CONTINUUM ENERGY DISTRIBUTION OF Be STARS

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Abstract. The continuum energy distributions of four Be stars – namely, HR 7708, HR 7807, HR 7927, and HR 8171 alongwith two normal B stars HR 7426 and HR 7613 are presented in the wavelength region $\lambda\lambda$3200–7800 Å. By a comparison the observed continuum energy distributions with that of theoretical models given by Kurucz (1979), their effective temperatures are determined and discussed.

The observed energy distribution curves show near infrared excess emission longward of λ6000 Å for HR 7807 and HR 8171 and a double Balmer jump for HR 7708.

1. Introduction

To determine the effective temperatures of early-type stars, continuum energy distribution in the visible is one of the important regions as most of the energy is radiated in this wavelength region. A complete knowledge of Be stars is not yet clear due to diversity of such objects and a wide range of phenomena exhibited by individual objects. Irregular variations of light, ultraviolet and infrared excesses, ultraviolet deficiency, emission line strengths, etc., are common features associated with Be stars.

Be stars also display a wide range of peculiarities in their continuum energy distributions. Barbier and Chalonge (1941) have found that the Balmer jump is smaller for Be stars than for normal B stars and also the colour temperatures for Be stars are lower than those of normal B stars. According to Mendoza (1958), the majority of Be stars show ultraviolet excess. Johnson (1967) has noted similar types of excesses in the infrared region. However, no excess or deficiency has been observed by Bottemiller (1972) and Briot (1978) in the ultraviolet region. Delplace and Van der Hucht (1976), Beeckmans (1976), Heap (1976), Schild (1978), and Chkhikvadze (1980) have found deficiency in the ultraviolet.

The purpose of this paper is to present our spectrophotometric observations of Be stars as compared to those of normal B stars and to study their continuum energy distributions and variable nature. The study of the continuum energy distribution can potentially improve our understanding of the exact nature of Be stars.

2. Observations and Reductions

The observations of all the programme stars listed in Table I, were made with the Hilger and Watts monochromator at the Cassegrain focus of 104-cm reflector during November, 1983 at Uttar Pradesh State Observatory, Naini Tal. Their spectral types and luminosity classes are taken from Jamar *et al.* (1976). An exit slot of 0.7 mm, admitting 50 Å of the spectrum on to the photomultiplier, was used for making the

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TABLE I

A list of stars observed in this study

HR	Star	Sp. type	m_{5500}	T_{eff}	log g	$E(B-V)$
			Be stars			
7708	28 Cyg	B3Ve	4.78	25 000 K	4.0	0$^m_.$08
7807	HR 7807	B2Ve	5.98	22 500 K	4.0	0$^m_.$02
7927	V568 Cyg	B2II–Ve	6.49	30 000 K	4.0	0$^m_.$08
8171	6 Cep	B3Ve	4.96	25 000 K	4.0	0$^m_.$09
			Normal B stars			
7426	8 Cyg	B3IV	4.59	20 000 K	4.0	0$^m_.$07
7613	22 Cyg	B5IV	4.92	20 000 K	4.0	0$^m_.$07

observations. Each star was observed four to five times. The reduction techniques were the same as used by us earlier (Goraya and Singh, 1985).

The standard stars α Lyr and ξ^2 Cet were observed alongwith programme stars. Two normal B stars HR 7426 and HR 7613 were also observed with programme Be stars to serve as comparison star and to define the effective temperatures and Balmer jumps as well as to check colour excess and the details of the interstellar reddening law. The nightly extinction coefficients were applied for each star using standard star's observations. Our transformation of observations to absolute flux values were carried out with the help of the absolute calibration of α Lyrae by Tug *et al.* (1977). The absolute monochromatic magnitude of programme stars were extracted at every 100 Å between $\lambda\lambda$ 3200–7800 Å. The standard deviation of the measurements does not exceed $\pm$ 0$^m_.$03 in the entire wavelength region. Finally, the magnitudes were corrected for interstellar reddening and were normalized to a wavelength λ 5500 Å. The reddening corrected magnitudes thus obtained are listed in Table II and a plot of these are shown in Figures 1 and 2.

3. Correction for Interstellar Reddening

The determination of interstellar reddening for Be stars is complicated due to the presence of circumstellar envelope. The normal Q method of Johnson and Morgan (1953), valid for the Main-Sequence O and B stars, is likely to produce large errors because of the ultraviolet and infrared excess emissions in these stars.

