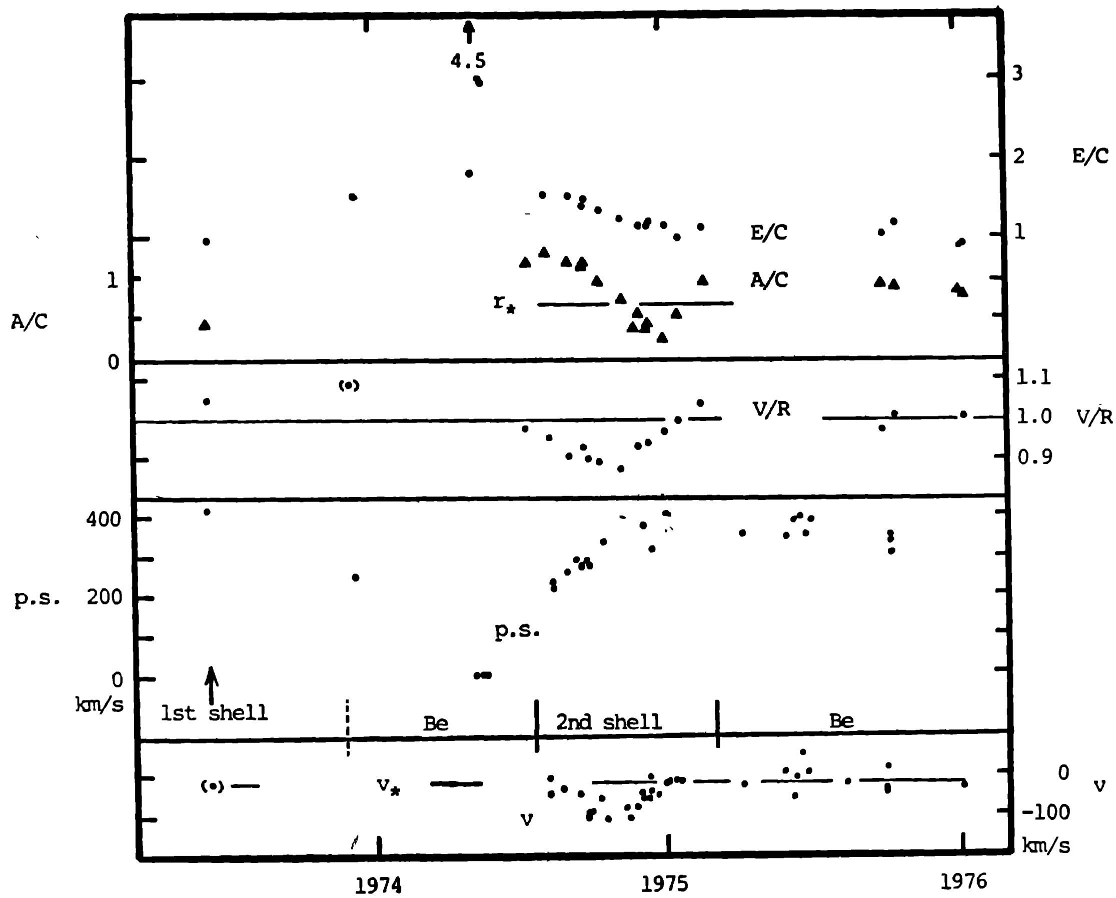

Figure 11. Variation of Hβ line in recent active phase of 59 cyg. See text for the definition of *E/C*, *A/C*, *V/R* and peak separation (p.s.). The velocity, v, is the average velocity of all shell lines measured.

even disappeared in 1976–1977, except for Hα. Thereafter the emission components exhibited a recovery (Doazan *et al.* 1980). Barker (1982b) also reports a cyclic *V/R* variation of Hα on a timescale of a few days.

Spectral feature in the UV region is also remarkable in 59 Cyg. First, the UV flux deficiency of 1 mag or even more has been observed in both the first and the second shell phases (Beeckmans 1976; Hubert-Delplace & Hubert 1981). Second, the high dispersion spectrograms revealed remarkable change of radial velocities in N v λ1240, for example, such as -50 km s^{-1} in 1972 October, -180 km s^{-1} in 1975 November, -750 km s^{-1} in 1978 December, $-400 \sim -800$ km s^{-1} in 1979, and $-600 \sim -1000$ km s^{-1} in 1980, with variable multiple-components (Marlborough & Snow 1980; Doazan *et al.* 1980, 1982). According to Doazan *et al.* (1982), UV resonance lines in the superionization state exhibit rather spectacular changes when the emission intensity of Hα becomes weak in Be phase. No high resolution UV spectrum in shell phases was unfortunately obtained. Also, the photometric behavior in the optical region is not known.

