SPECTROPHOTOMETRY OF BRIGHT Be STARS

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Abstract. We present new measurements of the distribution of energy in the continuum for eight Be stars in the optical region ($\lambda\lambda$ 3200–7600 Å). The effective temperatures of these stars have been estimated from their observed fluxes. It is found that, in general, 'pole-on' stars show near-infrared excess emission. It is interesting to note that the Balmer jumps for stars having an infrared excess are systematically smaller than for those lacking the infrared excess.

Variability of ultraviolet and infrared excess emissions in these stars has been discussed. The stars 59 Cyg, 66 Cyg, 28 ω CMa, and 27 CMa show large variations in their continuum at ultraviolet (UV) and infrared (IR) regions.

1. Introduction

The Be stars are quite attractive objects for observations, since most of them undergo unpredictable spectral and photometric variations – which, in a few cases, are very drastic. Among the confusing variety of stars with unusual properties, the Be stars perhaps form the group with the largest number of known intensive bright members. Nevertheless, Be stars are far from being properly understood; the main reason being the irregularity in the behaviour of nearly all Be stars. The observations of individual stars, normally, are not expected to contribute much to the improvement of models for Be stars.

Continuum scans of energy distributions are of utmost importance for investigating and understanding the origin and nature of ultraviolet and infrared excess emissions in Be stars. In the present paper we have included five 'pole-on' stars. The 'pole-on' stars were identified as objects with sharp emission lines superposed on broad, shallow absorption components and with relatively sharp He I absorption lines. Schild (1966) noticed the spectroscopic similarity of the extreme Be stars to the 'pole-on' stars. Schild (1973) has investigated that the 'pole-on' stars show large infrared excess and always show emission at Hα and Hβ and frequently at higher numbers. As a class, the 'pole-on' stars appear to be unusually active Be stars.

The purpose of the present paper is to discuss the continuum energy distributions of Be stars; particularly the 'pole-on' Be stars. For the Be stars, *o* Pup and I Hya, the energy distributions data are new. Some Be stars in the present paper have shown large variability of their continuum particularly in the ultraviolet and infrared region.

2. Observations and Reductions

The stars were observed during 1980–1981 on nine nights. The observations were secured with Hilger and Watts monochromator at 52 cm and 104 cm reflectors. The

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TABLE I

Observations of Be stars

No.	Star name	Observational date	No. of nights	Telescope
1	*o* Pup	4 Nov., 1980 6 Dec., 1980	2	52 cm
2	59 Cyg	19 Nov., 1980 20 Nov., 1980	2	104 cm
3	66 *υ* Cyg	18 Nov., 1980 19 Nov., 1980 20 Nov., 1980	3	104 cm,
4	31 Peg	4 Nov., 1980 10 Nov., 1980	2	52 cm
5	28 *ω* CMa	4 Nov., 1980 10 Nov., 1980	2	52 cm
6	27 CMa	16 Oct., 1980 31 Oct., 1980	2	52 cm
7	I Hya	19 Jan., 1981	1	104 cm
8	4 *β* Psc	16 Oct, 1980 31 Oct., 1980	2	52 cm

procedure and instrumentation used for taking scans has been described earlier (Goraya, 1984). An exit slit of 50 Å passband was used for securing continuous spectrum scans. The summary of observations is given in Table I.

The Be stars included in the present paper are listed in Table II. Each Be star was observed many times in a night. Each scan was reduced to instrumental magnitudes separately and all scans of individual star in a night were averaged. The observations of each Be star except I Hya were repeated on another night. The standard stars α Leo, γ Gem, and ξ^2 Cet were observed alongwih the programme Be stars to be used for applying extinction corrections and to reduce instrumental magnitudes of programme stars to absolute magnitudes. Our transformation of observations of programme stars to absolute fluxes corresponds to the absolute calibration system of Tug *et al.* (1977). The absolute monochromatic magnitudes of Be stars were extracted at upto 46 wavelengths separated by 100 Å. The standard deviation of the measurements on an individual night does not exceed $\pm\, 0\overset{m}{.}03$ in the entire wavelength range. The magnitudes of Be stars were corrected for interstellar reddening and were normalized to wavelength λ5500 Å. The de-reddened normalized magnitudes thus obtained are listed in Table III. A plot of these is shown in Figure 1.

