ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **129**, 289-311 (1998)

Long-term visual spectrophotometric behaviour of Be stars*

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Received March 11; accepted July 24, 1997

Abstract. The long-term spectrophotometric variations of 49 Be stars are studied using the U and V magnitudes of the UBV system, the total Balmer discontinuity D and the visible gradient $\Phi_{\rm rb}$. BCD spectrophotometric and photometric data in five different photometric systems, obtained in most cases since 1950 and reduced to the BCD system, were used. The (U,D), (V,D), $(\Phi_{\rm rb},D)$ and $(\Phi_{\rm rb},V)$ correlations obtained differ from star to star and they can be single or double-valued. They differ clearly for Be phases or Be-shell phases. Be stars with small $V\sin i$ showing the "spectrophotometric shell behaviour": $D > D_*$, were found. This finding implies either that strongly flattened models of circumstellar envelopes are in doubt for these stars, or that not all Be stars are rapid rotators. Comparison of observed variations with those predicted for model Be stars with spherical circumstellar envelopes of variable densities and dimensions implies that spectrophotometric patterns of Be phases are due to circumstellar envelopes in low opacity regimes, while those of spectrophotometric shell phases are due to circumstellar envelopes in high opacity regimes. In a given star, the envelope regions responsible for the observed variations of D and $\Phi_{\rm rb}$ in spectrophotometric shell phases seem to be smaller and denser than those producing the observed variations of these parameters in spectrophotometric Be phases. The high positive RV found in strong shell phases might favor the formation of compact circumstellar layers near the star.

Key words: stars: variable — stars: Be

1. Introduction

1.1. *General spectrophotometric characteristics of Be stars*

Be stars have long been known to be photometric variables. These variations can have periodic and/or irregular components of different time scales: (a) periodic or multiperiodic components with small amplitudes of roughly several hundredths of magnitude in the V magnitude, characterized by short time scales $t \sim 0.4$ to 3 days (Balona 1990, 1995) which are commonly interpreted as due to non-radial pulsations and/or to stellar surface spots or corotating features (Baade & Balona 1994); (b) periodic variations with intermediate time scales, $t \sim$ days to 100 days, with amplitudes ΔV of several hundredths or tenths of magnitude (Harmanec & Kříž 1976) which are observed only in binary Be stars; (c) quasi-cyclic or irregular variations with rather long time scales, months, years and sometimes decades, generally implying magnitude changes ΔV that range between 0.01 and 0.4 mag (Feinstein 1970, 1975; Feinstein & Marraco 1979; Alvarez & Schuster 1981; Kozok 1985; Percy et al. 1988). The latter can, however, be as high as $\Delta V \sim 0.5$ to 1.2 mag (Huffer 1939; Mook et al. 1974; Howarth 1979; Alvarez & Schuster 1981; Bernacca & Bianchi 1981; Divan et al. 1982, 1983; Mennickent & Vogt 1991; Apparao 1991; Roche et al. 1993; Mennickent et al. 1994; Ballereau et al. 1995). Though the irregular fluctuations are, as a rule, characterized by long time scales, these scales have been found in the case of very active Be stars to be as short as a few days (Hubert-Delplace et al. 1982). The quasi-cyclic or irregular photometric variations of Be stars are accompanied by more general spectrophotometric variations which concern a wide wavelength coverage. These variations have also been known for a long time (Chalonge & Safir 1936; Greaves & Martin 1938; Barbier & Chalonge 1941). Since Gerasimovic (1929); Chalonge & Safir (1936); Barbier & Chalonge (1939), it is also known that when line emission

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or "shell" features are pronounced, Be stars can present two Balmer discontinuities (hereafter BD). The first BD looks like that of a normal B star and it has the same spectral location. The second BD appears at shorter wavelengths, which means that it is formed in a medium with a lower pressure than in the photosphere of the central star. It can be in emission (during a strong emission line phase) or in absorption (during a strong "shell" or absorption line phase). The value of the second BD in emission not only depends on the spectral type (Peton 1981) but is correlated with Balmer emission line strength (Schild 1978; Feinstein & Marraco 1979; Peton 1981; Kaiser 1989; Dachs et al. 1989) and with Balmer decrement as well (Divan et al. 1982). The emission component of the BD is generally not higher than -0.15 dex, but may exceptionally be as high as -0.25 dex (Barbier 1947). When the second BD is in absorption, it can sometimes represent a flux deficiency stronger than 1 mag (Zorec 1986, 1994). The second BD disappears during a faint emission/shell line phase, so that the stellar continuum energy distribution near the BD looks like that of a normal B star. During the spectrophotometric variations of Be stars, the first BD maintains the value and mean spectral position measured during an emissionless phase to closer than 0.02 dex and $\Delta\lambda = 1$ Å respectively (Divan & Zorec 1982a,b). The constancy of the first BD to within 0.03 dex was also confirmed by Dachs et al. (1989) and it is currently used for spectral type classification (Divan 1979; Divan & Zorec 1982c; Divan et al. 1982, 1983). Therefore, it is also useful to determine the effective temperature of the central object (Divan & Zorec 1982c; Zorec et al. 1983; Zorec 1985, 1986; Kaiser 1989; Dachs et al. 1989; Zorec & Briot 1991) and the surface gravity (Divan & Zorec 1982a; Zorec 1985, 1986).

It has been shown that the irregular photometric variations imply a global continuum flux excess or deficiency as compared to stellar underlying photospheric radiation. This can be estimated as $\Delta F_{\rm c}/F_{\rm c} \lesssim 10^{-0.4\Delta V}$, where $\Delta V = V - V_*$ (V magnitude of the star+envelope system; V_* magnitude of the star alone) and it is $\Delta V \lesssim 0$ for continuum emission (or flux excess) and $\Delta V \gtrsim 0$ for continuum flux deficiency. The magnitude excess ΔV is positively correlated with Balmer line emission strength (Zorec & Briot 1985, 1991; Dachs et al. 1988, 1989; Ballereau et al. 1995) and with reddening of the Paschen continuum (Divan et al. 1978; Divan 1979; Chkhikvadze 1980; Dachs 1982). In turn, this reddening is correlated with Balmer line emission strength (Dachs et al. 1988). The visible flux deficiency is generally small ($\Delta V \lesssim 0.2$ mag) and it is not accompanied by marked changes of visible Paschen energy distribution (Divan & Zorec 1982c; Zorec et al. 1989; Zorec 1994). Quasi-cyclic and/or irregular changes from positive to negative flux excesses are symptomatic of the known Be "phase" variations Be $\rightleftharpoons$ B-normal $\rightleftharpoons$ Be-shell. The present paper is devoted to the irregular spectrophotometric variations of Be stars.

1.2. Some previous studies of long-term photometric and/or spectrophotometric variations of Be stars

The existing *observational* studies on long-term photometric and/or spectrophotometric variations of Be stars can be classified into two broad groups: (1) studies where authors used observations of their own; (2) studies based on compilations of published observations each made in a given photometric or spectrophotometric system.

(1) - The most relevant studies in the first group are those of Pavlowski et al. (1996) for northern Be stars and Manfroid et al. 1991, 1995; Sterken et al. 1992, 1993 for southern ones. Observations presented by Pavlowski et al. (1996), done in the UBV system, concern the monitoring of 76 Be stars over 18 years since 1972. In this program there are 28 well-observed stars with 9^{+8}_{-3} observing seasons and each with 392^{+805}_{-288} individual observations, and 48 less observed objects with 3^{+2}_{-2} observing seasons each and with 60^{+159}_{-57} individual UBV measurements. Manfroid's et al. 1991, 1995 and Sterken's et al. (1992, 1993) 12-year observing program also concerns, among other variable stars, 15 Be stars which were monitored in the *uvby* Strömgren system since 1982 for about 6 months per year and with a time frequency between 2 and 14 days. From Pavlovski's et al. (1996) study it appears that the number of stars with variations on time scales from months to years is about the same as the number with time scales of days or fractions of days. These variations are, however, 3 times more frequent among stars earlier than B5 than in the later ones. Six stars present orbital components of photometric variations and only 2 show sudden light changes. From the published light curves, which in many cases reveal complicated variations difficult to summarize, we can distinguish those with shell-type characteristics, where two dominant behaviours seem to appear: (i) those of stars where the $(U-B)$ colour index changes much less than the $(B-V)$ index; (ii) those, the most numerous, where the $(U-B)$ colour index changes much more than the $(B-V)$ index. Both types of behaviours are seen in early as well as in late type Be stars. Mennickent et al. (1994) report a detailed study on 13 Be stars based on *uvby* Manfroid & Sterken's et al. 1991-1995 observations. These authors note: (a) quasi-periodic oscillations on time scales between 10 and 20 days with amplitudes up to 0.2 mag preceding fading events; (b) in 7 stars, which mostly have shell characteristics, they observe that: (b$_1$) small or rather no variations of the $b-y$ index accompany the variation of magnitude u; (b$_2$) there is a correlation between index c_1 and magnitude u; (c) in all 13 studied Be stars and for all *uvby* magnitudes, there is, within the uncertainties of coefficients defining the regression lines, a mean relation between the long-term variation amplitudes and the standard deviation of short-term variability. Concerning the (c_1,u) relation, it is worth noting that in shell Be stars not only the variation of u is noticeably higher than in v but also $(b-v) \sim 0$, so that the

correlation between c_1 and u seems natural. However, the well-defined trend between the slope of the (c_1, u) relation and $V\sin i$, which identifies possible differences in the relative behaviours of Balmer to Paschen continua, could still deserve further attention.

The first group also comprises studies of long-term spectrophotometric variations of Be stars made using the *BCD* system (for definition of the *BCD* (Barbier-Chalonge-Divan) system, see Chalonge & Divan 1952). The great advantage of this system is that it reflects the variation of continuum energy distribution only, because it is not affected by spurious "reddening/blueing" effects introduced by variable spectral lines entering the wide wavelength intervals of some photometric filter pass-bands. The *BCD* data were obtained at irregular time intervals over more than 40 years. They concern a small number of Be stars, of which most are of early spectral types. These data led Divan (1979); Divan et al. (1982); Zorec (1986) to conclude that in the studied objects the continuum emission phases were characterized by well-defined relations between the visible gradients of energy distributions, total Balmer discontinuity and visual magnitude. These relations seem to be different for each star and unchanged even after the star had a phase of apparent loss of emission characteristics. These authors also found that, in general, reddening of the visible gradient is positively correlated with stellar brightening. Inversely, "shell" phases are characterized by very small changes, if any, in the visible energy distribution.

(2) - In the second group are papers concerning either a small number of objects at typical "Be" phases, or a large number of objects at any variation phase. In the first subgroup, works like Dachs (1982); Dachs & Hanuschik (1984) and Dachs et al. (1988) show that long-term photometric variations can be characterized by slopes $\Delta V/\Delta(B-V)$ ranging between about -0.1 and -0.3 for individual stars and that reddening of the $(B-V)$ index is related to stellar brightening. In the second subgroup, it is worth mentioning Nordh & Olofsson (1977); Hirata (1982) and Hirata & Hubert-Delplace (1981). From *UBV* data of 50 to 70 Be stars spread over more than 10 years, Hirata et al. concluded: (i) that early type Be stars get redder when they brighten, and on the contrary late type Be stars are bluer when they brighten; (ii) the slope $\Delta V/\Delta(B-V)$ is steeper when $V\sin i$ is higher, and that this slope has the same sign as the colour excess ratio $\Delta(U-B)/\Delta(B-V)$.

Finally, there are some attempts of a *theoretical* nature to explain the long-term photometric variations of Be stars. Using a cylindrical model for the CE, Hirata (1984) concluded that changes of V and $(B-V)$ are due to variations of the extent of the circumstellar envelope (hereafter CE) and that $\Delta V/\Delta(B-V)$ is a function of spectral type and aspect angle. The irregular variations of V magnitude were also discussed by Zorec & Briot (1991). They concluded that when $\Delta V < 0$, the irregular variations may correspond to two different opacity regimes of the circumstellar envelope: (a) a low opacity regime, where variations of V are mostly due to small changes of opacity, and (b) a high opacity regime, where variations of V are mainly due to changes of the extent of the CE. Inversely, for $\Delta V > 0$ there is only a high opacity regime. In a recent work, Hirata (1995) studied the long-term variations of some Be stars at shell phases and concluded that their variations are produced by extended photospheres.

As continuum and line variations correlate only when strong line emissions or line absorptions are present during "spectroscopic" Be and Be-shell phases respectively, to avoid misunderstandings relative to spectroscopic or spectrophotometric variations, whenever necessary we explicitly refer in this paper to "spectrophotometric Be phase" (hereafter SPh-Be) when the second *BD* is in emission and to "spectrophotometric shell phase" (hereafter SPh-shell) when the second *BD* is in absorption.