In case of 59 Cyg the timescale of spectral variations is short in its active phases as compared to other Be stars, *i.e.* 59 Cyg has experienced two shell phases and a strong-emission phase within about two years. Similar phase-change variations with short timescales are also observable in γ Cas (B0.5) (Merrill & Burwell 1943; Cowley & Marlborough 1968) and ζ Oph (O9.5) (Barker & Brown 1974; Ebbets 1981). These rapid phase changes may be a characteristic of Be stars around the subclass B0 (Barker 1982a).

28 Tau (B8(V :) e-shell, $V \sin i = 320$ km s^{-1} in Slettebak 1982)

In the past 100 years, 28 Tau has shown notable phase changes, *i.e.* Be-phase (< 1888–1903), B-phase (1905–1936), shell-phase (1938–1954), Be-phase (1955–1972), and the present shell-phase (1972—) (see Hirata & Kogure 1976). Gulliver (1977) gives a detailed review of spectroscopic change during 1938–1975. In figure 12 is shown the spectroscopic behaviour of Hβ line in the 50 years 1930–1980, based on Gulliver (1977) and Hirata *et al.* (1982b), and also the variation in B magnitude. The definitions of *E/C*, *A/C*, *V/R* and peak separation are the same as in figure 11. The radial velocity of shell lines during 1938–1954 is adopted from Merrill (1952) and Burd (1954).

The behaviour of *E/C* and peak separation in figure 12 imply that the variability in the emission profiles made one cycle in the 34 years 1938–1972. Then the shell episode, 1938-1954, and the subsequent Be phase 1955–1971, may be regarded as a series of phenomena within one cycle of activity. The magnitude variation of 28 Tau is also worthnoting. The decline of B magnitude in the shell phases is *notable*; the second minimum in 1947 corresponds to the maximum phase of shell episode.

Long timescale of spectral variations is an outstanding feature of 28 Tau, and resembles o And (B6 III), another late type Be star, in which shell episode lasts about 5 yr (Gulliver *et al.* 1980).

8.2. *Statistical nature of long-term variation*

We here present several properties and general trends of long-term variations in the *UBV* photometry, *E/C* and *V/R* variations.

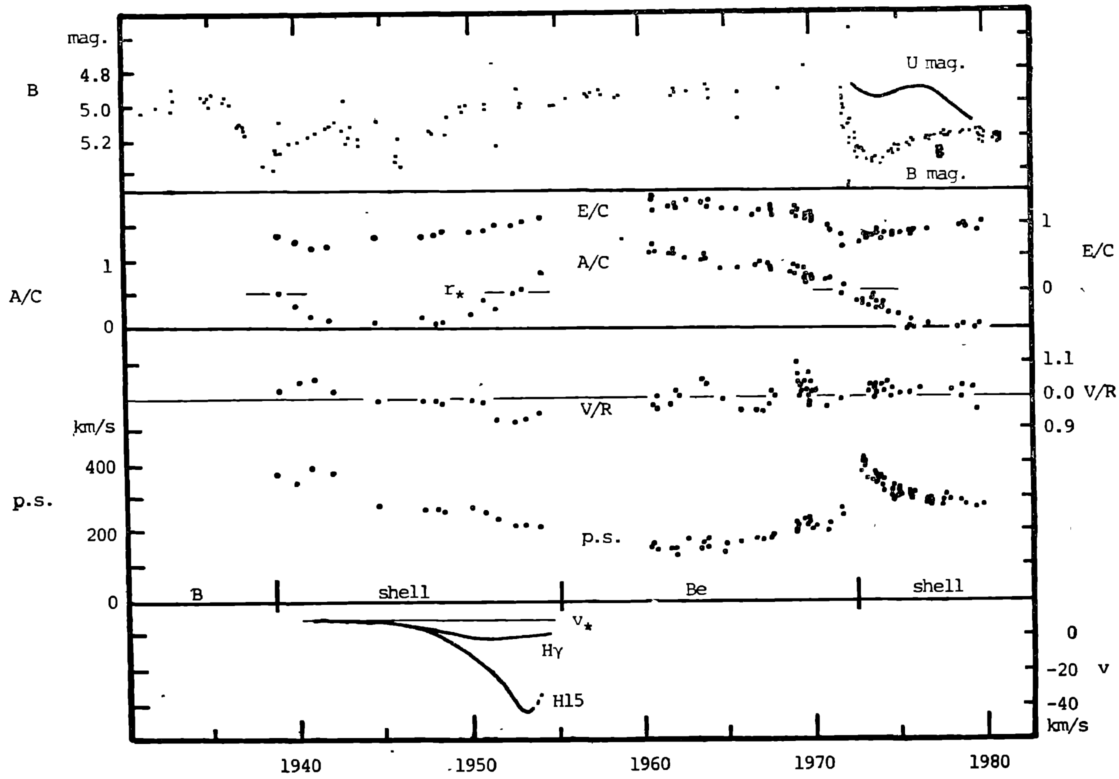

Figure 12. Long-term variation of 28 Tau in 1930–1980. The B-mag. and Hβ-line quantities (E/C, A/C, V/R, p.s.) are shown. The definition of Hβ-line quantities is the same as in figure 11. In addition, the U-mag variation in the present shell phase and the velocity variation of Hγ and H_{15} shell lines in the previous shell phase are schematically shown.