It has been discussed in an earlier paper (Goraya, 1984) that the direct determination of interstellar reddening in Be stars is difficult due to their high-rotational velocities and also because of the excess radiation emitted by their envelopes in the ultraviolet and infrared wavelengths. To avoid these difficulties we used the distance moduli method,

TABLE II

Parameters of Be stars included in the present study

Sr. no.	Star name	HD	Sp. t.[a]	m_v[a]	$E(B-V)$	Present paper		Other determinations		$v \sin i$[c] (km s^{-1})	Category
						T_{eff} (K)	log g	T_{eff} (K)[b]	log g		
1	o Pup	63462	B0Vpe	$4^m.50$	0.15 ± 0.02	30000	4.0	–	–	375	–
2	59 Cyg	200120	B1.5IVne	4.74	0.05 ± 0.02	25000	4.0	–	–	375	–
3	66 υ Cyg	202904	B2Vne	4.43	0.05 ± 0.02	22500	4.0	20000 23000	3.5 3.8[d]	255	Pole-on
4	31 Peg	212076	B22IV–Ve	5.01	0.08 ± 0.02	20000	4.0	20000	4.0	135	Pole-on
5	28 ω CMa	56139	B2IV–Ve	3.85	0.06 ± 0.02	20000	4.0	18000	4.0	110	Pole-on
6	27 CMa	56014	B3IIIe	4.66	0.00	18000	3.5	20000 20000[e]	4.0 3.8[e]	160	Pole-on
7	I Hya	83953	B6Ve	4.77	0.02 ± 0.02	15000	4.0	–	–	315	–
8	4 β Psc	217891	B6Ve	4.53	0.01 ± 0.02	15000	4.0	15000	4.0	130	Pole-on

References: The data are taken from the references indicates in the table:

[a] Hoffleit (1982).
[b] Schild (1976).
[c] Uesugi and Fukuda (1982).
[d] Breger (1976).
[e] Danks and Houziaux (1978).

TABLE III

De-reddened monochromatic magnitudes of observed Be stars normalised to wavelength $\lambda 5500$ Å

Wavelength (Å)	$1/\lambda$ (μm^{-1})	Star							
		o Pup	59 Cyg	66 *υ* Cyg	31 Peg	28 *ω* CMa	27 CMa	I Hya	4 *β* Psc
3200	3.13	$-0\overset{m}{.}725$	$-0\overset{m}{.}750$	$-0\overset{m}{.}475$	$-0\overset{m}{.}393$	$-0\overset{m}{.}200$	$-0\overset{m}{.}225$	$+0\overset{m}{.}099$	$+0\overset{m}{.}108$
3300	3.03	−0.758	−0.685	−0.461	−0.340	−0.170	−0.198	+0.150	+0.125
3400	2.94	−0.750	−0.650	−0.420	−0.348	−0.099	−0.170	+0.059	+0.146
3500	2.86	−0.700	−0.657	−0.444	−0.355	−0.076	−0.181	+0.060	+0.152
3600	2.78	−0.650	−0.588	−0.427	−0.350	−0.090	−0.146	+0.101	+0.150
3700	2.70	−0.452	−0.450	−0.320	−0.335	−0.125	−0.130	+0.198	+0.185
3800	2.63	−0.501	−0.465	−0.417	−0.348	−0.215	−0.336	−0.184	−0.036
3900	2.56	−0.533	−0.554	−0.550	−0.475	−0.425	−0.470	−0.399	−0.324
4000	2.50	−0.550	−0.550	−0.510	−0.506	−0.466	−0.468	−0.430	−0.400
4100	2.44	−0.545	−0.500	−0.482	−0.480	−0.475	−0.426	−0.401	−0.398
4200	2.38	−0.480	−0.463	−0.455	−0.425	−0.438	−0.397	−0.356	−0.357
4300	2.33	−0.445	−0.420	−0.410	−0.383	−0.386	−0.375	−0.343	−0.350
4400	2.27	−0.405	−0.385	−0.385	−0.369	−0.368	−0.342	−0.324	−0.294
4500	2.22	−0.353	−0.342	−0.342	−0.316	−0.314	−0.293	−0.293	−0.263
4600	2.17	−0.333	−0.315	−0.308	−0.274	−0.289	−0.271	−0.268	−0.266
4700	2.13	−0.277	−0.280	−0.267	−0.227	−0.240	−0.224	−0.218	−0.219
4800	2.08	−0.270	−0.243	−0.240	−0.239	−0.210	−0.214	−0.181	−0.195
4900	2.04	−0.221	−0.200	−0.215	−0.215	−0.208	−0.127	−0.162	−0.160
5000	2.00	−0.180	−0.170	−0.185	−0.148	−0.182	−0.138	−0.130	−0.127
5100	1.96	−0.152	−0.130	−0.150	−0.126	−0.140	−0.126	−0.088	−0.096
5200	1.92	−0.117	−0.108	−0.085	−0.092	−0.096	−0.077	−0.064	−0.095
5300	1.89	−0.065	−0.917	−0.062	−0.070	−0.062	−0.012	−0.056	−0.075