1.3. Aim of the present work

Results presented in the preceding section are consistent and complementary to each other. The relations obtained between photometric colour indices and/or spectrophotometric parameters show that they should somehow depend on the physical structure of the CE and on its changes. In particular, early *BCD* results suggested that these relations are permanent for each star and differ from one object to another, as would be the case if there were permanent characteristics related to the structure of the CE of Be stars which subsist even after phase changes or apparent losses of emission. However, in addition to opacity and geometrical factors cited in the preceding section, still other phenomena could be responsible for photometric/spectrophotometric changes of Be stars. In fact, as the contributing regions in the CE to the ΔV variations are expected to be located rather near the underlying star (Zorec & Briot 1991; Zorec & Garcia 1991; Cruzado et al. 1994) ionization/excitation balance changes in the deepest layers of the CE (Magnan 1979), as well as radiation transfer effects related to non-thermal phenomena (Gebbie & Thomas 1970, 1971; Thomas 1983) should also be relevant. Due to all these effects and because some of the above observational results were obtained from a small number, mostly early type Be stars, it would still be necessary: (a) to analyse a larger sample of Be stars of all possible subspectral types, each having been observed as frequently as possible and over a long time base; (b) to study the actual character (constancy, uniqueness, etc.) of relations among spectrophotometric parameters for each star, especially, if feasible, for those having undergone phase changes. This study aims at giving as far as possible comprehensive observational bases on long-term spectrophotometric variations of Be stars, derived from compiled photometric and spectrophotometric data obtained in various systems, to ensure a large time base coverage and for a quite a large number of stars.

2. Method

2.1. General remarks

To compare more or less heterogeneous photometric and spectrophotometric data, obtained at different epochs by different observers and systems, we reduced them all to a common set of spectrophotometric quantities. We transformed them to the spectrophotometric parameters derived in the *BCD* system. These are: (a) gradient $\Phi_{\rm rb}$ of the continuum energy distribution in the spectral domain $\lambda\lambda\ 0.40-0.63\ \mu$m; (b) total *BD* of Be stars, D, measured at $\lambda\ 0.37\ \mu$m, and (c) V magnitude as defined in the standard *UBV* system. As known, the total *BD* of Be stars has two components: $D=D_*+d$, where $D_*\geq 0$ accounts for the invariable stellar *BD*, and d is the variable component due to the CE. It is $d<0$ for Balmer continuum emission excess, and $d>0$ for Balmer continuum deficiency. In this paper we study the total *BD* only.

2.2. The ($\Phi_{\rm rb}$, D, V) parameters and the structure of the CE

Reduction of all data obtained from quite different photometric systems to the *BCD* parametric triptych ($\Phi_{\rm rb}$, D, V), allows us: (a) to have an uniform set of parameters with a clear physical meaning and easy to interpret theoretically; (b) to test previous conclusions obtained with the *BCD* data on long-term spectrophotometric behaviour of Be stars. Interpretation of the ($\Phi_{\rm rb}$, D, V) parameters in terms of CE opacity, extent and temperature will be sketched in Sect. 4.

2.3. Photometric systems of compiled data

Data of Be stars used in this work were obtained in (or reduced in the original publications to) the following photometric systems: (a) the *UBV* standard system (Johnson & Morgan 1951, 1953); (b) the *UBVRI* system (Johnson 1965; Cousins 1976, 1978); (c) the seven-colour $(U,B,V,B1,B2,V1,G)$ Geneva photometric system (Golay 1963; Rufener & Maeder 1971; Rufener & Nicolet 1988; Rufener 1979); (d) the *uvby* Strömgren system (Strömgren 1966; Grønbech et al. 1976; Grønbech & Olsen 1977); (e) 13-colour photometry (Johnson & Mitchell 1975); (f) photographic spectrophotometric data (*BCD*).

2.4. The stellar sample

From all known Be stars (Jaschek & Egret 1982) we have chosen the brightest ones because they were liable to yield more frequent and detailed observations. Among them we preferred those known for their strong spectroscopic variations (Hubert-Delplace & Hubert 1979) or because they had rather strong photometric changes (Feinstein 1975; Feinstein & Marraco 1979; Alvarez & Schuster 1981). We discarded those objects in binaries where variations of Be characteristics are strongly correlated with the orbital phase, such as HR 2142. The studied Be stars are presented in Table 1. The spectral classification is preferentially from the *BCD* system and in such cases it is indicated with an upper index "^{a}". Otherwise, it is taken from the Hipparcos Input Catalogue (Turon et al. 1992); Buscombe (1977, 1980, 1981, 1988); Hubert-Delplace & Hubert (1979); Slettebak (1982), the Bright Stars Catalogue (Hoffleit & Jaschek 1982) and the Supplement to the Bright Stars Catalogue (Hoffleit et al 1983). For each Be star are given: the stellar *BD*, D_* (an upper index "^{a}" indicates *BCD* values of D_*, otherwise D_* is a mean value for the adopted MK spectral classification); the mean values of V, D and $\Phi_{\rm rb}$ calculated from all collected data and the respective standard deviations $(\sigma_V,\sigma_D,\sigma_\Phi)$; the JD-2400000 of the first and the last observation; the number of individual triads $(V,D,\Phi_{\rm rb})$; the references of collected data. The standard deviation of variations in the $(B-V)$ and $(U-B)$ colour indices can straightforwardly be derived using the transformations: $\sigma_{\rm (B-V)}=0.56\sigma_\Phi$ and $\sigma^2_{\rm (U-B)}=3.89\sigma^2_{\rm D}+0.54\sigma^2_\Phi$.

2.5. Reduction to spectrophotometric parameters

2.5.1. Comparison stars

We took as comparison stars a set of 82 well-observed O, B and A0 type stars in the *BCD* system, all presented in Zorec & Briot (1991), whose $\Phi_{\rm rb}$ and D parameters are determined to closer than $\delta(\Phi_{\rm rb})=0.05\ \mu$m and $\delta(D)=0.01$ dex respectively. We considered stars of luminosity classes from dwarfs to bright giants and with different rotational velocities to get a first and direct insight on the possible scatter that differences in intensities of spectral lines can introduce in the transformations (photometric indices) → (spectrophotometric parameters). A large number of these stars (75%) are used either as MK, photometric or spectrophotometric standard/comparison stars (Divan 1966; Golay 1973; Rufener 1979; Hauck 1985; Tüg 1980; Thé et al. 1986; Perry et al. 1987; Zorec et al. 1983; Harmanec et al. 1994). Table 2 gives the adopted comparison stars, with the $\Phi_{\rm rb}$ and D parameters and the corresponding MK spectral type as derived using the *BCD* system.

2.5.2. Transformation of photometric data into the $\Phi_{\rm rb}$ and D spectrophotometric parameters

i) The *UBV* system.

The best correlation between the *UBV* colour indices and the *BD* given in the *BCD* system was found using Johnson's (1958) Q index, which leads, as in the *BCD* system, to *BD* free from interstellar medium (ISM) absorption. We used the definition of the Q index given by Gutierrez-Moreno (1975):

$$Q_{UBV}=(U-B)-0.67(B-V)\ \ \text{mag.} \qquad (1)$$

Table 1. The studied Be stars

HD	HR Name	Sp.Type	D_* dex	$\overline{V}$ σ_V	$\overline{D}$ σ_D	$\overline{\Phi_{\rm rb}}$ σ_Φ	$\mathrm{JD_f}-\mathrm{JD_l}$	N	References
4180	193 o Cas	B5-6IIIe ^{a}	0.270 ^{a}	4.55 0.06	0.261 0.006	1.00 0.02	35400−42021	17	10,15,32,34,38,80,91,110,114,115,142,198
5394	264 γ Cas	O9Ve ^{a}	0.04: ^{a}	2.41 0.22	−0.038 0.054	0.97 0.13	28070−47528	389	7,12,13,14,15,32,38,67,80,101,104,109,110,111,112,114,115,142,155,198
23862	1180 28 Tau	B8IV-Ve ^{a}	0.370 ^{a}	5.17 0.09	0.399 0.079	1.01 0.06	33976−48341	341	2,11,12,13,14,19,33,35,42,53,56,65,80,85,99,100,110,114,115,116,158,172,178,196 197,198
24534	1209 X Per	O9IVe ^{a}	0.050 ^{a}	6.55 0.21	0.000 0.045	1.44 0.12	34271−49029	331	2,13,17,18,38,43,66,67,69,87,94,95,105,106,118,127,141,142,147,151,164,198
25940	1273 48 Per	B4IVe ^{a}	0.230 ^{a}	4.04 0.02	0.225 0.013	1.06 0.02	35400−40560	18	32,38,80,81,82,87,110,114,115,142,144,198
28497	1423 DU Eri	B1.5Ve ^{a}	0.124 ^{a}	5.51 0.04	0.066 0.016	0.81 0.03	35400−48202	92	6,26,37,58,64,68,73,110,142,157,198
32343	1622 11 Cam	B4Ve ^{a}	0.223 ^{a}	5.13 0.09	0.152 0.023	0.97 0.02	32809−45697	25	38,51,110,128,142,155,196,198
33328	1679 λ Eri	B2III-IVe ^{a}	0.145 ^{a}	4.26 0.02	0.113 0.006	0.79 0.02	37666−49278	404	3,26,30,38,68,78,110,114,115,139,140,159,181,182,198
35439	1789 25 Ori	B1.5III-IVe ^{a}	0.121 ^{a}	4.80 0.10	0.065 0.026	0.86 0.07	33966−48313	117	2,8,22,30,38,73,80,110,114,115,126,142,143,174,191,198
37202	1910 ζ Tau	B2IIIe ^{a}-shell	0.142 ^{a}	2.97 0.05	0.178 0.026	0.80 0.04	35400−48974	78	32,38,59,76,80,85,110,114 115,142,198
37967	1961 V731 Tau	B4Ve ^{a}	0.220 ^{a}	6.23 0.05	0.191 0.012	1.00 0.03	35400−48600	26	32,38,85,110,142,193,198
48914		B5Ib-II	0.200	7.27 0.07	0.300 0.035	1.12 0.03	41329−47934	640	55,184,187,198
48917	2492 10 CMa	B2III-IVe ^{a}	0.147 ^{a}	5.21 0.06	0.069 0.015	0.93 0.04	38441−49407	406	22,37,45,57,59,60,62,73,139,140,179,181,182,185,198
50123	2545	B5IIIe ^{a}	0.220 ^{a}	5.75 0.03	0.158 0.008	1.36 0.03	40967−49401	186	73,92,125,139,140,179,181,182,198
56014	2745 27 CMa	B3IIIe ^{a}	0.190 ^{a}	4.59 0.08	0.146 0.030	0.81 0.03	38104−47232	182	6,22,58,60,62,73,114,139,140,181,182,198
56139	2749 ω CMa	B2IVe ^{a}	0.165 ^{a}	3.77 0.17	0.164 0.030	0.92 0.08	38384−48349	182	6,22,26,45,59,60,62,78,108,114,139,140,179,181,198
58050	2817	B2Ve ^{a}	0.160 ^{a}	6.56 0.09	0.145 0.010	0.76 0.02	35400−48344	41	38,110,142,163,170,198
58978	2855 FY CMa	B0Ve ^{a}	0.07: ^{a}	5.62 0.04	0.031 0.006	0.95 0.02	38135−49399	275	1,22,24,37,57,58,59,62,64,73,74,91,131,139,140,179,181,182,198
60848	 BN Gem	O8Vpe ^{a}	0.050 ^{a}	6.85 0.07	0.009 0.027	0.85 0.06	35571−48347	14	48,74,135,198
60855	2921	B3IVe	0.190	5.69 0.03	0.171 0.011	0.91 0.03	41484−45746	19	26,31,37,59,73,97,134,136,142,169,170,175,198
63462	3034 o Pup	B0Ve ^{a}	0.04: ^{a}	4.49 0.02	−0.000 0.007	1.25 0.02	38076−49439	180	26,30,36,58,59,73,98,114,140,143,179,181,182,198
65875	3135	B2IVe ^{a}	0.140 ^{a}	6.51 0.05	0.127 0.023	0.94 0.05	35400−48178	23	38,58,59,73,110,132,142,170,187,189,198
68980	3237 MX Pup	B0.5IV-Ve ^{a}	0.090 ^{a}	4.73 0.09	0.036 0.016	0.94 0.04	38076−49399	155	26,30,58,59,60,61,62,64,78,139,140,179,181,182,192,198
83953	3858	B5IV-Ve ^{a}	0.260 ^{a}	4.76 0.02	0.238 0.011	0.89 0.02	35400−48972	66	8,26,30,36,58,59,64,73,78,114,129,140,142,150,179,181,182,198
89890	4074	B4III-IVe	0.235	4.49 0.01	0.252 0.007	0.91 0.02	37666−49400	153	26,30,36,44,64,73,139,140,179,181,182,198