In order to estimate the interstellar reddening for the stars discussed in this paper the colour excess $E(B-V)$ was determined through distance modulii method. For this a graph was plotted between colour excess $E(B-V)$ for some 100 normal B stars lying in the direction of the programme stars and apparent distance modulii $(m_v - M_v)$. The $E(B-V)$ values for normal B stars were computed through the Q method. The normal B stars were selected from photometric catalogue (Blanco *et al.*, 1968). To estimate

TABLE II

Reddening corrected monochromatic magnitudes of the programme stars normalised to wavelength λ5500 Å

λ (Å)	$1/\lambda$ (μ^{-1})	Be stars				Normal B stars	
		HR 7708	HR 7807	HR 7927	HR 8171	HR 7426	HR 7613
3200	3.13	$-0^{m}.330$	$-0^{m}.498$	$0^{m}.793$	$-0^{m}.564$	$-0^{m}.295$	$-0^{m}.309$
3300	3.03	−0.310	−0.364	−0.763	−0.594	−0.300	−0.320
3400	2.94	−0.280	−0.304	−0.673	−0.494	−0.274	−0.290
3500	2.86	−0.460	−0.364	−0.693	−0.514	−0.248	−0.253
3600	2.78	−0.430	−0.314	−0.572	−0.445	−0.194	−0.264
3700	2.70	−0.376	−0.284	−0.573	−0.411	−0.556	−0.306
3800	2.63	−0.507	−0.483	−0.643	−0.544	−0.395	−0.252
3900	2.56	−0.561	−0.584	−0.713	−0.614	−0.545	−0.351
4000	2.50	−0.552	−0.517	−0.643	−0.579	−0.611	−0.537
4100	2.44	−0.497	−0.598	−0.593	−0.563	−0.564	−0.509
4200	2.38	−0.483	−0.534	−0.543	−0.514	−0.535	−0.537
4300	2.53	−0.401	−0.474	−0.513	−0.455	−0.505	−0.430
4400	2.27	−0.396	−0.424	−0.475	−0.445	−0.458	−0.389
4500	2.22	−0.357	−0.371	−0.443	−0.402	−0.441	−0.359
4600	2.17	−0.307	−0.339	−0.393	−0.364	−0.368	−0.308
4700	2.13	−0.276	−0.318	−0.327	−0.333	−0.364	−0.285
4800	2.08	−0.248	−0.248	−0.313	−0.254	−0.274	−0.255
4900	2.04	−0.210	−0.232	−0.273	−0.228	−0.264	−0.221
5000	2.00	−0.181	−0.197	−0.228	−0.194	−0.198	−0.175
5100	1.96	−0.166	−0.126	−0.188	−0.144	−0.142	−0.134
5200	1.92	−0.097	−0.097	−0.155	−0.126	−0.126	−0.121
5300	1.89	−0.062	−0.079	−0.069	−0.056	−0.071	−0.054
5400	1.85	−0.034	−0.039	−0.042	−0.034	−0.044	−0.033
5500	1.82	0.000	0.000	0.000	0.000	0.000	0.000
5600	1.79	+0.045	+0.069	+0.052	+0.044	+0.027	+0.027
5700	1.75	+0.073	+0.086	+0.068	+0.060	+0.039	+0.050
5800	1.72	+0.121	+0.129	+0.068	+0.055	+0.078	+0.085
5900	1.69	+0.150	+0.108	+0.101	+0.117	+0.141	+0.108
6000	1.67	+0.192	+0.143	+0.129	+0.120	+0.140	+0.115
6100	1.64	+0.223	+0.175	+0.226	+0.124	+0.156	+0.134
6200	1.61	+0.272	+0.191	+0.242	+0.127	+0.176	+0.154
6300	1.59	+0.288	+0.178	+0.263	+0.176	+0.229	+0.210
6400	1.56	+0.288	+0.199	+0.295	+0.189	+0.251	+0.205
6500	1.53	+0.343	+0.214	+0.357	+0.258	+0.267	+0.265
6600	1.51	+0.381	+0.236	+0.403	+0.271	+0.273	+0.264
6700	1.49	+0.407	+0.242	+0.410	+0.279	+0.330	+0.278
6800	1.47	+0.420	+0.285	+0.424	+0.315	+0.462	+0.316
6900	1.45	+0.452	+0.320	+0.425	+0.319	+0.415	+0.375
7000	1.43	+0.481	+0.377	+0.451	+0.310	+0.430	+0.380
7100	1.41	+0.528	+0.411	+0.458	+0.327	+0.402	+0.401
7200	1.39	+0.550	+0.439	+0.482	+0.415	+0.417	+0.427
7300	1.37	+0.590	+0.471	+0.463	+0.397	+0.437	+0.450
7400	1.35	+0.621	+0.468	+0.453	+0.476	+0.465	+0.477
7500	1.33	+0.650	+0.469	+0.472	+0.491	+0.475	+0.507
7600	1.31	+0.680	+0.469	+0.492	+0.516	+0.485	+0.537
7700	1.29	+0.693	+0.475	+0.510	+0.533	+0.497	+0.670
7800	1.27	+0.712	+0.477	+0.531	+0.557	+0.416	+0.629