Table III (continued)

Wavelength (Å)	$1/\lambda$ (μm^{-1})	Star							
		o Pup	59 Cyg	66 υ Cyg	31 Peg	28 ω CMa	27 CMa	I Hya	4 β Psc
5400	1.85	−0.055	−0.032	−0.040	−0.020	−0.030	−0.019	−0.026	−0.014
5500	1.82	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5600	1.79	0.017	0.030	0.025	0.019	0.032	0.033	0.012	0.024
5700	1.75	0.067	0.080	0.055	0.033	0.060	0.066	0.030	0.036
5800	1.72	0.112	0.120	0.090	0.059	0.098	0.065	0.077	0.062
5900	1.69	0.135	0.135	0.112	0.075	0.096	0.088	0.089	0.090
6000	1.67	0.186	0.152	0.153	0.098	0.155	0.110	0.134	0.140
6100	1.64	0.240	0.188	0.151	0.086	0.182	0.136	0.164	0.170
6200	1.61	0.290	0.212	0.150	0.121	0.184	0.162	0.180	0.160
6300	1.59	0.320	0.225	0.188	0.141	0.230	0.165	0.196	0.220
6400	1.56	0.322	0.235	0.210	0.155	0.264	0.180	0.232	0.216
6500	1.53	0.338	0.290	0.256	0.148	0.293	0.209	0.250	0.250
6600	1.51	0.350	0.336	0.255	0.182	0.296	0.224	0.272	0.280
6700	1.49	0.349	0.370	0.267	0.222	0.345	0.284	0.302	0.278
6800	1.47	0.375	0.375	0.280	0.241	0.356	0.294	0.320	0.320
6900	1.45	0.416	0.420	0.300	0.233	0.358	0.301	0.330	0.308
7000	1.43	0.444	0.402	0.339	0.281	0.419	0.319	0.352	0.350
7100	1.41	0.496	0.455	0.355	0.314	0.443	0.350	0.380	0.367
7200	1.39	0.525	0.508	0.373	0.325	0.487	0.353	0.414	0.370
7300	1.37	0.585	0.510	0.391	0.376	0.480	0.406	0.435	0.382
7400	1.35	0.590	0.500	0.394	0.361	0.514	0.436	0.458	0.400
7500	1.33	0.620	0.501	0.399	0.349	0.531	0.469	0.422	0.416
7600	1.31	0.664	0.544	0.400	0.368	0.524	0.476	0.492	0.429