Table 1. continued

HD	HR	Sp.Type	D_*	$\overline{V}$	$\overline{D}$	$\overline{\Phi_{\rm rb}}$	$\rm JD_f - JD_l$	N	References
	Name		dex	σ_V	σ_D	σ_Φ			
91120	4123	B9IVe ^{a}	0.430 ^{a}	5.60	0.450	1.04	37666−48219	22	23,33,73,110,170,183,198
				0.01	0.008	0.02			
91465	4140	B3IIIe ^{a}	0.187 ^{a}	3.31	0.166	0.90	38807−48258	23	23,27,36,58,179,181,198
	PP car			0.08	0.013	0.04			
109387	4787	B5-6IVe ^{a}	0.292 ^{a}	3.87	0.243	0.88	35400−47110	201	2,10,19,20,38,42,75,79,80,
	κ Dra			0.05	0.020	0.05			110,114,115,117,142,154,
									170,198
120991	5223	B2IIIe	0.140	6.07	0.063	0.98	38472−48851	229	23,37,58,62,63,64,72,73,
	V767 Cen			0.14	0.042	0.08			119,121,124,177,179,194,198
131492	5551	B3Ve ^{a}	0.187 ^{a}	5.29	0.165	1.04	38031−48117	52	58,62,64,73,77,122,179,185
	θ Cir			0.17	0.069	0.06			198
142983	5941	B3-4III-IVe ^{a}	0.212 ^{a}	4.88	0.334	0.97	38031−49593	595	2,6,26,36,58,60,62,64,73,
	48 Lib	-shell		0.07	0.063	0.02			77,110,114,115,139,140,145
									170,177,181,182,196,198
148184	6118	B0.5Ve ^{a}	0.09: ^{a}	4.30	−0.011	1.67	35400−48123	175	2,6,26,58,62,64,77,83,92,
	χ Oph			0.07	0.020	0.06			110,114,115,142,170,196,198
162428		B7IV-Ve	0.345	7.12	0.298	0.99	43304−47744	9	2,122,169,198
				0.02	0.052	0.03			
162732	6664	B6IVe ^{a}-shell	0.300 ^{a}	6.80	0.341	0.89	37666−49234	197	2,5,9,19,33,39,47,49,84,85,
	88 Her			0.07	0.029	0.04			89,91,96,110,149,151,160,
									170,198
168797	6873	B4IVe	0.220	6.13	0.191	1.06	35400−48328	43	4,28,38,54,110,122,142,160,
				0.03	0.011	0.02			166,198
171780	6984	B5Vne	0.264	6.10	0.248	0.90	38913−48375	11	38,110,142,169,170,178,198
				0.03	0.013	0.02			
173219		B0Ve	0.07:	7.85	0.004	1.49	34271−49594	343	88,94,122,139,140,142,181,
				0.02	0.005	0.02			182,198
178175	7249	B2Ve	0.162	5.54	0.175	1.00	35400−48341	36	24,37,58,59,60,62,64,73,
	V4024 Sgr			0.05	0.015	0.02			110,122,142,198
183656	7415	B6Ve-shell	0.315	6.07	0.378	1.12	39902−49591	162	19,28,73,91,139,140,181,
	V923 Aql			0.03	0.031	0.02			182,198
184279		B0Ve	0.06:	7.01	0.092	1.23	34013−49591	340	2,29,30,40,91,110,113,122,
	V1294 Aql			0.11	0.031	0.04			138,140,142,148,161,162,
									170,181,181,186,188,198
187811	7565	B2.5Ve	0.170	4.89	0.208	0.82	35400−46664	79	38,54,55,110,114,115,130,
	12 Vul			0.04	0.012	0.02			142,146,160,198
191610	7708	B3IVe	0.190	4.93	0.144	0.85	35400−48441	192	1,19,38,54,71,114,115,130,
	28 Cyg			0.03	0.012	0.03			142,146,156,160,198
195325	7836	B9e-Shell	0.44:	6.03	0.485	1.08	39902−48372	11	19,91,110,153,171,198
	1 Del			0.04	0.038	0.02			
200120	8047	B1.5Ve ^{a}	0.116 ^{a}	4.80	0.052	0.95	32833−49719	660	2,10,15,38,46,50,52,107,
	59 Cyg			0.08	0.016	0.06			110,114,115,130,133,134,
									142,155,160,167,196,198
205637	8260	B3II-IIIe ^{a}	0.155 ^{a}	4.54	0.203	0.79	35400−49593	449	22,26,28,30,58,59,60,64,73
	ϵ Cap	-shell		0.06	0.026	0.02			78,91,114,115,123,139,140,
									142,150,181,182,198
210129	8438	B6-7Vne	0.317	5.71	0.283	0.96	39316−43555	13	19,33,39,110,114,152,165,
	25 Peg			0.06	0.031	0.02			169,198
217050	8731	B3IIIe ^{a}-shell	0.165 ^{a}	5.31	0.231	0.96	35400−43796	419	2,38,80,85,91,110,142,198
	EW Lac			0.05	0.041	0.04			
217543	8758	B3-4IV-Ve ^{a}	0.210 ^{a}	6.53	0.183	0.90	34348−43373	51	38,85,86,91,110,142,198
				0.02	0.013	0.03			
218674		B3IVeShell	0.186	6.76	0.212	1.09	34348−47028	198	85,86,91,110,160,198
	KY And			0.02	0.011	0.02			

Table 1. continued

Notes: D_* is the stellar BD; $(\overline{V}, \overline{D}, \overline{\Phi_{\rm rb}})$ and $(\sigma_V, \sigma_D, \sigma_\Phi)$ are the mean values of all found magnitudes V, BD, visible gradients and the respective dispersions; $\mathrm{JD_f}-\mathrm{JD_l}$ are JD$-$2400000 of the first and last observation; N is the number of individual triads $(V, D, \Phi_{\rm rb})$; " ^{a} " stands for BCD classification and for BCD values of D_*.

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Table 2. Stars used to represent the spectrophotometric parameters D and $\Phi_{\rm rb}$ as functions of photometric indices

HD	HR	Sp.Type	D dex	$\Phi_{\rm rb}$ μm	Notes
886	39	B2IV	0.146	0.680	3,4
3360	153	B2IV	0.146	0.760	3,4,7
4142	189	B5V	0.272	0.760	2,7
11241	533	B2V	0.144	0.840	1,7
16582	779	B2III	0.136	0.760	3
19356	936	B7-8V	0.350	0.930	
20365	987	B4V	0.234	1.010	
20418	989	B4IV	0.244	0.970	7
21071	1029	B5V	0.270	0.980	7
21278	1034	B4-5V	0.249	0.980	2,4,7
21428	1044	B4V	0.235	0.940	7
21856	1074	B1IV-V	0.094	1.040	2,7
22928	1122	B5-6III	0.286	0.880	3,7
22951	1123	B0.5V	0.089	1.090	5
23288	1140	B7V	0.340	1.080	4,5
23324	1144	B7V	0.342	1.060	2,4,7
23338	1145	B6IV	0.297	0.970	3,4
23408	1149	B6-7III	0.315	1.030	
23432	1151	B8IV-V	0.376	1.060	4
23753	1172	B7V	0.352	1.070	4,7
23850	1178	B7III	0.340	0.980	3,5
23923	1183	B9V	0.413	0.960	4
24131	1191	B1V	0.100	1.150	
24640	1215	B2V	0.145	1.010	
24760	1220	B0III	0.075	0.760	3,5,7
25638	1260	B0III	0.059	1.940	
30211	1520	B5IV	0.251	0.790	7
32630	1641	B4V	0.230	0.780	1,3,4,7
35468	1790	B2III	0.132	0.710	1,3,7
35600	1804	B9Ib	0.363	1.490	
36371	1843	B4Ia	0.110	1.790	
36959	1886	B1V	0.115	0.730	
36960	1887	B0IV	0.072	0.720	1,7
37016	1891	B3-4V	0.196	0.840	
37040	1898	B3V	0.184	0.860	
37043	1899	O7III-IV	0.035	0.700	3,6
37209	1911	B1V	0.109	0.760	7
37468	1931	O9V	0.057	0.700	6
37481	1933	B1V	0.116	0.750	7
37744	1950	B1.5V	0.124	0.790	7
38666	1996	O8-9V	0.050	0.700	6
40111	2084	B1Ib	0.062	1.070	
40589	2111	B9Iab	0.266	1.580	
41753	2159	B3-4V	0.217	0.790	7
43112	2222	B1IV	0.096	0.700	1,7
43384	2240	B4Ia	0.107	1.940	
44743	2294	B1II-III	0.089	0.729	4
45563	2347	B9V	0.422	0.839	
46075	2374	B6IV-V	0.316	0.920	
47240	2432	B1Iab	0.070	1.400	6
47432	2442	O8Ia	0.021	1.390	1,6
47756	2454	B5-6IV	0.292	0.920	
47964	2461	B7III	0.340	1.030	
48434	2479	O9.5Ib	0.042	1.110	7
48977	2494	B3V	0.196	0.800	
49567	2517	B4II-III	0.195	0.870	
71155	3314	A1V	0.487	0.808	2,3,4,5,7
74280	3454	B3V	0.181	0.730	3,4,5,7
83754	3849	B5V	0.250	0.870	3,4,7
87901	3982	B7IV	0.348	0.762	3,4,5,6,7
100600	4456	B3-4V	0.212	0.820	4
120315	5191	B4V	0.222	0.750	4,5,7
147394	6092	B5IV-V	0.265	0.850	2,4,7
160762	6588	B3IV	0.204	0.750	4,5,7
166182	6787	B2.5III	0.156	0.830	2,7
184915	7446	B1II	0.076	1.040	4,6,7
191692	7710	A0IV	0.502	0.820	6
202850	8143	B9Ia	0.240	0.981	4,7
204172	8209	B0Ib	0.048	1.010	7
205021	8238	B1III-IV	0.095	0.710	
206165	8279	B2.5Ib	0.108	1.620	4,7
208218		B2II-III	0.110	1.520	2
208440		B1IV	0.091	1.210	2
209339	8399	O9IV	0.052	1.210	7
209961	8427	B2III-IV	0.156	0.835	
212978	8553	B2III	0.150	0.850	5
214240	8606	B4-5III	0.252	0.848	2
214680	8622	O8:V	0.048	0.790	1,2,4,5
217101	8733	B2V	0.132	0.780	2,7
218376	8797	B0.5II	0.074	1.050	1,7
218407	8800	B2V	0.165	0.845	2
222173	8965	B8IV	0.380	0.833	2,3,4,5,7

Notes: 1 = *BCD* standards (Divan 1966), 2 = *UBV* stds. (Harmanec et al. 1994), 3 = MK stds. (Golay 1973), 4 = *uvbyβ* stds. (Perry et al. 1987), 5 = Geneva stds. (Rufener 1979; Hauck 1985), 6 = Thé et al. (1986), 7 = Zorec et al. (1983)

UBV data of comparison stars were taken from Mermilliod & Mermilliod's (1994) compilation. The relation giving the BD from Q_{UBV} is then:

$$D_{UBV} = (0.507 \pm 0.008) Q_{UBV} + (0.496 \pm 0.005) \ \text{dex.} \quad (2)$$

Figure 1a shows D_{BCD} versus Q_{UBV}. Relation (2) has a linear correlation coefficient $r = 0.992$ and leads to a mean (O−C) dispersion $\sigma_{\rm (O-C)} = 0.014$ dex. The gradient $\Phi_{\rm rb}$ is obtained using the $(B-V)$ colour index as:

$$\Phi_{{\rm rb}(UBV)} = (1.80 \pm 0.11)(B-V) + (1.11 \pm 0.02) \ \mu\text{m.} \quad (3)$$

The correlation between $\Phi_{{\rm rb}(UBV)}$ and $\Phi_{{\rm rb}(BCD)}$ is given by:

$$\Phi_{{\rm rb}(UBV)} = (1.00 \pm 0.11)\Phi_{{\rm rb}(BCD)} + (0.00 \pm 0.10) \ \mu\text{m} \quad (4)$$

with $r = 0.975$ and $\sigma_{(\mathrm{O-C})} = 0.06$ μm. Figure 1b shows the correlation between the $\Phi_{\mathrm{rb}(BCD)}$ gradient and the $(B-V)$ index.

ii) The *UBVRI* system.

The *BD* is obtained from relation (2) as for data in the *UBV* system. The gradient Φ_{rb} is now defined by also taking into account the $(V-R)$ colour index, in order to better respect the wavelength interval over which the original $\Phi_{\mathrm{rb}(BCD)}$ gradient is defined. However, with the inclusion of the $(V-R)$ index we cannot avoid introducing a new source of error. The resulting relation is:

$$\begin{aligned}\Phi_{\mathrm{rb}(UBVRI)} \;=\; & (1.63 \pm 0.02)(B-V) + (0.39 \pm 0.11) \\ & (V-R) + (1.10 \pm 0.09)\ \ \mu\mathrm{m}. \qquad (5)\end{aligned}$$

The correlation between $\Phi_{\mathrm{rb}(UBVRI)}$ and $\Phi_{\mathrm{rb}(BCD)}$ is:

$$\Phi_{\mathrm{rb}(UBVRI)} = (0.94 \pm 0.05)\Phi_{\mathrm{rb}(BCD)} + (0.06 \pm 0.05)\ \ \mu\mathrm{m} \qquad (6)$$

with $r = 0.968$ and $\sigma_{(\mathrm{O-C})} = 0.07$ μm. Gradients $\Phi_{\mathrm{rb}(UBVRI)}$ against $\Phi_{\mathrm{rb}(BCD)}$ are shown in Figure 1. The *UBVRI* photometric data used to derive relation (5) are from the "Photoelectric Photometric Catalogue in the Johnson *UBVRI* System" (Lanz 1986).

iii) The Strömgren *uvby* system.