UBV VARIATION

The variability of stellar magnitude is now a well established feature (*e.g.* Feinstein & Marraco 1979). The typical amplitudes of variation ΔV, in V band, are $\Delta V \lesssim 0^{\rm m}.05$ for variations of a day, $\Delta V \simeq 0^{\rm m}.1 \sim 9^{\rm m}.2$ for variations of a month, and $\Delta V \simeq 0^{\rm m}.3 \sim 0^{\rm m}.4$ for variations on the scale of years or longer. Occasionally ΔV exceeds $0^{\rm m}.5$ for some stars. The long-term variations reveal the following general trends (Hirata 1982, Hirata & Hubert-Delplace 1981):

(a) On the colour-magnitude diagram, early type Be stars are getting redder when they brighten, and, inversely, late type Be stars are getting bluer when they brighten. The gradient $\Delta V/\Delta\,(B - V)$ depends on the value of $V \sin i$ in the sense that it becomes larger for larger value of $V \sin i$. (b) The gradients of $\Delta V/\Delta\,(B - V)$ and $\Delta\,(U - B)/\Delta\,(B - V)$ both essentially show the same sign.

E/C VARIATION

Hubert-Delplace *et al.* (1982b) have examined the E/C variations of 140 northern Be stars in a time span of 24 yr. According to them, the fraction of Be stars in which E/C variations are detected is 81 per cent for B0–B5 stars, and 48 per cent for B6–A0 stars. For stars for which the phase change B $\leftrightarrow$ Be is detected, the total span of B and Be phases is $10 \sim 20$ yr in B0–B5 stars and much longer in late-type Be stars. E/C variation in a Be phase often reveals fluctuations, and its timescale is $1/3 \sim 1/5$

of the total span of B + Be. Adding other several pieces of evidence, Hirata & Hubert-Delplace (1981) have suggested that the time scale of E/C is generally shorter in early-type Be stars than in late-type stars.

V/R VARIATION

Most prominent V/R variations also occur in long term variations. Copeland & Heard (1963) in their monitoring observations of 54 northern Be stars for 24 yr have found the V/R variations in two thirds of the observed stars, among which 15 stars have revealed quasi-periodic variations with a mean period of 6.8 yr. Hirata & Hubert-Delplace (1981) have determined the time scale of long-term V/R variations for 28 stars (including those from Copeland & Heard 1963) and found a similar mean period of 7 yr. It seems that the time scale of V/R variations is generally shorter than that of E/C variations. The V/R variations in days or months are reported by Slettebak & Reynolds (1978) and Dachs *et al.* (1981).

It should also be mentioned that the V/R variations sometimes reveal different behaviour in different emission lines. Slettebak (1982) has detected such a qualitative feature in the case of Balmer lines and other lines such as Fe II, *e.g.* Fe II line shows $V < R$ whereas $V > R$ in Balmer lines. Kogure *et al.* (1981, 1982) have found a kind of progression of $V > R$ or $V <$ R feature from higher to lower members of the Balmer series in EW Lac. These behaviours reflect complex structure of the Be star envelopes.

CORRELATION AMONG MAGNITUDE, E/C AND V/R LONG-TERM VARIATIONS

Dachs (1982) and Mon *et al.* (1981) have found the existence of both parallel and anitparallel relations between magnitude and E/C variations. That is, the emission intensity of H_α or H_β increases with the brightening of a star in the case of parallel relationship, and vice versa in the antiparallel case. The correlation between magnitude and V/R variations has been examined by Hubert-Delplace *et al.* (1982b) who found antiparallelism in three stars (V/R becomes smaller with the brightening of a star, or vice versa). Hirata & Hubert-Delplace (1981) report that 228 Eri and γ Cas are in parallel relationship between magnitude and E/C variations, and V/R variation appears in a phase of stable state in magnitude and E/C variations. Anyway, observational material is still very insufficient to detect or to discuss these relationships statistically.