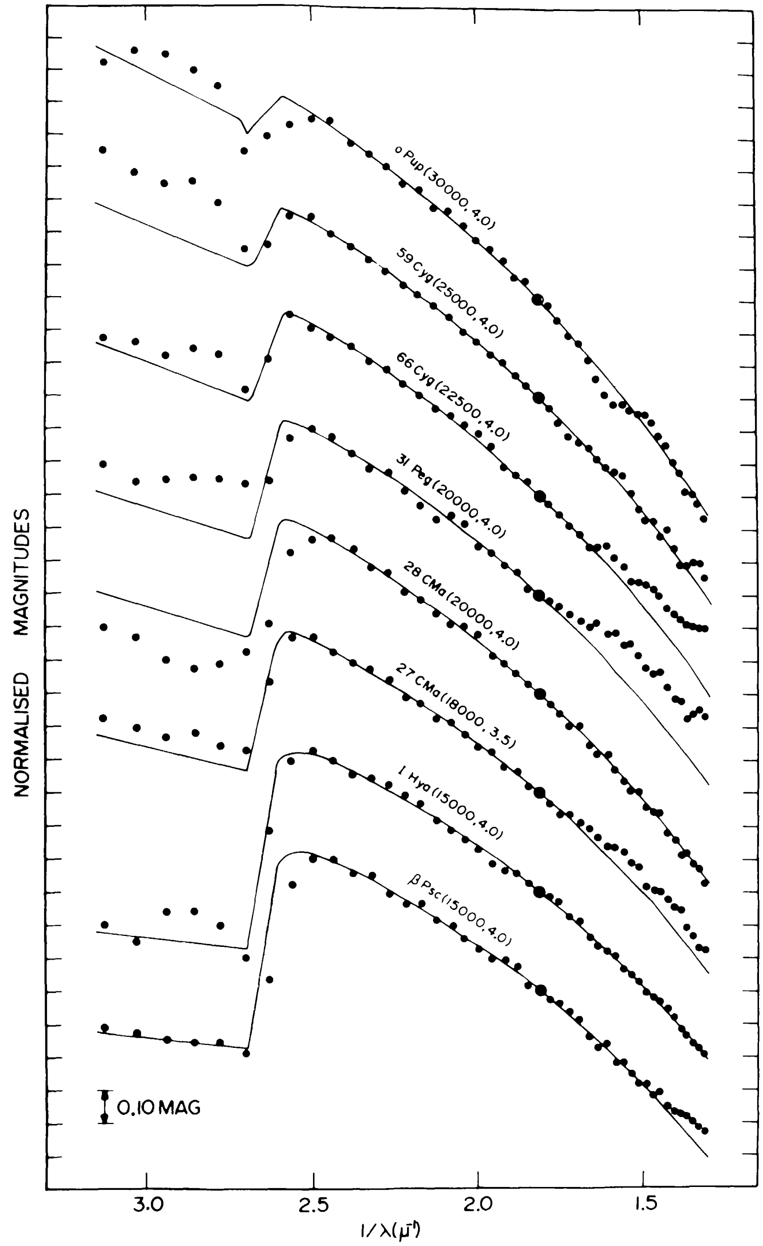

Fig. 1. Normalised de-reddened observed energy distribution curves of Be stars (filled circles) superimposed by appropriate models (solid continuous curves). The normalisation has been done at λ5500 Å which is shown by double circles. The matching of observed curves with models has been done by eye.

described earlier (Goraya, 1984), for the determination of colour excess $E(B - V)$ of programme Be stars. The $E(B - V)$ values of Be stars estimated are listed in Table II. The reddening corrections were calculated by adopting the mean value of $R = 3.25$ (Moffat and Schmidt-Kaler, 1976) and using the interstellar reddening curve given by Lucke (1980) for particular regions.

3. Continuum Energy Distributions and Effective Temperatures

The de-reddened scanner energy distribution curves of Be stars are shown in Figure 1. In this figure the filled circles are the observed points and the continuous curves are the theoretical models. We have used the synthetic models, with normal chemical composition, constructed by Kurucz (1979) for deriving the effective temperatures of Be stars. Kurucz (1979) models have been tested for a large number of normal early-type stars (Kontizas and Theodossiu, 1980; Goraya, 1984). It has been found that these models represent the observed spectra of normal B stars very well. These models resemble the values of effective temperatures of normal B stars corresponding to their spectral type and luminosity class.