As for the *UBV* system, we derive the value of the *BD* by defining an ISM reddening-free Johnson's like index Q in the Strömgren *uvby* system. This index was determined using the mean ISM absorption law of Mathis (1990) to determine the colour excess factor $E(u-v)/E(b-y)$:

$$Q_{uvby} = (u-v) - 1.079(b-y) \quad \mathrm{mag}. \qquad (7)$$

The *BD* is then given by:

$$D_{uvby} = (0.349 \pm 0.006)Q_{uvby} + (0.070 \pm 0.003)\ \ \mathrm{dex} \qquad (8)$$

with $r = 0.997$ and $\sigma_{(\mathrm{O-C})} = 0.009$ dex. The *BD* could also be derived using the c_1 index of the *uvby* system by:

$$D_{uvby} = (0.383 \pm 0.007)c_1 + (0.086 \pm 0.002)\ \ \mathrm{dex} \qquad (9)$$

but $r = 0.986$ and $\sigma_{(\mathrm{O-C})} = 0.014$ dex. In our work we used relation (8). The gradient Φ_{rb} is obtained from:

$$\begin{aligned}\Phi_{\mathrm{rb}(uvby)} \;=\; & (1.28 \pm 0.20)(v-b) + (1.61 \pm 0.13)(b-y) \\ & +(0.91 \pm 0.01)\ \ \mu\mathrm{m}. \qquad (10)\end{aligned}$$

The correlation between $\Phi_{\mathrm{rb}(uvby)}$ and $\Phi_{\mathrm{rb}(BCD)}$ is:

$$\Phi_{\mathrm{rb}(uvby)} = (0.97 \pm 0.05)\Phi_{\mathrm{rb}(BCD)} + (0.03 \pm 0.05)\ \ \mu\mathrm{m} \qquad (11)$$

where $r = 0.986$ and $\sigma_{(\mathrm{O-C})} = 0.04$ μm. In Fig. 3a we show the relation between D_{uvby} and Q_{uvby}, and in Fig. 3b the relation between $\Phi_{\mathrm{rb}(uvby)}$ and $\Phi_{\mathrm{rb}(BCD)}$. Relations (8) to (10) were derived using data given in the $uvby-\beta$ Photoelectric Photometric Catalogue (distributed by the CDS) (Hauck & Mermilliod 1975; Grønbech & Olsen 1976, 1977).

iv) Thirteen-colour photometry.

As in preceding cases, we also defined an ISM reddening-free index $Q_{13\mathrm{c}}$ using the $(m_{35} - m_{40})$ and $(m_{45} - m_{52})$ colour indices, where m_{35}, m_{40}, m_{45} and m_{52} are magnitudes respectively at 0.3536, 0.4030, 0.4571 and 0.5183 μm effective wavelengths of the 13-colour medium-narrow-band photometric system (Johnson & Mitchell 1975). The $Q_{13\mathrm{c}}$ index is defined as:

$$Q_{13\mathrm{c}} = (m_{35} - m_{40}) - 0.995(m_{45} - m_{52}) \quad \mathrm{mag}. \qquad (12)$$

The resulting relation for the *BD* is:

$$D_{13\mathrm{c}} = (0.382 \pm 0.008)Q_{13\mathrm{c}} + (0.499 \pm 0.007) \quad \mathrm{dex} \qquad (13)$$

where $r = 0.994$ and $\sigma_{(\mathrm{O-C})} = 0.013$ dex. For the gradient Φ_{rb} the relation is:

$$\begin{aligned}\Phi_{\mathrm{rb}(13\mathrm{c})} \;=\; & (1.43 \pm 0.28)(m_{45} - m_{52}) + (1.26 \pm 0.20) \\ & (m_{52} - m_{62}) + (0.99 \pm 0.03). \qquad (14)\end{aligned}$$

The relation between $\Phi_{\mathrm{rb}(13\mathrm{c})}$ and $\Phi_{\mathrm{rb}(BCD)}$ is given by:

$$\Phi_{\mathrm{rb}(13\mathrm{c})} = (0.95 \pm 0.06)\Phi_{\mathrm{rb}(BCD)} + (0.05 \pm 0.06)\ \ \mu\mathrm{m} \qquad (15)$$

for which $r = 0.977$ and $\sigma_{(\mathrm{O-C})} = 0.06$ μm. In the 13-colour photometric system the V magnitude was obtained as:

$$\begin{aligned}V \;=\; & (0.528 \pm 0.002)m_{52} + (0.469 \pm 0.002)m_{58} \\ & +(0.002 \pm 0.010)\ \ \mathrm{mag} \qquad (16)\end{aligned}$$

whose comparison with the original V magnitude of the *UBV* system has a correlation coefficient $r = 0.999$ and $\sigma_{(\mathrm{O-C})} = 0.030$ mag. Figure 4a shows the relation between $D_{13\mathrm{c}}$ and Q_{uvby}, Fig. 4b that between $\Phi_{\mathrm{rb}(13\mathrm{c})}$ and $\Phi_{\mathrm{rb}(BCD)}$ and Fig. 4c that between V and $V_{13\mathrm{c}}$.

v) The Geneva photometric system.

The ISM reddening-free Q index corresponding to this system was defined as:

$$Q_{\mathrm{G}} = (U - B_1) - 1.48(B_1 - B_2)\ \ \mathrm{mag} \qquad (17)$$

from which the respective *BD* can be derived as:

$$D_{\mathrm{G}} = (0.482 \pm 0.007)Q_{\mathrm{G}} - (0.267 \pm 0.007)\ \ \mathrm{dex} \qquad (18)$$

where $r = 0.985$ and $\sigma_{(\mathrm{O-C})} = 0.019$ dex. It can also be shown that:

$$D_{\mathrm{G}} = (0.473 \pm 0.024)d - (0.243 \pm 0.022)\ \ \mathrm{dex} \qquad (19)$$

where d is a measure of the *BD* defined in the Geneva photometric system (Rufener 1981); here we have $r = 0.978$

and $\sigma_{(\mathrm{O-C})} = 0.024$ dex. In our work we used the value D_{G} given by (18). The gradient Φ_{rb} is defined as:

$$\begin{aligned}\Phi_{\mathrm{rb(G)}} = {} & (0.44 \pm 0.08)(B_2 - V_1) + (1.15 \pm 0.06) \\ & (B_2 - G) + (1.83 \pm 0.03) \ \ \mu\mathrm{m}\end{aligned} \quad (20)$$

which compares with $\Phi_{\mathrm{rb}(BCD)}$ as:

$$\Phi_{\mathrm{rb(G)}} = (0.93 \pm 0.04)\Phi_{\mathrm{rb}(BCD)} + (0.07 \pm 0.04) \ \ \mu\mathrm{m} \quad (21)$$

so that $r = 0.964$ and $\sigma_{(\mathrm{O-C})} = 0.07$ μm. Data for comparison stars concerning the Geneva photometric system were taken from Rufener (1980, 1988). Figure 5a shows the relation between D_{G} and Q_{G} and Figure 5b that between $\Phi_{\mathrm{rb(G)}}$ and $\Phi_{\mathrm{rb}(BCD)}$.

2.6. Uncertainties affecting the Φ_{rb} and D parameters

BDs of Be stars in the *BCD* system are given with typical errors $\delta D_* \simeq 0.015$ dex. The width of a D_* interval of a given spectral type-box in the *BCD* system depends on the effective temperature and on the luminosity class. The mean value of these widths is $\Delta D_* = 0.040 \pm 0.008$ dex (Chalonge & Divan 1973). Comparing the *BCD* spectral type determinations of program stars with those given in the MK system for the same objects (Slettebak 1982) we derived the mean absolute spectral type deviation between *BCD* and MK determinations Δ(Sp.T.) = 0.5 ± 0.4 (of sub-spectral type). Hence, we can argue that for those Be stars where only MK classification exists, the value of D_* adopted in Table 1 may be in error by $\delta D_* \lesssim 0.04$ dex.

Among the most important uncertainties affecting the indirect Φ_{rb} and D parameters derived from relations given in Sect 2.5.2 are: (1) random uncertainties of original photometric data; (2) systematic differences related to the effective wavelengths of photometric magnitudes; (3) presence of variable spectral lines in the filter wavelength pass-bands; (4) extrapolations of D values in phases of strong emission in the second *BD* component.

(1) - Uncertainties related to photometric measurements are difficult to determine, as it is not easy to compare measurements given in different systems or even in the various versions of the same photometric system (Sterken & Manfroid 1992). Using the mean errors of individual measurements of colour indices in different photometric systems (CETAMA 1978; Crawford & Barnes 1970; Johnson et al. 1967; Manfroid et al. 1991; Rufener 1981; Shuster 1976; Sterken & Manfroid 1992) and the relations between D, Φ_{rb} and the concerned colour indices given in Sect. 2.5.2, we derived the expected mean errors of individual D and Φ_{rb} for each photometric system used in this work. They are given in Table 3. Whenever possible, we checked that the photometric indices of B0-A1 comparison and/or check stars in the various photometric systems used or versions of same systems did not introduce systematic scatterings higher than those found when establishing the transformation relations of Sect. 2.5.2. It is however known, mainly for the $(U-B)$ colour indices, that according to different authors high systematic deviations may exist. When such deviations were detected, the data concerned were discarded. Systematic differences are sometimes found among *uvby* photometric indices if the filters used are not the same. By comparing non variable stars observed in these slightly different systems and/or looking for simultaneous observations of the studied Be stars, we reduced such observations to a common frame. When these reductions were not possible we did no use the existent data.

Table 3. Mean errors of individual Φ_{rb} and D

System	$\epsilon(\Phi)$ μm	$\epsilon(D)$ dex
BCD	0.035	0.015
Genève	0.040	0.020
uvby	0.070	0.020
13-c	0.085	0.024
UBV	0.054	0.026
UBVRI	0.075	0.026

(2) - The strongest emission in the Balmer continuum appears at $\lambda 0.365$ μm. As the filter-detector response in near-UV is frequently only a few per cent at this wavelength, the reddening effect induced by the CE continuum emission near the *BD* (scaled by calibrations based on normal B stars of Sect. 2.5) can then be underestimated. Hence, relations like (8) or (9) of the *uvby* system and (13) in the Thirteen-colour photometry may in principle give slightly underestimated values of the total *BD*.

(3) - Variations of the (Φ_{rb}, D) parameters cannot always be attributed to variations of the continuum spectrum alone. Spurious reddening and bluening effects can be produced by variable CE emission/absorption components in lines entering the filter wavelength pass-bands. A very rough upper limit of the reddening effect produced by absorption lines in the (Φ_{rb}, D) parameters can be estimated by comparing the *UBV* colour indices of low and high line-blanketed models of stellar atmospheres (Kurucz et al. 1974; Kurucz 1992). Thus, the averaged systematic reddening effect found in the $(B-V)$ and $(U-B)$ indices for log $g = 2.0$ to 4.5 and for all effective temperatures from $T_{\mathrm{eff}} = 8000$ to 30000 K leads to a change $\Delta\Phi_{\mathrm{rb}} = 0.09 \pm 0.04$. Similarly, the highest increase of the *BD*, $\Delta D = 0.06 \pm 0.02$ dex, is for $T_{\mathrm{eff}} = 10^4$ K. It is however much lower for other effective temperatures, especially among the hottest ones. In actual Be stars, we may then expect that, depending on the relative degree of the line emission/absorption variability produced by the CE entering the photometric filter pass-bands, the (Φ_{rb}, D) will show reddening or blueing components which do

not directly reflect variations of the continuum spectrum only.

(4) - As relations between spectrophotometric D and the photometric colour indices were obtained using stars without emission, when $D \sim 0$ or $D < 0$ they are necessarily extrapolated. We compared such extrapolated values of D with those obtained in the BCD for similar strong emission phases of HD 5394, HD 24534, HD 60848, HD 148184 and HD 200120 which can be seen in Fig. 6. However, the nice agreement between both determinations do not indicate the existence of any strong deviation.