8.3. Quasi-periodic variations

One of the Be star phenomena which has received wide attention in recent years is the quasi-periodic variation on the time scale of a day. Table 6 gives a list of Be stars which show such quasi-periodic variations in their photometric or the spectroscopic behaviours. Among the listed stars, strict periodicity seems to be well established in the radial velocity of λ Eri and 28 CMa, and in the magnitude of λ Eri and 19 Mon. Balona & Engelbrecht (1979) identified 19 Mon as a β Cep type star.

As an interpretation of these (quasi-) periodicities, nonradial pulsation has been suggested by Percy *et al.* (1981), Baade (1982a) and Bolton (1982). Baade (1981) has emphasized the relationship with 53 Per stars. The short-term light variations in rapidly-rotating normal B stars are reviewed by Jerzykiewicz & Sterken (1982).

Table 6. Be stars which show the short-time, quasi-periodic variation

HD	name	sp. type	$V \sin i$*	Period (day) photometric	Period (day) spectroscopic	Sources
212571	π Agr	B1 III-IVe	300	~ 0.1	0.887	Fernie (1975), Ringuelet & Machado (1974)
13890	—	B1 III	150	1.24		Hill (1967)
52918	19 Mon	B1.5III	270	0.191, 0.197		Balona & Engelbrecht (1979)
58050	—	B2V	105	0.125 or 0.143		Figer (1981)
33328	λ Eri	B2 III (e) p	220	0.702	0.702	Balona (1977), Bolton (1982)
189687	25 Cyg	B2.5V (e)	200	~ 0.2		Percy *et al.* (1981), Percy (1981)
56139	28 CMa	B2.5Ve	80	0.435	1.36	Baade (1982a, b)
191610	28 Cyg	B3IVe	320	~ 0.7		Spear *et al.* (1981), Percy (1981)
217050	EW Lac	B3 : IV : e-shell	300	~ 0.7		Walker (1953), Lester (1975), Percy (1981)
224559	HR 9070	B4Vn	—	~ 0.25	var	Percy (1979, 1981), Percy *et al.* (1981), Fraquelli (1979)
42549	69 Ori	B5Vn	300		~ 1.3	Bossi *et al.* (1982)
212675	o And	B6III	260	0.8, 1.6	0.8, 1.6	see refs in Baade (1981)

*The values are in the new Slettebak system.

Although the relationship between quasi-periodic short-term variations and long-term variations hitherto mentioned is still unclear, one possible interpretation is the excitation of nonradial pulsation through the shear instability as a consequence of release of rotational energy in a strongly-differential rapid rotator (Hirata & Hubert-Delplace 1981).

As we have seen, the variabilities in Be star phenomena occur in various forms in various wavelength regions and in various timescales. However, their general tendencies, their mutual correlations and the overall picture are not well understood. A wide network of coordinated observations by many participating observatories is desirable.

The international campaigns proposed by Harmanec *et al.* (1982) for photoelectric observations and by Barker (1982c) for spectroscopic observations are steps in the right direction. The proposal on cooperative UV and visual observations (*e.g.* Doazan *et al.* 1980) is on the same line. We would like to emphasize the need for the x-ray observations to be incorporated in the network of these international campaigns.

9. Summary

After defining a Be star as a B-type dwarf with a cool envelope as detected from its visual spectrum, we have summarized the general characteristics of Be stars. We have paid special attention to the statistical behaviour of Be stars which should be taken into account when considering the structure and origin of Be stars. As stressed frequently, our present knowledge on Be stars is fragmentary. Table 7 summarizes Be star phenomena along the spectral sequence.

The percentage of Be stars among B stars is about 20 per cent for early B stars, and 10 per cent for late B stars. Be stars are distributed over the whole main sequence band from the zero-age main sequence to the core contraction phase (Mermilliod 1982).

The rotational velocity does not reach the break-up velocity in the earlier Be stars. The distribution of Be-star rotational velocities in each spectral type overlaps appreciably that of normal B dwarfs in the spectral types earlier than B3. There are no essential differences in stellar parameters between early B and Be stars except for a

Table 7. Summary

Spectral range	Early Be (O9–B2 or B3)	Middle to late Be (B3 or B4–B8)	Early Ae and A-shell (B9–A3)
Frequency Be/B	$\sim 20\%$ Peak in B2	10% at B8 decrease from B3 to B8	low except Algols
Rotation			
$\langle V \rangle / V_{\text{break-up}}$	small	0.5 $\sim$ 1.0	small
Distribution	mostly overlap in B and Be	Be stars are rapid rotators	
Duplicity			Algol fraction maximum
x-ray			
Strong source	exist	No.?	?
Weak source	many	rare ?	?
Superionization	high	low	absent
Mass loss in UV			
$\dot{M}$	no spectral dependence ?		?
$\alpha = V_\infty / V_{\text{escape}}$	$\alpha \sim 1$		
Variability			
Time scale of E/C	short	long	?

slight difference in the average rotational velocity. That is, there exist normal B and Be stars which are located at the same position on the colour magnitude diagram and have the same rotational velocity. This suggests that the radiation pressure does not play an important role in the formation of cool equatorial disks of Be stars. The mass supply or mass accumulation mechanism should be due to some other internal or external causes. In late B stars, normal B and Be stars can be discriminated by their rotational velocities. Be stars are essentially the rapidly rotating counterparts of B stars, and their rotational velocities range from 200 km s^{-1} to the break-up velocity ($\sim$ 400 km s^{-1}).