In Figure 1, we have compared the observed energy curves of Be stars with models for deriving the effective temperatures. The numbers in the brackets, in Figure 1, denote the values of T_{eff} and $\log g$, respectively, of the best fitted models. One should note that the values of $\log g$ assigned to each Be star are the assumed values. We assumed $\log g = 4.0$ for luminosity class V and IV and $\log g = 3.5$ for luminosity class III. The effect of gravity on energy distributions of early-type stars is relatively small. Therefore, in using energy distributions for the determination of effective temperatures of early-type stars, the gravity will not need to be known with great accuracy (Nandy and Schmidt,

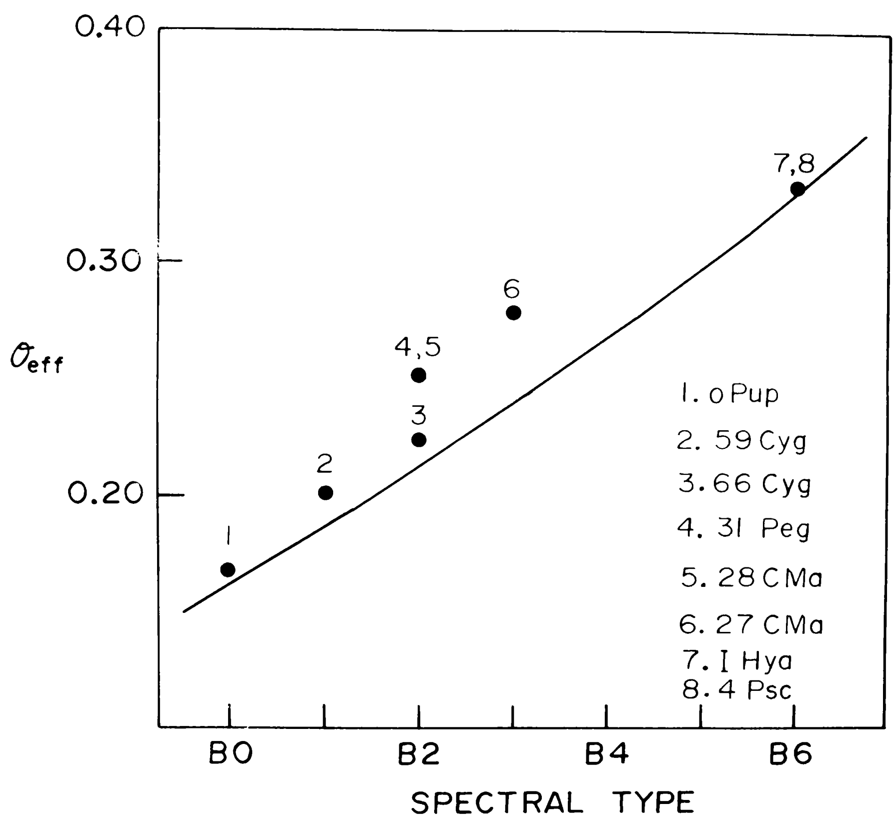

Fig. 2. The position of observed Be stars (filled circles) on the θ_{eff}-spectral-type relation for normal B stars. The solid continuous curve is the mean relation for normal B stars.

1975). The effective temperatures thus estimated are tabulated in Table II, alongwith those determined by others. The uncertainty in T_{eff} due photometric error of the observed fluxes is $\pm 5\%$ around 25000 K and $\pm 3\%$ around 15000 K. The fit of the computed to the observed fluxes introduces an additional error that varies from $\pm$ 500 K for cool stars to $\pm$ 800 K for the hot ones.

In Figure 2, we have shown the observed Be stars on the θ_{eff}-spectral type plot for normal B stars. The continuous curve for normal B stars, in Figure 2, was obtained from the T_{eff} and spectral-type data for early-type stars given by Kontizas and Theodossiu (1980). The spectral types of Be stars are those adopted from Hoffleit (1982). The values of T_{eff} estimated in the present paper were converted to θ_{eff}. Figure 2 shows that, in general, nearly all the observed Be stars have a tendency to show lower effective temperatures than those of the normal B stars of the same spectral types. The Be stars 31 Peg, 28 ω CMa, and 27 CMa deviate strongly from the mean curve indicating that these stars have certainly lower effective temperature. These stars have also been classified as 'pole-on' stars by Schild (1973).