The total amount of the quoted uncertainties is almost impossible to estimate, because they depend on the star and on its variation phase. However, using as reference the $(\Phi_{\rm rb}, D)$ relations derived from BCD system measurements only [which are independent of uncertainties (1) to (4)] of strongly variable Be stars, we can obtain a rough estimate of the mean total amount of possible deviations which affect the indirect $\Phi_{\rm rb}$ and D parameters derived from multicolour filter photometry. Comparing the mean deviations of data in each photometric system with the mean regression lines derived with genuine BCD parameters, we obtain $\overline{\Delta D} = 0.02$ dex and $\overline{\Delta\Phi_{\rm rb}} = 0.050$ μm.

3. Results

The spectrophotometric data gathered for all program stars are presented in Fig. 6 (available in electronic form). For each star there are three panels. The first shows the observed time variability of the V, $\Phi_{\rm rb}$ and D. The second panel shows the (U, D), (V, D) and $(\Phi_{\rm rb}, D)$ correlations and the third the $(\Phi_{\rm rb}, V)$ correlation. The symbols used are: black dots for the BCD data, crosses for UBV data, stars for $UBVRI$, triangles for Geneva photometry, diamonds for the $uvby$ system and squares for 13-colour data. The following comments for individual stars are divided into two subsections according to the degree of known spectrophotometric and spectroscopic variations.

3.1. Spectrophotometric and spectroscopic behaviour of some well-studied Be stars

This subsection deals with program Be stars, for which we have enough BCD spectrophotometric observations to allow us: (a) to estimate the uncertainties discussed in Sect. 2.6; (b) to assign not only a degree of reliability to relations derived using only indirect $(V, \Phi_{\rm rb}, D)$ parameters, but also to judge the likelihood of scatters and more or less systematic deviations from the sketched mean relations. As for all these objects rather copious spectroscopic observations exist, in this section we also summarize their main spectroscopic variations over the last fifty years, more or less simultaneous to photometric data which are analyzed in this paper. The qualitative description of the correlated spectroscopic and spectrophotometric behaviours of these objects can be used as a reference for the remaining program stars, for which only spectrophotometric variations are presented. These stars are divided into two groups: (1) Be stars most commonly seen in Be phases: γ Cas, X Per, 11 Cam, χ Oph and 59 Cyg; (2) Be stars most frequently observed in Be-shell phases: Pleione, 48 Lib and 88 Her.

3.1.1. Stars most frequently seen in Be phases

γ Cas (HD 5394)

Observed since 1866, γ Cas firstly showed a long Be phase of strong emission. Then, between 1932 and 1942, dramatic changes occurred in its spectrum; two strong Be phases, each followed by a strong shell phase, have been observed (Doazan et al. 1983 and references therein). In 1942, γ Cas entered a quasi-normal B phase. Four years later, a subsequent Be phase increased slowly and irregularly. Weak secondary minima in emission were reported in 1956-1961 (Hubert-Delplace & Hubert 1979 hereafter referred to as "Atlas"), end 1975, 1983-1984 (Horaguchi et al. 1994 and references therein) and in 1990-1991 (Peters 1990, 1991); a "veiling" effect of lines was seen from the end of 1963 to 1972 (Atlas). According to Horaguchi et al. (1994), Hα intensity has oscillated with a time scale of several years. Long-term far UV and visual variability seems to be associated (Doazan et al. 1987).

It is interesting to note that the minima in the $\Phi_{\rm rb}$ gradient correspond to minima in emission strength and the maximum of $\Phi_{\rm rb}$ in 1966 to a veiling in line spectra. Furthermore the total BD is strongly negative at the epochs of strong outbursts (1932-1942). Somewhat scattered but single ($\Phi_{\rm rb}$, D) and ($\Phi_{\rm rb}$, V) correlations with $\partial\Phi_{\rm rb}/\partial(D, V) < 0$ slopes are present, although photometric and spectrophotometric data correspond to epochs before and after a number of Be $\rightleftharpoons$ B-normal $\rightleftharpoons$ Be-shell phase transitions. We note, however, that the (V, D) relation has two branches in $-0.025 \lesssim D \lesssim D_*$ dex. Let us finally note that the rapid photometric variability which is commonly associated with surface stellar activity is still debated for this object.

***X* Per (HD 24534)**

Variable but generally weak emission was noted in the spectrum of X Per before the end of the forties (Cowley et al. 1972). In 1951-1953, a strong emission phase phase with a "veiling" effect began; afterwards marked strengthening (outburst) of emission lines (H I, He I, Fe II, Si II) and of the "veiling" effect from 1957 to 1961 has been reported, with a maximum in 1961 (Cowley et al. 1972; Wackerling 1972, Atlas). In 1974 the emission decreased for 2 years, becoming bright again by the end of 1976. In 1978, only very weak emission was seen in Hα, the spectrum was consistent with a quasi-normal O9-B0 star (de Loore et al. 1979). By the end of 1978, a new emission phase reappeared (Roche et al. 1993 and references therein). Still fairly bright in February 1990, the Hα line was seen converted to absorption in September 1990. A strong shell feature superposed on the photospheric component of Hα and He I 6678 in Nov., Dec. 1990 and Jan. 1991 was reported

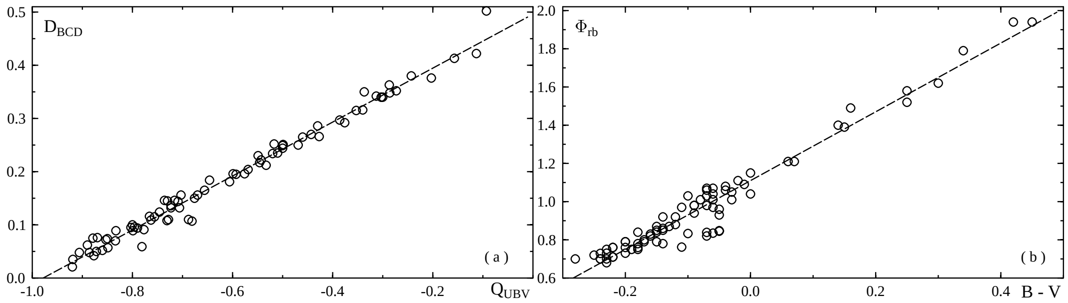

Fig. 1. a) Transformation of Q_{UBV} to D_{BCD}. **b)** Transformation of the $(B-V)$ colour index to the gradient $\Phi_{\rm rb}$

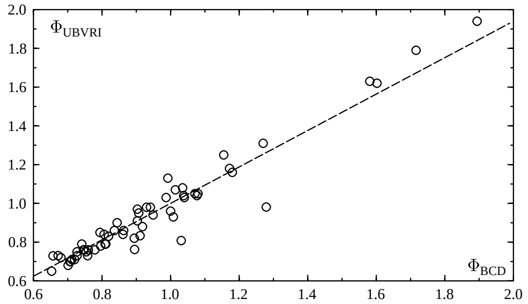

Fig. 2. Comparison of $\Phi_{{\rm rb}(UBVIR)}$ with $\Phi_{{\rm rb}(BCD)}$ gradients

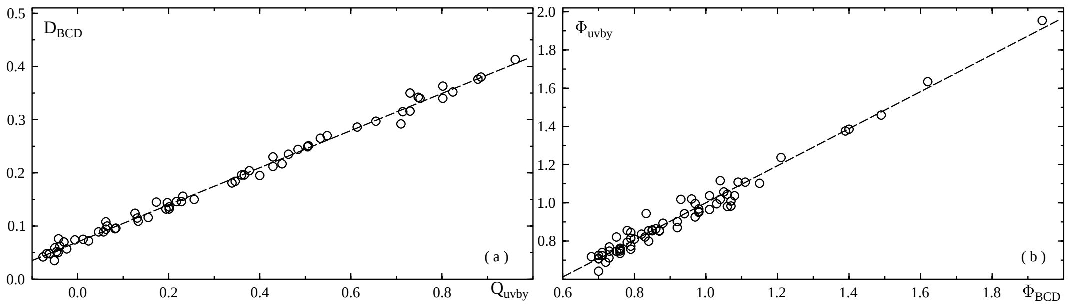

Fig. 3. a) Transformation of $Q_{\rm uvby}$ to D_{BCD}. **b)** Comparison of $\Phi_{{\rm rb}(uvby)}$ with $\Phi_{{\rm rb}(BCD)}$ gradients

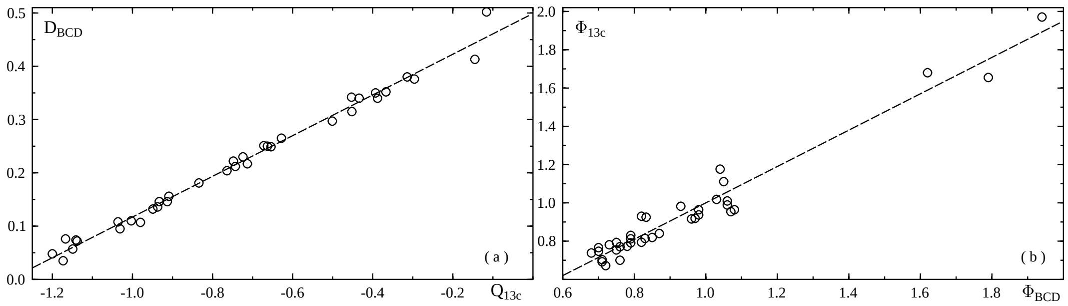

Fig. 4. a) Transformation of $Q_{\rm 13c}$ to D_{BCD}. **b)** Comparison of $\Phi_{\rm 13c}$ with $\Phi_{{\rm rb}(BCD)}$ gradients

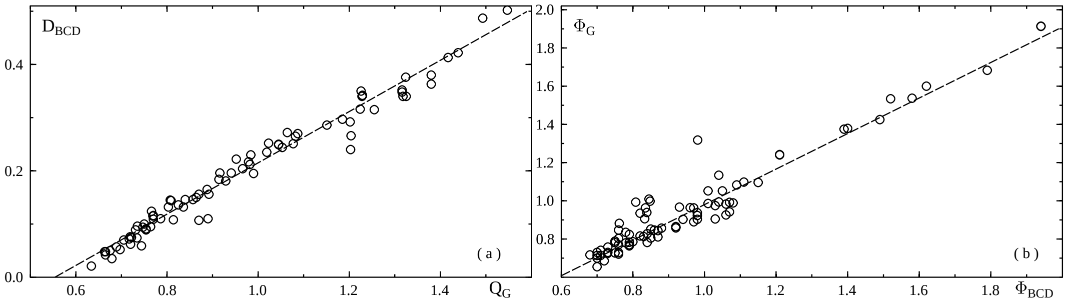

Fig. 5. a) Transformation of $Q_{\rm G}$ to D_{BCD}. **b)** Comparison of $\Phi_{\rm rb(G)}$ with $\Phi_{{\rm rb}(BCD)}$ gradients

by Norton et al. 1991. Still in absorption in Sept. 1991 (Reynolds et al. 1992), weak emission was again present on Hα in Oct. 1991 (Kaper & van Kerkwijk 1992).

Decrease and minima of line emission generally correspond to lower brightness states. Single ($\Phi_{\rm rb}$, D) and ($\Phi_{\rm rb}$, V) correlations are accompanied by bifurcated or doublefold (U, D), (V, D) relations with $\partial(U,V)/\partial D > 0$ slopes in $D < D_*$ corresponding to definite Be phases. The stellar BD is $D_* = 0.050$ dex (de Loore et al. 1979). For $D \gtrsim D_*$ incipient horizontal relations: $\partial(V, \Phi_{\rm rb}, U)/\partial D \simeq 0$ are apparent which correspond to the shell phase.

11 Cam (HD 32343)

11 Cam has always had strong emission observed up to high Balmer lines. Often observed before 1975, this star has presented recurrent outbursts. Schild (1973) reported outbursts in 1916-1919, 1929-1931 and 1943-1949. From 1953 to 1974, emission was always strong in Balmer lines with a weak minimum in 1961. Bright and particularly clear Fe II lines were reported from 1963 to 1971 during maximum emission. Afterwards they seem to have disappeared (Atlas). Isolated observations between 1980 and 1989 of the Hα emission line have revealed a rather constant strength of this line except in October 1983 (Ballereau & Chauville 1987) for which the line is very strong (no photometry available at that time). Conversely no spectra are available at maximum brightness in November 1977. The rapid photometric variability of this star is suspected although not yet confirmed.

Single (U, D), (V, D), and ($\Phi_{\rm rb}$, V) relations are seen, although they all have $\partial(U,V)/\partial D < 0$ and $\partial\Phi_{\rm rb}/\partial V > 0$ slopes. The ($\Phi_{\rm rb}$, D) relation is scattered and single, however it has a $\partial\Phi_{\rm rb}/\partial D < 0$ slope.