The hot phenomena of Be stars detected from x-ray and UV data have given much new information on the origin and structure of hot and cool regions of Be stars. While x-ray emission is detected both in normal B and Be stars, superionization phenomena in the UV region are well developed only in Be stars. A parallel appearance of superionized ions along the spectral sequence is seen in Be stars and supergiants. The superionized ions also show the high-velocity expansion, although the low ionized ions do not show clear evidence of mass loss. The problem of the structure of hot and cool envelopes was one of the main subjects at *IAU Symp. No. 98*, and we shall discuss this problem in part II of this article. It is also an unsolved problem whether or not the mass outflows from the equatorial region of rapidly rotating, normal B0–B3 stars are physically related to the hot expansion region and/or cool equatorial region of Be stars. The timescale of activities of Be stars detected from visual spectra is definitely shorter in early Be stars than in late Be stars.

Finally we discuss the mass supply sources of Be envelopes. The first point to be noted is that the hot, high-velocity expansion phenomena of Be stars which are detected from the *UV* data is not necessarily the direct evidence of mass loss from B stars. The coronae can be formed by the accretion disks (Icke 1976), and the hot plasma phenomena are also detected in stars with accreting disks (*e.g.* Peters 1982a). Our conclusion from the binary statistics is that the Be envelopes can be formed in two ways, either by mass loss from a single star or by mass accretion from the companion in a binary system. Then the problem is : which process is dominant in actual Be stars? In this context we point out that the binary hypothesis in its general form meets with a difficulty in explaining the spectral-type dependence of various Be phenomena such as shown in table 7, *i.e.* according to this hypothesis the Be phenomena should be mainly governed by the nature of binary systems rather than of the parent B stars.

In this way we have now two basic problems related to the Be star phenomena : The first is the relationship between hot and cool regions in the envelopes, and the second is the role of binary interaction in the formation and structure of the envelopes. Obviously, both the problems are deeply connected with the variabilities of phenomena on any timescale.

In Part II of this article, we shall deal with the interpretation of spectral features and discuss the problems of the structure of Be envelopes.

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References

Abbot, D. C., Bieging, J. H. & Churchwell, E. (1981) *Ap. J.* **250**, 645.
Allen, C. W. (1973) *Astrophysical Quantities*, Athlone Press, p. 209.
Andrillat, Y. & Houziaux, L. (1975) cited by J. P. Swings (1976) *IAU Symp. No. 70*, p. 219.
Baade, D. (1981) *Proc. Workshop on Pulsating B Stars*, Nice Observatory, p. 267.
Baade, D. (1982a) *Astr. Ap.* **105**, 65.
Baade, D. (1982b) *Astr. Ap.* **110**, L15.
Baliunas, S. L. & Guinan, E. F. (1976) *Publ. Astr. Soc. Pacific* **88**, 10.
Balona, L. A. (1977) *Mem. R. A. S.* **84**, 101.
Balona, L. A. & Engelbrecht, C. (1979) *M. N. R. A. S.* **189**, 171.
Barker, P. K. (1982a) *Ap. J. Suppl.* **49**, 89.
Barker, P. K. (1982b) *IAU Symp. No. 98*, p. 147.
Barker, P. K. (1982c) *IAU Symp. No. 98*, p. 275.
Barker, P. K. & Brown, T. (1974) *Ap. J.* (Lett.) **192**. L11.
Batten, A. H., Fletcher, J. M. & Mann, P. J. (1978) *Publ. Dominion Ap. Obs. Victoria* **15**, 121.
Beeckmans, F. (1976) *Astr. Ap.* **52**, 465.
Bidelman, W. P. (1976) *IAU Symp. No. 70*, p. 453.
Bolton, C. T. (1982) *IAU Symp. No. 98*, p. 181.
Bossi, M., Guerrero, G. & Mantegazza, L. (1982) *IAU Symp. No. 98*, p. 185.
Bradt, H. V., Doxsey, R. E. & Jernigan, I. G. (1979) in *X-ray Astronomy* (eds. : *W. A. Baity & L. E. Peterson*) Pergamon, p. 3; *Advances in Space Exploration*, **3**.
Briot, D. (1971) *Astr. Ap.* **11**, 57.
Briot, D. & Zorec, J. (1981) *Proc. Workshop on Pulsating B Stars*, Nice Observatory, p. 109.
Burd, S. (1954) *Publ. Astr. Soc. Pacific* **66**, 208.
Cassinelli, J. P. & Abbot, D. C. (1981) *The Universe at Ultraviolet Wavelengths : The First Two Years of IUE* (ed.: R. D. Chapman) NASA CP-2171, p. 127.
Cassinelli, J. P., Castor, J. I. & Lamers, H. J. G. L. M. (1978) *Publ. Astr. Soc. Pacific* **90**, 496.
Cassinelli, J. P. & Olson, G. L. (1979) *Ap. J.* **229**, 304.