4. Discussion Concerning Individual Stars

Of the eight Be stars included in the present paper, five stars have been classified as 'pole-on' Be stars by Schild (1973). The term 'pole-on' was introduced by Slettebak (1949) to describe a group of Be stars displaying relatively narrow photospheric absorption lines accompanied by emission lines from the envelope which show no significant shell-type absorption cores. These objects typically have values of $v \sin i$ less than 280 km s^{-1}. If all Be stars are indeed rotating at a velocity near critical, the 'pole-on' stars have an inclination of 30° or less to our line-of-sight (Peters, 1979).

The Be stars 59 Cyg, 66 υ Cyg, 28 ω CMa, and 27 CMa are seen to exhibit enormous changes in their continuum, specially in the ultraviolet and infrared wavelength regions in their history.

o Pup. This early Be star has been poorly studied. No continuum energy distribution data for this star are available in the past literature. The present first scanner observations of the continuum show that *o* Pup has slight near-ultraviolet excess emission. Its continuum towards near-infrared wavelengths is normal. It is a single Be star.

59 Cyg. The well-known Be star 59 Cyg has displayed remarkable activity, specially throughout the past decade. It has been extensively monitored in the ultraviolet (UV), primary with IUE, since the end of 1978. The most striking aspect of this star's ultraviolet spectrum is the spectacular variation in the resonance lines of C IV and N V (Doazan *et al.*, 1980a, b, 1982). This star also varies irregularly in brightness by ~ 0.1 magn (Hoffleit, 1964). This star exhibited, from 1972 to 1976, two enhancements of the emission lines, respectively, followed by a shell phase in mid-1973, and in December 1974 and 1975. The second enhancement of the emission from the end of 1973 to mid-1974 was very prominent and the second shell phase (of 160 days) was also much more important than that of 1973.

The spectroscopic history from 1904 to 1980, together with a complete description of the 1974–1975 (second) shell episode is given by Barker (1982) (see also Hubert-Delplace and Hubert, 1981). The UV observations covering the period 1972–1979 are discussed by Marlborough and Snow (1980) and Doazan *et al.* (1980b). From UV observations made in December 1978, Doazan *et al.* (1980a) deduced that mass loss is strongly variable in 59 Cyg. Their long-term study of Hα behaviour, combined with the far-UV data, suggest that large mass flux coincides with a phase of rapidly increasing Hα emission. A comparison of Marlborough and Snow (1980) and Doazan *et al.* (1980a, b) results shows conclusively that this 59 Cyg mass flux is variable, supporting previous observations of such general mass-flux variability (Snow, 1977; York *et al.*, 1977; Snow and Hayes, 1978).

Recently, Barker (1983) reported the V/R variations of 59 Cyg on a short-lived quasi-period not longer than 28 days as observed during 1980. He has also shown that 59 Cyg is certainly a binary as deduced from speckle interferometry. Grady *et al.* (1982) has reported that the observations of 59 Cyg made in December 1978, December 1980, and January 1981 suggest short time-scale (1–3 days) line profile variability in the ultraviolet region in 59 Cyg. This variability further suggests that major changes in the wind occurred on time-scales larger than 1–2 days.

Observations of continuum energy distributions by Schild *et al.* (1974) show strong ultraviolet excess in 59 Cyg in September 1968. However, the energy distributions reported by Briot (1978) show both ultraviolet and IR excess emissions. The present observations made in November 1980 show strong near-ultraviolet excess emission in 59 Cyg.

66 υ Cyg. This B2V Be star is an interesting object which has displayed significant changes at Balmer jump. This unusual Be star has been classified as a 'pole-on' star by Schild (1973). From an analysis of the far-ultraviolet spectra of 66 υ Cyg, Peters (1979) concluded that this star is suspected as a mass-transfer binary system. Recently, Barker (1984) has reported a broad, strong single emission at Hα line.