χ Oph (HD 148184)

Since 1919 χ Oph has been characterized by strong emission in Balmer lines (Schild 1973; Slettebak 1982). A very strong emission in Balmer and Fe II lines between 1953 and 1973 with a veiling effect seen up to 1969 (Atlas). From 1979, Fe II emission lines have decreased in intensity; they were barely visible in 1975. Andrillat & Fehrenbach (1982) and Dachs et al. (1981) noted a steady decrease in the strength of Hα emission from 1972 to 1980. Then it seems to have slightly increased in 1982-1983, with a maximum through March 1983 (Dachs et al. 1986), and afterwards fluctuated with maxima $I/I_{\rm c} = 10 - 11$ in 1985, 1989 and 1993 (Hanuschik et al. 1996). The decrease of the Hα emission line from 1972 to 1980 corresponds to an increase of brightness and to reddening of the gradient $\Phi_{\rm rb}$. Total Balmer discontinuity D varied strongly during this period with a strong minimum near 1983. D is at minimum when $I/I_{\rm c}$ of Hα emission is at maximum. χ Oph is a rapid photometric variable star (Balona 1995) with a moderate $V\sin i$ (< 130 km s^{-1}).

The (U, D) and (V, D) relations are single for $D < 0$ with $\partial(U,V)/\partial D < 0$ slopes, but two branches with $\partial(U,V)/\partial D > 0$ slopes seem to appear at $D \simeq 0$. The ($\Phi_{\rm rb}$, D) and ($\Phi_{\rm rb}$, V) relations are scattered and whilst the first is likely to be single with a $\partial\Phi_{\rm rb}/\partial D < 0$ slope, the second seems to be double valued with one of the branches with a $\partial\Phi_{\rm rb}/\partial V > 0$ slope.

59 Cyg (HD 200120)

Since 1904, 59 Cyg has presented active and quiescent phases in the behaviour of its CE, successively producing spectra with the appearance of a quasi-normal B, Be and Be-shell star. Long-term, rather stable, strong emission-line phases alternate with phases of marked changes, generally characterized by slow increase and shorter decreases of the strength of emission lines. A slow increase of emission was observed from 1945 to 1950 (Merrill & Burwell 1949). Afterwards, a quiescent phase set in from 1953 to 1970, the emission features being relatively stable; emission was at maximum in 1956 and in 1961, and at minimum in 1967 (Atlas). Short-lived outbursts were then observed from July to the end of 1972 and from December 1973 to June 1974, each followed by a strong shell phase of several months duration. After that, emission vanished and almost completely disappeared in 1976-1977 (Hubert-Delplace & Hubert 1981). An increase of emission started in the end of 1979 and ended near mid-1980. Emission decreased again to a minimum in 1982, and again increased from 1983 to 1986. From 1979 to 1985 strong Hα emission strength changes occurred, being correlated with the wind observed in the far UV (Doazan et al. 1989). From 1986, a new, rather stable quiescent emission phase has been established (Peters 1989-1992, 1994).

Strong emission lines are present when $D < D_*$ and the line emission decrease corresponds to a progressive increase of the BD, which ended at $D = D_*$ in 1977 when the line emission almost disappeared. From the existing photometric data, it is seen that after 1961 the mean V magnitude suddenly began decreasing until 1977, fluctuating at intervals of 3.4 ± 0.4 yrs. with a variable, damped-like amplitude whose maximum was nearly 0.4 mag. The intrinsic continuum reddening seems to be strongest when the star is brightest but not necessarily well correlated with line emission intensity as $\Phi_{\rm rb}$ remains high even in 1967 at a relative minimum of line emission. This reddening cleared up in 1977, so that $\Phi_{\rm rb}$ became that of a B1V normal star for $D_* = 0.116$ dex shown by a dashed vertical line in Fig. 6. Unfortunately, there are no photometric data corresponding to epochs of short-lived shell phases in 1973 and 1974. It is seen, however, that the (U, D), (V, D), $(\Phi_{\rm rb}, D)$ and $(\Phi_{\rm rb}, V)$ relations are single with $\partial(U, V)/\partial D > 0$ and $\partial\Phi_{\rm rb}/\partial(D, V) < 0$ slopes and that they are nicely conserved, even after the shell phases and the periods of loss of emission characteristics. A photometric microvariability of this star was observed, but there is no period determination at the present time.

3.1.2. Stars most frequently seen in Be-shell phases

Pleione (HD 23862)

Notable long-term changes are reported in the literature, for this star, see Hirata (1995) and references therein. Recently this star was discovered by Katahira et al. (1996) to be a binary with an orbital period of 218.0 days. We give here only a summary of spectral variations. Observed in a Be phase until 1904, Pleione entered a phase showing a rapidly rotating B normal-like star from 1905 to 1936. The first Be-metallic shell phase occurred in 1938 and ended in 1954. From 1954 to 1972, this star again entered a Be phase with strong Balmer and Fe II emission lines at maximum around 1960. Then gradual weakening began; in 1972, the Hα emission line was very weak. In late 1972 another metallic shell phase started and developed with a maximum near mid-1982. The metallic lines faded and disappeared in 1988 (Hirata 1995). The star entered a new Be phase; the Hα emission line gradually increased from 1982 (epoch of maximum strength in shell lines) to 1993 and decreased after. The global behaviour of spectral and light changes has been studied by many authors (Hirata & Kogure 1976; Kogure & Hirata 1982; Goraya & Tur 1988). A steep decline in brightness occurred in 1938 and 1972 as each respective shell phase started. Furthermore, a strong weakening in the U magnitude came with the maximum of metallic shell lines in 1982-1983.

From our study it is shown that in 1972, at the epoch of the appearance of a new Be-metallic shell phase associated with a rapid fainting in the UBV colours, the $\Phi_{\rm rb}$ gradient rapidly increased and total BD decreased indicating the contribution of a secondary BD in emission. Between 1972 and 1988 the behaviour of the total BD was the same as the strength of the metallic shell lines. It is interesting to note that the maximum value of the total BD reported in 1982 corresponds to a maximum of the absorption strength of metallic lines. In the short interval of $D < D_*$, this star shows two (U, D) and (V, D) relations which are continued in the region of $D > D_*$, where normally in Be shell phases there is a single relation. The $(\Phi_{\rm rb}, D)$ and $(\Phi_{\rm rb}, V)$ seem to be single, unless for $D < D_*$ possible double relations are not well resolved. The $(\Phi_{\rm rb}, D)$ relation is slopeless, while $(\Phi_{\rm rb}, V)$ seems to have a global $\partial\Phi_{\rm rb}/\partial V > 0$ slope. Rapid photometric variability was found in this object (McNamara 1987).

48 Lib (HD 142983)

48 Lib is one of the best examples of shell stars. The variable shell episode of 48 Lib started in 1935: RV cycles (8−13 yr), marked variations of intensity and in line profiles. These phenomena become more striking with increase of the amplitude of radial velocity (RV) (Aydin & Faraggiana 1978 and references therein; Mon 1984; Hubert et al. 1987). In 48 Lib successive cycles exhibit negative RV phases longer than positive ones. The strength of shell lines has varied strongly since 1935. It was near or at maximum in 1943, 1965, 1970, 1974 and towards the end of 1993, according to recent observations published by Hanuschik et al. (1996). Maxima in the strength of emission in the first Balmer lines were generally seen at the same time or very close. Long-term photometric variations associated with spectroscopic cycles, and mid-term quasi-periodic oscillations (10−20 days) and sudden fadings (1−2 days) were reported by Mennickent et al. (1994) . These authors noted a brightness maximum in 1988 and possible minima in 1982 and 1991. In compiled data presented in this study, pronounced maxima of brightness were observed in 1976 and 1988. Balmer discontinuity is respectively lower and higher at epochs close to minima and maxima of the strength of shell metallic lines. Single relations are seen in (U, D), (V, D), $(\Phi_{\rm rb}, D)$ and $(\Phi_{\rm rb}, V)$. The (U, D) has a $\partial U/\partial D > 0$ slope, while in all others there is no slope. This star is a rapid photometric variable, which may in part explain the width of spectrophotometric relations.

88 Her (HD 162732)

88 Her is well-known to have presented associated long-term changes in its spectrum and in its light; in addition it was discovered by Harmanec et al. (1972) to be a binary ($P = 86.72$ days). This star exhibited a Be phase with a hydrogen and metallic shell from 1955 to 1960. The Hα emission line gradually weakened from 1961 to 1971; the metallic shell lines, very weak from 1966, disappeared near 1970 (Atlas). In 1972-1976, the star was in a quasi-normal B phase, the Hα emission line was very weak in 1976-1977, and at the same epoch a minimum of the linear optical

polarization was seen (Arsenijević et al. 1987). Then, the Hα emission line again gradually increased from 1977 to 1986. In addition, from 1978 to 1982, a new metallic shell phase was increasing, followed from 1983 to 1986 by a decreasing metallic shell and mild Be phase (Doazan et al. 1982a; Hirata 1995). It was reported that the gradual weakening of Balmer emission and metallic shell lines in 1966-1970 was associated with brightening of the star (Doazan et al. 1982b) and that a large and rapid drop of the luminosity occurred near 1978, just before the development (1978-1982) of a new Be-shell metallic phase (Harmanec et al. 1980; Doazan et al. 1986; Hirata 1995). The polarization percentage rapidly increased in 1978, followed by a slow decline from 1979 to 1985 (Arsenijević et al. 1987).

From this study, it is seen that the total BD was at minimum when the metallic shell lines disappeared towards 1970 and during the quasi-normal B phase (1972-1976). Then it gradually increased to mid-1982, in the same manner as the strength of shell lines. On the other hand, the star became brighter as the equivalent width of the Hα emission line increased (1978-1986), according to Hirata (1995). It is worth noting that BCD observations of the stellar BD from mid-1977 to the end of 1983 do not reveal any change in the photospheric $T_{\rm eff}$ and $\log g$ parameters of this star during its phase changes (Zorec et al. 1989). The difference of brightness in the U and V magnitudes between the regions of $D < D_*$ and $D > D_*$ are clearly seen in Fig. 6. Single and slopeless relations (U, D), (V, D), ($\Phi_{\rm rb}$, D) and ($\Phi_{\rm rb}$, V) are characteristic for $D > D_*$. No rapid photometric variability was found in this object.

3.2. Brief remarks on the remaining Be stars

HD 28497. A rapid photometric variable star. The emission is strong when D is small. The emission was low from 1989 to 1992; since then, D and V are increasing.

HD 35439. After a B normal-like phase, Hα emission appeared when D was at its minimum value.

HD 37202. A shell and rapidly variable star. D is at minimum when the strength of the shell is at minimum, but in such a case the RV is not at minimum in this star.

HD 37967. Emission is strong and there is almost no variation.

HD 48917. A rapidly variable star. Only a few spectroscopic data exist for this star.

HD 50123. Interacting binary having a composite B spectrum with a giant K companion. "Ellipsoidal" photometric variations with a period of $P = 28.6$ days were found by Sterken et al. (1994).

HD 56014. Star with a moderate rotation ($V\sin i = 150$ km s^{-1}) showing at epochs a shell behaviour $D > D_*$.

HD 56139. A rapidly variable star with a small $V\sin i$ (60 km s^{-1}) but sometimes showing the shell behaviour $D > D_*$. The value of $I/I_{\rm c}$ for Hα is rather high ($I/I_{\rm c} = 6$). When D is smallest, Hα emission is weak.

HD 58978. A helium-shell star. The strong spectroscopic variations in 1990 and in 1991 do not seem to be apparent for the spectrophotometric variations.

HD 60848. One of the hottest Be stars where the Balmer and Paschen line emission is well correlated with the Balmer continuum emission.

HD 60855. Star with moderate line emission showing B $\leftrightarrows$ Be phase transitions. There are no strong spectrophotometric variations.

HD 63462. Star showing slight variations in the Hα emission intensity.

HD 65875. A rapidly variable star with moderate $V\sin i$ (150 km s^{-1}) and showing however phases with the shell behaviour $D > D_*$. The star has a high value of $I/I_{\rm c}$ in Hα ($I/I_{\rm c} = 9$). Slopes $\partial(U,V)/\partial D < 0$ and $\partial\Phi_{\rm rb}/\partial V > 0$ seem to exist for this star.

HD 68980. Star with a very moderate $V\sin i$ (95 km s^{-1}) and with very strong Hα emission ($I/I_{\rm c} = 12$). D seems to be smallest when Hα emission is strongest. Two relations between U, V versus D and for $\Phi_{\rm rb}$ against V are apparent.

HD 83953. A rapidly variable star where D is probably at maximum when the emission is low.

HD 89890. A star with a low rotation, $V\sin i = 70$ km s^{-1}, having $D > D_*$.

HD 91120. Emission is moderate with few variations.

HD 109387. A rapidly variable star. Emission is strong when D is low and $\Phi_{\rm rb}$ is high. There is a high dispersion in the (D, V) diagram for $D \sim D_*$ in 1986.

HD 120991. Star with small $V\sin i$ (70 km s^{-1}). Sometimes $I/I_{\rm c}$ is high for Hα ($I/I_{\rm c} = 7$ in 1993). D diminishes when the emission increases. There are probably two correlations for U and V as a function of D.