Cassinelli, J. P., Waldron, W. L., Sanders, W. T., Harnden, F. R., Rosner, R. (Jr.) & Vaiana, G. S. (1981) *Ap. J.* **250**, 677.
Clarke, D., McLean, I. S. & Wyllie, T. H. A. (1975) *Astr. Ap.* **43**, 215.
Collins, G. W. II (1974) *Ap. J.* **191**, 157.
Conti, P. S. & de Loore, C. W. H. (1979) *IAU Symp. No. 83*, session 4.
Copeland, J. A. & Heard, J. F. (1963) *Publ. David Dunlap Obs.* **2**, 317.
Cowley, A. P. & Marlborough, J. M. (1968) *Publ. Astr. Soc. Pacific* **80**, 42.
Dachs, J. (1980) *Proc. Second European IUE Conference*, Tuebingen, Germany (ESA SP-157), p. 139.
Dachs, J. (1982) *IAU Symp. No. 98*, p. 19.
Dachs, J., Eichendorf, W., Scheicher, H., Schmidt-Kaler, T., Stift, M. & Tug, H. (1981) *Astr. Ap. Suppl.* **43**, 427.
Doazan, V. (1976) *IAU Symp. No. 70*, p. 37.
Doazan, V., Bourdonneau, B. & Letourneur, N. (1977) *Astr. Ap.* **56**, 481.
Doazan, V., Briot, D. & Bourdonneau, B. (1975) *Astr. Ap.* **42**, 161.
Doazan, V., Grady, C., Kuhi, L. V., Marlborough, J. M., Snow, T. P. & Thomas, R. N. (1982) *IAU Symp. No. 98*, p. 415.
Doazan, V., Kuhi, L. V., Marlborough, J. M., Snow, T. P. & Thomas, R. N. (1980) *Proc. Second European IUE Conference*, Tuebingen, Germany (ESA SP-157), p. 151.
Ebbets, D. (1981) *Publ. Astr. Soc. Pacific* **93**, 119.
Edwards, D. L. (1956) *Vistas Astr.* **2**, 1470.
Feinstein, A. & Marraco, H. G. (1979) *Astr. J.* **84**, 1713.
Fernie, J. D. (1975) *Ap. J.* **201**, 179.
Figer, A. (1981) *Proc. Workshop on Pulsating B Stars*, Nice Observatory, p. 237.
Fraquelli, D. A. (1979) *Publ. Astr. Soc. Pacific* **91**, 502.
Fukuda, I. (1982) *Publ. Astr. Soc. Pacific* **94**, 271.
Furenlid, I. & Young, A. (1980) *Ap. J. (Lett.)* **240**, L59.
Garmany, C. D., Olson, G. L. & Conti, P. S. (1981) *Ap. J.* **250**, 660.
Gulliver, A. F. (1977) *Ap. J. Suppl.* **35**, 441.
Gulliver, A. F., Bolton, C. T. & Poeckert, R. (1980) *Publ. Astr. Soc. Pacific* **92**, 774.
Harmanec, P. (1982) *IAU Symp. No. 98*, p. 279.
Harmanec, P., Horn, J. & Koubsky, P. (1982) *IAU Symp. No. 98*, p. 269.
Harmanec, P. & Kříž, S. (1976) *IAU Symp. No. 70*, p. 385.
Harnden, F. R. (Jr.) *et al.* (1979) *Ap. J. (Lett.)* **234**, L51.
Henize, K. G. (1976) *Ap. J. Suppl.* **30**, 491.
Henrichs, H. F. (1982) *IAU Symp. No. 98*, p. 431.
Higurashi, T. & Hirata, R. (1978) *Publ. Astr. Soc. Japan* **30**, 615.
Hill, G. (1967) *Ap. J. Suppl.* **14**, 263.
Hirata, R. (1982) *IAU Symp. No. 98*, p. 41.
Hirata, R. & Asada, Y. (1976) *Publ. Astr. Soc. Japan* **28**, 713.
Hirata, R., Ballereau, D. & Hubert-Delplace, A. M. (1982b) in preparation.
Hirata, R., Katahira, J. & Jugaku, J. (1982a) *IAU Symp. No. 98*, p. 161.
Hirata, R. & Hubert-Delplace, A. M. (1981) *Proc. Workshop on Pulsating B Stars*, Nice Observatory, p. 217.
Hirata, R. & Kogure, T. (1976) *Publ. Astr. Soc. Japan* **28**, 509.
Hoffleit, D. (1964) *Catalogue of Bright Stars*, Yale University Observatory.
Hubert-Delplace, A. M. & Hubert, H. (1979) *An Atlas of Be Stars*, Meudon Observatory, Paris.
Hubert-Delplace, A. M. & Hubert, H. (1981) *Astr. Ap. Suppl.* **44**, 109.
Hubert-Delplace, A. M. & Hubert, H., Ballereau. D. & Chambon M. Th. (1982a) *IAU Symp.No.98*. p. 195.
Hubert-Delplace, A. M., Jaschek, M., Hubert, H. & Chambon, M. Th. (1982b) *IAU Symp. No. 98*, p. 125.
Hutchings, J. B. (1970) *M.N.R.A.S.* **150**, 55.
Icke, V. (1976) *IAU Symp. No. 73*, p. 267.
Irvine, N. J. (1975) *Ap. J.* **196**, 773.
Irvine, N. J. & Irvine, C. E. (1979) *Publ. Astr. Soc. Pacific* **91**, 105.