In the long past, Chalonge and Divan (1952), from spectrophotometric measurements, found its Balmer jump ($D = 0\overset{m}{.}10$) in emission indicating ultraviolet excess emission in this star. Four years later Zio Day (1956) found the Balmer jump ($D = 0\overset{m}{.}53$) strongly in absorption indicating severe ultraviolet deficiency by as much as $\sim 0\overset{m}{.}40$ as compared to a normal B star's Balmer jump ($D = 0\overset{m}{.}14$) of the same spectral type. This is an unusual behaviour for a star having classified as 'pole-on'.

The 1968 energy distributions of this star show no near-infrared and near-ultraviolet excess emission as reported by Schild *et al.* (1974). But Schild (1976) noted ultraviolet and infrared excess emissions in 66 υ Cyg. The present observations again shown near-ultraviolet and near-infrared excess emissions in 66 υ Cyg during November 1980.

31 Peg. Schild (1973) classified this single star as true 'pole-on' Be star. Recently, Barker (1984) observed a sharp single-emission peak of Hα line (characteristic of 'pole-on' stars) during 1980–1983. Continuum flux distribution of this star, reported by Schild (1976), show slight ultraviolet and infrared excess emissions. The present scans of the continuum show strong ultraviolet and infrared excess emissions.

28 ω CMa. This is again a 'pole-on' star (Schild, 1973). Feinstein (1970) identified this star as showing large photometric changes ($\Delta V = -0^m.32$ and $\Delta R = -0^m.44$). Baade (1979) has reported the radial velocity variations connected with a weak V/R variations of emission lines (H I and Fe II) during 1976–1978. The most important feature was the strict periodicity of all variations with a period of $P = 1^d.36$ (stable period over more than nine years). It is by far the shortest stable period so far observed in Be stars. From observations of 28 ω CMa during 1976–1978, Baade (1979) discovered that this is a β Cephei star. The β Cephei stars are nonradially pulsating stars with fundamental oscillation period of 4–6 hr.

Schild (1976) has reported the ultraviolet excess of 28 ω CMa, whereas Briot (1978) has shown the ultraviolet deficiency. The present observations also show ultraviolet deficiency in 28 ω CMa during November 1980.

27 CMa. This true 'pole-on' star has been shown to undergo small photometric changes by $\sim 0^m.02$ in *UBV* (Feinstein, 1968). Feinstein (1970) showed this star exhibiting large photometric variations ($\Delta V = +0^m.14$ and $\Delta R = 0^m.14$). Its binary nature was reported by Finsen (1952). Struve and Kao (1948) discussed its radial-velocity variations. It was studied in detail by Burbidge and Burbidge (1954), Ringuelet-Kaswalder *et al.* (1960) and Ringuelet-Kaswalder (1962, 1963a, b).

Danks and Houziaux (1978) has reported the optical (*UBV*) and infrared (*HKLM*) observations of 27 CMa observed during 1977 and 1975, respectively. They found that the star possesses infrared excess and verified the variations of the continuum in the ultraviolet and visible region. Schild (1976) has observed slight ultraviolet excess emission in 27 CMa. We have observed the moderate near-ultraviolet and near-infrared excess emissin in this star.

I Hya. This star has been poorly investigated. We present the first continuum energy distribution data for this star. Our results show that this star has normal continuum energy distribution.

4 β Psc. This star belongs to the category of 'pole-on' Be stars. Barker (1984) observed a very sharp single emission Hα line indicating its 'pole-on' nature. Schild (1976) reported its continuum energy distribution to be normal. Our measured energy distributions show very faint near-infrared excess emission.

5. Conclusions

The investigation carried out in the present paper show that, in general, Be stars have some tendency to show lower effective temperatures. The 'pole-on' Be stars, in general, possess infrared excess emission and have Hα and Hβ emission as the permanent feature. It is inferred from the comparison of the present results with earlier findings that the Be stars 59 Cyg and 66 υ Cyg are strongly variable in the ultraviolet region. The stars 28 ω CMa and 27 CMa possess strong photometric variability in *UBVRI* bands. The four Be stars: 59 Cyg, 66 υ Cyg, 28 ω CMa, and 27 CMa are thus deserving candidates for concentrated photometry, high-resolution spectroscopy, and spectrophotometry at all possible wavelengths.

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