HD 131492. A temporary strong shell phase was observed by Slettebak in 1980 which corresponded to a minimum in V and to a maximum in D (Slettebak 1982). This is responsible for the horizontal part in the diagram of $\Phi_{\rm rb}$ against D. The shell behaviour $D > D_*$ is clearly seen, although the star apparently has moderate rotation ($V\sin i = 100$ km s^{-1}).

HD 162428. The emission and the shell are variable.

HD 168797. This is a B $\leftrightarrows$ Be phase variable star. Emission is moderate.

HD 171780. A B $\leftrightarrows$ Be variable star with moderate emission.

HD 178175. Star observed in spectroscopy very irregularly. The shell behaviour $D > D_*$ is slightly present and the star has a moderate rotation ($V\sin i = 120$ km s^{-1}).

HD 183656. A rapidly variable shell star. D is correlated with the V/R variations (the V/R and radial velocity curves are given in Koubsky et al. 1989). D is at maximum when the RV is at maximum.

HD 184279. A shell star, where D is correlated with the magnitude V and with the RV curve: D is at maximum as RV is maximum (in 1979).

HD 187811. A B $\leftrightarrows$ Be variable star with rather moderate emission.

HD 191610. A rapidly variable star. It has been seen in B phase in 1955 to 1958, and in a Be phase since then. Emission is moderate.

HD 195325. A late Be star with a hydrogen and metallic shell.

HD 205637. A rapidly variable star where the hydrogen and metallic-line shell are variable.

HD 217050. A rapidly variable shell star. D is at maximum when the strength of the shell is at maximum.

HD 217543. Star with moderate emission showing B $\leftrightarrows$ Be phase transitions.

HD 218674. Star with rapid variability. It also shows strong emissions and a hydrogen-shell.

3.3. Comments on the correlations obtained

3.3.1. General spectrophotometric behaviour

We may conclude that patterns in Fig. 6 show that spectrophotometric changes in Be stars are characterized by $(U, V, \Phi_{\rm rb}; D)$ and $(\Phi_{\rm rb}, V)$ relations which differ on the emission/absorption phase and may differ from star to star. More or less well-defined relations involving $D < D_*$ correspond to definite Be-phases. They can be either single or bivalued, mostly with $\partial(U,V)/\partial D > 0$ and $\partial\Phi_{\rm rb}/\partial D < 0$, but sometimes also with slopes $\partial(U,V)/\partial D > 0$ and $\partial\Phi_{\rm rb}/\partial D > 0$. On the contrary, the most current shape of relation during SPh-shell phases where $D > D_*$ can be summarized by: $\partial(V,\Phi_{\rm rb})/\partial D \simeq 0$, and depending on the stars $\partial U/\partial D \simeq 0$ or $\partial U/\partial D > 0$. The constancy of the magnitude V is within 0.15 mag and sometimes even more. However, for some Be-shell stars, variation in V can be as high as 0.25 mag.

In general, of those Be stars which have two correlations of U, V against D, and, $\Phi_{\rm rb}$ against V in Be phases $(D < D_*)$, nearly all have strong Balmer emission lines. The fact that there are two relations or only one is not related to particular values of $V\sin i$.

3.3.2. Stars with low $V\sin i$ in SPh-shell phases

It is noteworthy the behaviour of some stars like HD 56014, HD 56139, HD 65875, HD 131492, where all have D_* determined in the *BCD* system, which show both SPh-Be and SPh-shell phases. The mean deviation of these objects for the SPh-shell phase is $\overline{D - D_*} = 0.09 \pm 0.04$ dex which is more than 3 times the expected error $\epsilon(D)$ given in Table 3. Most of these deviations are depicted by data from the Geneva photometric system, which is one of the most stable and uniform (Sterken & Manfroid 1991). These comments are also relevant to HD 178175, where D_* is only for the mean MK spectral type and the $D - D_* \le 0.04$ dex deviations of the SPh-shell like phase are established from the Geneva photometric data. In Fig. 6 we see that for most of the above mentioned stars, the transition between a SPh-Be and a SPh-shell phase is characterized by a change of slopes in the spectrophotometric correlations. It would be difficult to understand such slope changes in terms of errors affecting the BDs, as they would likely conserve one of the observed slopes.

Among those stars where both spectrophotometric behaviours: Be $(\Delta V < 0;\ D < D_*)$ and shell $(\Delta V \gtrsim 0;\ D > D_*)$ were seen, there are some with small or moderate $V\sin i$. We also note that two Be stars with low $V\sin i$ were seen *only* in SPh-shell phases where $\Delta D > 0$ (HD 89890 ($V\sin i = 70$ km s^{-1}) and HD 178175 ($V\sin i = 120$ km s^{-1}). Low values of $V\sin i$ may correspond either to small $\sin i$ or to low velocity V. In the first case, the SPh-shell phase: $D > D_*$, cannot be explained by highly flattened CE seen pole-on. In the second case, we should admit the existence of an important fraction of slowly rotating Be stars (Mennickent et al. 1994). Nevertheless, for most Be-shell stars studied in this paper it is $\overline{V\sin i} \sim 300$ km s^{-1}.

On the other hand, it is also worth noting that in Be-shell stars where enough RV data existed to be correlated with D (HD 142983, HD 183656, HD 184279 etc.), the highest RV > 0 appear when the line shell phenomenon and the absorption in the *BD* due to the CE are strongest. This phenomenon might favor the formation of compact CE layers near the star.

4. Discussion

Using a simple phenomenological model for a star-CE system, we give in this section an outline for a discussion which aims at obtaining the first indications on the continuum opacity regimes of CE in Be stars, responsible for their most characteristic spectrophotometric changes, namely: (a) single relations in definite SPh-Be phases with slopes $\partial V/\partial D > 0$ and $\partial\Phi_{\rm rb}/\partial(D,V) < 0$; (b) no variation of V and $\Phi_{\rm rb}$ in SPh-shell phases $(\partial(V,\Phi_{\rm rb})/\partial D = 0)$.

4.1. Model of the CE

Assuming an ellipsoidal CE with ellipticity $E = h/R_{\rm e}$ (h is the polar height of the CE and $R_{\rm e}$ its equatorial radius), the radiation flux emitted by a Be star can, in a first approximation, be described with an ellipsoidal slab-like model as:

$$F_\lambda/F_\lambda^* \simeq s_\lambda + \delta \times (1 - {\rm e}^{-2\tau_\lambda}) \qquad (22)$$

where the geometrical factor δ, which is also proportional to the ratio of the envelope source function to the underlying stellar flux, is:

$$\delta = \Omega \times [B_\lambda(T_{\rm env})/F_\lambda^*]. \qquad (23)$$

In (22) we have $s_\lambda = \mathrm{e}^{-\tau_\lambda}$ for $h > R_*$, where $\tau_\lambda = \tau_\lambda^\circ[1-(1-E^2)\sin i^2]^{-1/2}$ is the radial optical thickness of the shell. For cases where $h < R_*$ and $i \leq i_\mathrm{h} = \mathrm{arc}\,\cos(h/R_*)$ (polar regions of the star not shielded by the CE) it is $s_\lambda = 1$. In (23) $\Omega = (R_\mathrm{e}/R_*)^2[1-(1-E^2)\sin i^2]^{1/2}$ is the normalized projected area of the CE; B_λ is the Planck function for the CE excitation temperature T_env; F_λ^* is the stellar flux. Except for $i \leq i_\mathrm{h}$ when $h < R_*$ so that $s_\lambda = 1$, we see that τ_λ and δ are scaled by the same constant factor $[1-(1-E^2)\sin i^2]$. For a qualitative discussion of (22) we may then use either a given value of $[1-(1-E^2)\sin i^2]$ or simply, for the sake of brevity, consider $E = 1$, which corresponds to a spherical CE. This approximation was widely used in the literature to discuss visible energy distributions of Be stars. We also assume that the stellar components (V_*, Φ^*_rb, D_*) are not variable (Zorec & Briot 1991). Thus, using (22) with $E = 1$, the magnitude excess $\Delta V = V - V_*$, the colour excess $\Delta\Phi_\mathrm{rb} = \Phi_\mathrm{rb} - \Phi^*_\mathrm{rb}$ and the BD discrepancy $\Delta D = D - D_*$ produced by the CE, can be represented as:

$$\left.\begin{array}{rcl}\Delta V(\delta,\tau_{\lambda_\mathrm{V}}) & = & -2.5\times\log\,(F_{\lambda_\mathrm{V}}/F^*_{\lambda_\mathrm{V}}) \\ \Delta\Phi_\mathrm{rb}(\Phi_\mathrm{e},\delta,\tau_{\lambda_\mathrm{V}}) & = & -[\mathrm{d}\,\ln(F_\lambda/F^*_\lambda)/\mathrm{d}\,(1/\lambda)]_{\lambda_\mathrm{V}} \\ \Delta D(\Phi_\mathrm{e},\delta,\tau_{\lambda_\mathrm{V}}) & = & \log\,[F_{\lambda^+_\mathrm{D}}/F^*_{\lambda^+_\mathrm{D}})/(F_{\lambda^-_\mathrm{D}}/F^*_{\lambda^-_\mathrm{D}})]\end{array}\right\}\quad(24)$$

where $\lambda_\mathrm{V} = 0.55\ \mu$m; $\lambda^\pm_\mathrm{D}$ stand for the Paschen and Balmer sides of the continuum energy distribution at $\lambda_\mathrm{D} = 0.37\ \mu$m. The gradients are obtained using the classic definition (Allen 1973): $\Phi = 5\lambda - \mathrm{d}\,\ln F_\lambda/\mathrm{d}(1/\lambda)$. The gradient Φ_e is derived from $B_{\lambda_\mathrm{V}}(T_\mathrm{env})$, so that $\Phi_\mathrm{e} \propto 1/T_\mathrm{env}$.

Before going into details of (24), let us comment on the curves $\delta = \delta(\Delta V, \tau_{\lambda_\mathrm{V}})$ shown in Fig. 7 which describe the main characteristics of (22) regarding the photometric variations of Be stars. Depending on the sign of ΔV, two behaviours can be distinguished: (a) that corresponding to $\Delta V < 0$, which is typical for a SPh-Be phase and where we always have $2\delta > 1$; (b) that of $\Delta V > 0$, which corresponds to a SPh-shell phase and where it is always $0 \leq \delta \leq 1$. In (a) two distinct regimes may clearly be identified: (*i*) a low opacity regime characterized by $\tau_{\lambda_\mathrm{V}} < \tau_\mathrm{or} \sim 0.7|\Delta V|^{0.55}$ (vertical side of $\delta(\tau_{\lambda_\mathrm{V}})$ curves); (*ii*) a high opacity regime, where $\tau_{\lambda_\mathrm{V}} > \tau_\mathrm{or}$ (horizontal side of $\delta(\tau_{\lambda_\mathrm{V}})$ curves). Both regimes are schematically separated in Fig. 7 by dashed lines at τ_or (to sketch out the separation of opacity regimes τ_or was choosen so that $\partial\delta/\partial\tau_\mathrm{V} = -1$). In Fig. 7, it can also be seen that in the low opacity regime: $\tau_{\lambda_\mathrm{V}} < \tau_\mathrm{or}$, changes in the magnitude V are mainly an opacity effect, because even if δ do not remain constant, small variations of $\tau_{\lambda_\mathrm{V}}$ will introduce marked changes of ΔV. On the contrary, when $\tau_{\lambda_\mathrm{V}} > \tau_\mathrm{or}$, variations in V mostly reflect changes of δ. In (b), that is, for a SPh-shell behaviour, $\tau_{\lambda_\mathrm{V}} \geq \tau_\mathrm{sh} = 0.92\Delta V$, which corresponds to a high opacity regime. Curves $\delta(\Delta\Phi)$ and $\delta(\Delta D)$ against $\tau_{\lambda_\mathrm{V}}$ also have the same kind of patterns as $\delta(\Delta V)$, but their dependences on Φ_e and ΔD reveal some more subtle behaviours.

We note that the sign of ΔV is a function of δ and $\tau_{\lambda_\mathrm{V}}$ only. Hence, the magnitude changes corresponding to *both* spectrophotometric phase variations in the *same* star can be described with a simple *spherical* CE. In the next subsection we shall also see that for the same star this model is enough to explain the main spectrophotometric characteristics of both SPh-Be and SPh-shell phases. We note again that for flattened CE with $h \leq R_*$ seen at angles $i \lesssim i_\mathrm{h}$, as $s_\lambda = 1$ we cannot have $\Delta V > 0$. On the other hand, it may happen that $\Delta V = 0$, even if $\delta \neq 0$ and $\tau_{\lambda_\mathrm{V}} \neq 0$.