Ivanova, N. L., Kupo, I. D., Mamatkazima, A. Ch. (1969) *Non-Periodic Phenomena in Variable Stars* (ed.: L. Detre) D. Reidel, p. 215.
Jaschek, M. (1978) Catalog of Selected Spectral Types in the MK System, *Inf. Bull. Centre Donn. Stell.* (*Strasbourg Obs.*) **15**, 121.
Jaschek, M., Hubert- Delplace, A. M. Hubert, H. & Jaschek, C. (1980) *Astr. Ap. Suppl.* **42**, 103.
Jaschek, M., Slettebak, A. & Jaschek, C. (1981) *Be Star Newsletter No. 4,* p. 9.
Jerzykiewicz, M. & Sterken, C. (1982) *IAU Symp. No. 98*, p. 49.
Kahn, F. D. (1981) *M. N. R. A. S.* **196**, 641.
Kitchin, C. R. (1970) *Ap. Sp. Sci.* **8**, 3.
Kogure, T. (1981) *Publ. Astr. Soc. Japan* **33**, 399.
Kogure, T., Asada, Y. & Suzuki, M. (1982) *Proc. Second Asian Pacific Regional Meeting* (in press).
Kogure, T., Suzuki, M., Asada, Y. & Ichimoto, K. (1981) *Inf. Bull. Var. Stars No. 1952.*
Křiž, S. & Harmanec, P. (1975) *Bull. Astr. Inst. Czech.* **26**, 65.
Kucewicz, B. (1975) *Inf. Bull Southern Hemisphere No. 27*, p. 24.
Kukarkin, B. V. *et al.* (1969) *General Catalogue of Variable Stars* **1**, Akademié Nauk, Moskva.
Kukarkin, B. V. *et al.* (1970) *General Catalogue of Variable Stars* **2**, Akademié Nauk, Moskva.
Lamers, H. J. G. L. M. (1981a) *Ap. J.* **245**, 593.
Lamers, H. J. G. L. M. (1981b) *The Universe at Ultraviolet Wavelengths : The First Two Years of IUE* (ed.: R. D. Chapman) (NASA CP-2171), p. 93.
Lester, D. F. (1975) *Publ. Astr. Soc. Pacific* **87**, 177.
Long, K. S. & White, R. L. (1980) *Ap. J.* (*Lett.*) **239**, L65.
Lucy, L. B. (1982) *Ap. J.* **255**, 286.
Lucy, L. B. & White, R. L. (1980) *Ap. J.* **241**, 300
Marlborough, J. M. (1976) *IAU Symp. No. 70*, p. 335.
Marlborough, J. M. (1982) *IAU Symp. No. 98*, p. 366.
Marlborough, J. M. & Snow, T. P. (1976) *IAU Symp. No. 70*, p. 179.
Marlborough, J. M. & Snow, T. P. (1980) *Ap. J.* **235**, 85.
Massa, D. (1975) *Publ. Astr. Soc. Pacific* **87**, 777.
McLaughlin, D. B. (1932) *Publ. Obs. Univ. Michigan* **4**, 175.
Meadows, A. J. (1960) *Astr. J.* **65**, 335.
Mermilliod, J. C. (1982) *Astr. Ap.* **109**, 48.
Merrill, P. W. (1933) *Publ. Astr. Soc. Pacific* **45**, 198.
Merrill, P. W. (1952) *Ap. J.* **115**, 145.
Merrill, P. W. & Burwell, C. G. (1943) *Ap. J.* **98**, 153.
Merrill, P. W. & Burwell, C. G. (1949) *Ap. J.* **110**, 387.
Mon, M., Kogure, T. & Hirata, R. (1981) in preparation.
Nordsiek, K. M., Cassinelli, J. P. & Anderson, C. M. (1981) *Ap. J.* **248**, 678.
Pallavicini, R., Golub, L., Rosner, R. & Vaiana, G. S. (1981) *Ap. J.* **248**, 279.
Percy. J. R. (1979) *Inf. Bull. Var. Stars No. 1530.*
Percy, J. R. (1981) *Proc. Workshop on Pulsating B Stars*, Nice Observatory, p. 227.
Percy, J. R., Jakate, S. M. & Matthews, J. M. (1981) *Astr. J.* **86**, 53.
Peters, G. J. (1976) *IAU Spmp. No. 70*, p. 417.
Peters, G. J. (1980) *IAU Symp. No. 88*, p. 287.
Peters, G. J. (1982a) *IAU Symp. No. 98*, p. 311.
Peters, G. J. (1982b) *IAU Symp. No. 98*, p. 353.
Peters, G. J. (1982c) *Ap. J.* (*Lett.*) **253**, L33.
Piirola, V. (1979) *Astr. Ap. Suppl.* **38**, 193.
Plavec, M. (1976a) *IAU Symp. No. 70*, p. 1.
Plavec, M. (1976b) *IAU Symp. No. 70*, p. 439.
Plavec, M. & Polidan, R. S. (1976) *IAU Symp. No. 73*, p. 289.
Rappaport, S. & van den Heuvel, E. P. J. (1982) *IAU Symp. No. 98*, p. 327.
Ringuelet, A. E. & Machado, M. E. (1974) *Ap. J.* **189**, 285.
Rosner, R. & Vaiana, G. S. (1980) in *X-Ray Astronomy* (eds : G. Giacconi & G. Setti) D. Reidel, p. 129.
Schild, R. & Romanishin, W. (1976) *Ap. J.* **204**, 473.

Slettebak, A. (1969) Non-Periodic Phenomena in Variable Stars (ed.: L. Detre) D. Reidel, p. 179.
Slettebak, A. (1976) *IAU Symp. No. 70*, p. 123.
Slettebak, A. (1979) *Sp. Sci. Rev.* **23**, 541.
Slettebak, A. (1982) *Ap. J. Suppl.* **50** 55.
Slettebak, A., Collins, G. W. II, Boyce, P. B., White, N. M. & Parkinson, T. D. (1975) *Ap. J. Suppl.* **29**, 137.
Slettebak, A. & Reynolds, R. C. (1978) *Ap. J. Suppl.* **38**, 205.
Slettebak, A. & Snow, T. P. (1978) *Ap. J. (Lett.)* **224**, L127.
Snow, T. P. (1981) *Ap. J.* **251**, 139.
Snow, T. P. (1982) *Ap. J. (Lett.)* **253**, L39.
Spear, G. G., Mills, J. (Jr) & Snedden, S. A, (1981) *Publ. Astr. Soc. Pacific* **93**, 460.
Stewart, G. C. & Fabian, A. C. (1981) *M.N.R.A.S.* **197**,713.
Struve, O. (1931) *Ap. J.* 73, 94.
Uesugi, A. (1976) *Revised Catalogue of Stellar Rotational Velocities, Preliminary Edition*. Kyoto University.
Uesugi, A. & Fukuda, I. (1970) *Mem. Fac. Sci. Kyoto Univ.* **33**, 205.
Uesugi, A. & Fukuda, I. (1982) *Revised Catalogue of Stellar Rotational Velocities*, Dept Astr., Kyoto University.
Underhill, A. & Doazan, U. (1982) *B stars With and Without Emission Lines*, NASA SP-456.
Vaiana, G. S. (1981) *Sp. Sci. Rev.* **30**, 151.
Vaiana, G. S., *et al.* (1981) *Ap. J.* **245**, 163.
Wackerling, L. R. (1970) *Mem. R. A. S.* **73**, 153.
Walker, M. F. (1953) *Ap. J.* **118**, 481.
Waldron, W. L. (1982) *Wisconsin Ap. No. 148.*