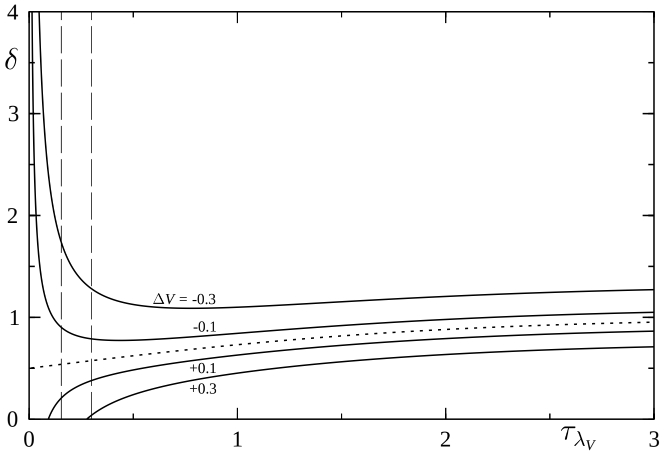

Fig. 7. Ratio δ (for $E = 1$) as a function of optical depth $\tau_{\lambda_\mathrm{V}}$ for several values of ΔV corresponding to Be phases ($\Delta V < 0$) and Be-shell phases ($\Delta V > 0$). The vertical dashed lines schematically divide zones of low and high opacity for the respective $\Delta V < 0$. The dotted curve corresponds to $\Delta V = 0$

4.2. Spectrophotometric variations

In patterns of Fig. 6, two spectrophotometric behaviours seem to be the most relevant: (a) in SPh-Be phases, where $\Delta D = D - D_* < 0$, there are linear correlations between (V, D) and (Φ_rb, D) so that $\partial V/\partial D > 0$ and $\partial\Phi_\mathrm{rb}/\partial(D, V) < 0$; (b) in shell phases, where $\Delta D > 0$, there is a very small variation, if any, of Φ_rb and V as a function of D. Let us then see in what opacity regime these variations can take place.

4.2.1. Low opacity regime

For $\tau_{\lambda_\mathrm{V}} < \tau_\mathrm{or} < 1$, where $\delta > 1$, from (24) we derive the following relations:

$$\left.\begin{array}{rcc}\Delta V & \sim & -0.9\tau_{\lambda_\mathrm{V}}(2\delta-1) \\ \Delta\Phi_\mathrm{rb} & \sim & \tau_{\lambda_\mathrm{V}}[\delta(2\Delta\Phi_\mathrm{e}+6\lambda_\mathrm{V})-3\lambda_\mathrm{V}]/(1+2\tau_{\lambda_\mathrm{V}}\delta) \\ \Delta D & \sim & -0.13\tau_{\lambda_\mathrm{V}}\mathrm{a}(2\delta 10^{D_*}-1)\end{array}\right\}(25)$$

where $a = \tau_{\lambda_D^-}/\tau_{\lambda_D^+} \sim 3.4\exp(2.2\times10^4/T_{\rm env}) \gg 1$, with $\tau^+_{\lambda_D} \simeq (\lambda_D/\lambda_V)^3\tau_{\lambda_V}$. Using (25) we readily realize that:

$$\Delta V/\Delta D > 0;\ \Delta\Phi_{\rm rb}/\Delta D < 0;\ \Delta\Phi_{\rm rb}/\Delta V < 0 \tag{26}$$

which are characteristic for SPh-Be phases. This suggests that SPh-Be variations are likely to be produced by CE in low opacity regimes. As for $\tau_{\lambda_V} < 1$ it is $T_{\rm env} \simeq$ const., changes of δ as a function of $\tau_{\lambda_V} < 1$ represent variations of the CE extent R_e/R_*. It follows from (22) that for a given value of $\Delta V \lesssim 0$ when $\tau_{\lambda_V} < 1$, δ (and so R_e/R_*) is an increasing function of $1/\tau_{\lambda_V}$ that easily reach $2\delta \geq 1$, which implies a rather extended CE. To an order of magnitude estimate, if we assume a B2e star ($T_{\rm eff} \simeq 22500$ K), $\Delta V \simeq -0.2$ mag and $\tau_{\lambda_V} \simeq 0.05$ for $T_{\rm env} \sim 10^4$ K, it follows from (22) that $R_e/R_* \simeq 3.5$.

4.2.2. High opacity regime

Two situations can be distinguished: (a) $\Delta V < 0$, which implies emission excess in the Paschen continuum; (b) $\Delta V > 0$, which indicates flux deficiency.

In (a) we have $\tau_{\lambda_V} > \tau_{\rm or}$ and:

$$0.5{\rm e}^{\tau_{\rm or}} \lesssim \delta(\tau_{\lambda_V}) < 10^{-0.4\Delta V} \tag{27}$$

where mostly $\Delta D < 0$.

In (b) it is $\tau_{\lambda_V} > \tau_{\rm sh}$ and it always happens that:

$$\delta(\tau_{\lambda_V}) < 1 \tag{28}$$

but the behaviour of ΔD deserves some additional explanations. Following the comments given in Sect. 3, the typical spectrophotometric behaviour in SPh-shell phases seems to be summarized by:

$$\left.\begin{array}{rcl}\partial\Delta\Phi_{\rm rb}/\partial D &=& 0\\ \partial\Delta V/\partial D &=& 0\end{array}\right\}. \tag{29}$$

Using (29) in (24), we derive a differential equation for $\Delta\Phi_e = \Phi_e - \Phi^*_{\rm rb}$ whose solution for $\tau_{\rm sh} < \tau_{\lambda_V} \lesssim 1$ and for a wide range of $\Delta V > 0$ can roughly be represented by:

$$\Delta\Phi_e \simeq 0.3\tau^{0.9}_{\lambda_V}. \tag{30}$$

Hence, knowing that:

$$\Phi_e \propto 1/T_{\rm env} \tag{31}$$

conditions (29) imply that SPh-shell phases reveal sensitivity of CE to temperature changes of the CE and that $T_{\rm env}$ is a decreasing function of τ_{λ_V}. On the other hand, with (24) and (30), it can be shown numerically that the BD difference ΔD increases with τ_{λ_V}. So, the increase of D in SPh-shell phases is probably due to CE in high opacity regimes with a decreasing temperature as the opacity becomes higher.

As noted before for ΔV, it is also not possible to produce $F_\lambda < F^*_\lambda$ at $\lambda < \lambda_D$ to have $\Delta D > 0$, as needed for SPh-shell phases in pole-on Be stars with flattened CE where $h \leq R_*$.

Relation (28) implies that in SPh-shell phases CE are rather shrunk. As in the preceding section, we assume that for a shell phase of a B2e star $\Delta V \simeq 0.2$ mag and $\tau_{\lambda_V} \simeq 1$ are characteristic parameters. Writing $T_{\rm env} = \epsilon T_{\rm eff}$ where for most shell stars $\epsilon \simeq 0.5$ (Zorec & Garcia 1991) we get $T_{\rm env} \lesssim 14700$ K so that $R_e/R_* \simeq 1.3$. Using spectroscopic data, Kogure (1989) also concluded that regions of the CE responsible for spectroscopic shell spectra are smaller and denser than those producing spectroscopic Be phases. A more detailed discussion of these phenomena will be presented in a following paper.

5. Conclusions

In this work we studied the long-term spectrophotometric variations of 49 classic Be stars. The parameters used in this study are: the U and V magnitudes of the UBV photometric system, total Balmer discontinuity D, and the gradient of the energy distribution $\Phi_{\rm rb}$ defined for $\lambda\lambda$0.40 to 0.63 μm. To obtain these quantities for as long a time base as possible, we used genuine BCD spectrophotometric data and photometric data obtained in most cases since 1950 in five different photometric systems: UBV, $UBVRI$, Geneva system, Strömgren's $uvby$ and 13-colour system, which we reduced to a common spectrophotometric scale given by the BCD system.

Variations of the $(V, D, \Phi_{\rm rb})$ parameters were qualitatively compared with the spectroscopic variation of a small number of well-studied Be stars, which were mostly observed either in Be phases or in shell phases. From this comparison it generally follows that line emission is stronger when stars are brighter and redder, and that for strong reddening a veiling in the lines is also observed. Total Balmer discontinuity is smallest at phases of strong emission. In Be-shell phases the strength of the shell is always stronger when total Balmer discontinuity is greatest. RV are also highest in these cases.

For SPh-Be phases total Balmer discontinuity is smaller than the stellar component and for each star there are well-defined (U, D), (V, D), $(\Phi_{\rm rb}, D)$ and $(\Phi_{\rm rb}, V)$ linear-like correlations which can be single or double-valued. Slopes of these correlations are $\partial(U, V)/\partial D > 0$ and $\partial\Phi_{\rm rb}/\partial(D, V) < 0$ in most cases, but sometimes their signes are changed. In SPh-shell phases the total BD is higher than the stellar BD, and generally no variation of V and $\Phi_{\rm rb}$ accompanies the increase of D. In some rare cases a slight variation of V and $\Phi_{\rm rb}$ and even a bluening is observed near $D \gtrsim D_*$. However, when a spectroscopic shell spectrum develops, reddenings or bluenings may sometimes be spurious effects due to shell lines entering the photometric filter pass-bands which are not considered in the calibration of photometric indices in spectrophotometric quantities.

The fact that the spectrophotometric patterns are single or double-valued does not seem to correlate with $V \sin i$.

For a number of Be stars a unique pattern was observed for both ranges of D, $D \gtrless D_*$, even after having passed through several shell phases and apparent loss of emission characteristics. Slopes of these patterns are different whether it is $D < D_*$ or $D > D_*$.

SPh-shell behaviours such that $D > D_*$ have been observed for several stars which have moderate $V \sin i$ parameters. If these values of $V \sin i$ are due to small aspect angles i, this will mean that in such stars the CE in the neighbouring stellar regions cannot be strongly flattened.

Sometimes, the spectrophotometric correlations are somewhat dispersed. This phenomenon may possibly be due to high photometric variability, produced by activities in the underlying stellar surface, which does not obey the "smoothed" long-term variation due to the CE.

We showed that the spectrophotometric variations in SPh-Be phases may well be produced by CE in low opacity regimes ($\tau_{\lambda_{\rm V}} < \tau_{\rm or}$, $\Delta V < 0$). Those observed in SPh-shell phases are due to CE in high opacity regimes ($\tau_{\lambda_{\rm V}} > \tau_{\rm sh}$, $\Delta V > 0$), where the temperature decreases as their opacity increases. The low opacity CE seem to be more extended than those of high opacity. The high positive values of RV observed in the stronger shell phases should probably favor the appearance of compact formations near the star.

The formation of CE in Be stars, as well as their structure, are still open questions. They may not only depend on the mass loss mechanisms, but also on the way the mass is lost and its dynamics. Polarimetric data cannot be interpreted if CE are not somewhat flattened. Nevertheless, recent interferometric measurements of some Be stars (Stee et al. 1995, 1997; Quirrenbach et al. 1997) reveal that the effective ellipticities of CE for the Hα line formation region are $E \sim 0.4 \pm 0.3$, which clearly rule out the spherical geometry of CE regions exceeding $R_{\rm e} \sim 6\ R_*$. However, for the visible continuum, for which $R_{\rm e} \lesssim 4R_*$ (Stee et al. 1997), such an approximation can still be reliable. The present study allowed us to appreciate some systematic spectrophotometric behaviours of Be stars. In particular, it showed that not only SPh-Be and SPh-shell phases can be present in a same star, but that they can both take place in stars with low values of $V \sin i$. If these low $V \sin i$ are due to $\sin i$, CE geometries preventing the shielding of stellar polar regions: high flattened disks, lemniscate shaped CE at $R_{\rm e} \lesssim 4R_*$, should probably be not appropriate to model the spectrophotometric behaviour of these objects. In order to better constrain models of CE for Be stars (their geometries in particular) and/or understand the phenomena underlying the observed spectrophotometric behaviours, a number of complementary observational and/or quantitative studies have still to be done. Correlations of spectrophotometric vs. spectroscopic behaviours, time lags between both, as well as a study of the properties of spectrophotometric relations presented in this paper against the stellar fundamental parameters and the aspect angle i will be presented in a next contribution. Using different model envelopes, a quantitative discussion in terms of opacity, size and temperature of CE will complete the present work.

Acknowledgements. Many thanks are due to Dr. Ch. Sterken for having helped us to manage the data archives of the Long-Term Photometry of Variables (LTPV) program at ESO. We are indebted to Dr. J. Percy, who kindly provided us with some unpublished photometric data and to all those observers whose work is included in the IAU Archive of Unpublished Photoelectric Observations (accessible by CDS). We are particularly grateful to Dr. P. Harmanec and Dr. K. Pavlovski for having provided us before publication with some *UBV* data collected at the Hvar Observatory. Discussions with Dr. S. Štefl on 59 Cyg are warmly acknowledged. Useful comments and painstaking reading of the manuscript by the referee, Pr. J. Dachs, which helped to improve the presentation of the paper are greatly acknowledged. This research has made use of several databases and abstract services: Centre de Données Stellaires de Strasbourg (CDS), The General Catalogue of Photometric Data (GCPD, University of Lausanne), Astronomical Data Analysis Center (ADAC, NAO Japan) and NASA's Astrophysics Data System Abstract Service (ADS).

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