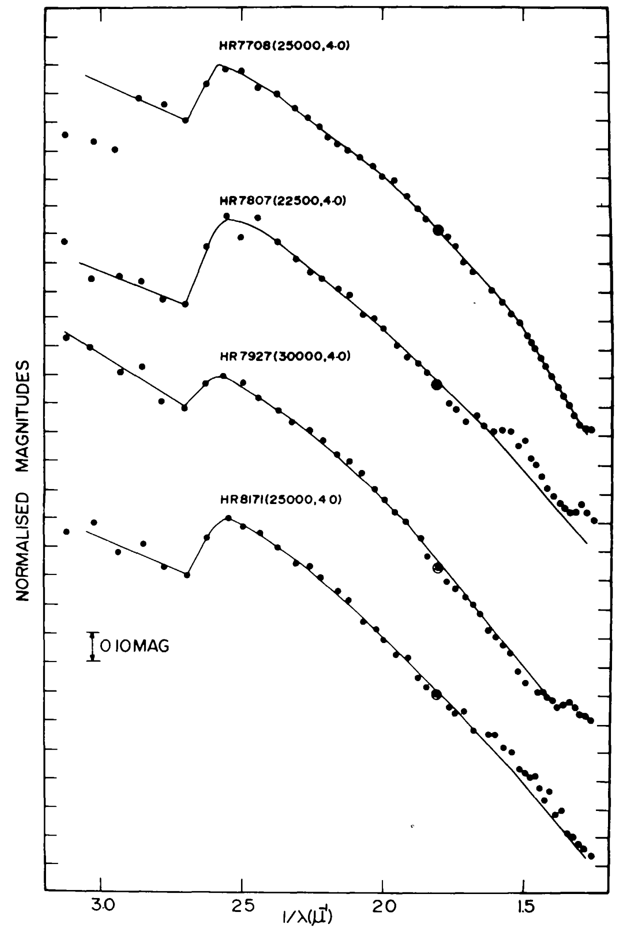

Fig. 1. Normalised de-reddened energy distribution curves of Be stars (filled circles) superimposed by best fitting models (solid continuous curves). The normalisation has been done at λ5500 Å which is denoted by filled circle surrounded by open circle. The matching has been done by eye.

apparent distance modulii of normal B stars, the M_v magnitudes were taken from the spectral type and luminosity class verses M_v calibration for early-type stars (Allen, 1976). From the distance modulus verses $E(B - V)$ relation for normal B stars, the $E(B - V)$ values for programme Be stars corresponding to their distance modulii were estimated. The $E(B - V)$ determined through this method is given in Table I. The $E(B - V)$ values of normal B stars are those adopted from the *Ultraviolet Bright Star Spectrophotometric Catalogue* (Jamar *et al.*, 1976). The reddening corrections were calculated by adopting a mean value of total-to-selective extinction; $R = 3.25$ (Moffat and Schmidt-Kaler, 1976) and using the interstellar reddening curve given by Lucke (1980) for the particular region. The de-reddened monochromatic magnitude normalised to wavelength λ5500 Å is given in Table II.

4. Continua and Effective Temperatures

The energy radiated from Be stars comprise of stellar radiation, radiation from circumstellar envelope and scattered radiation. In this way the radiation received is

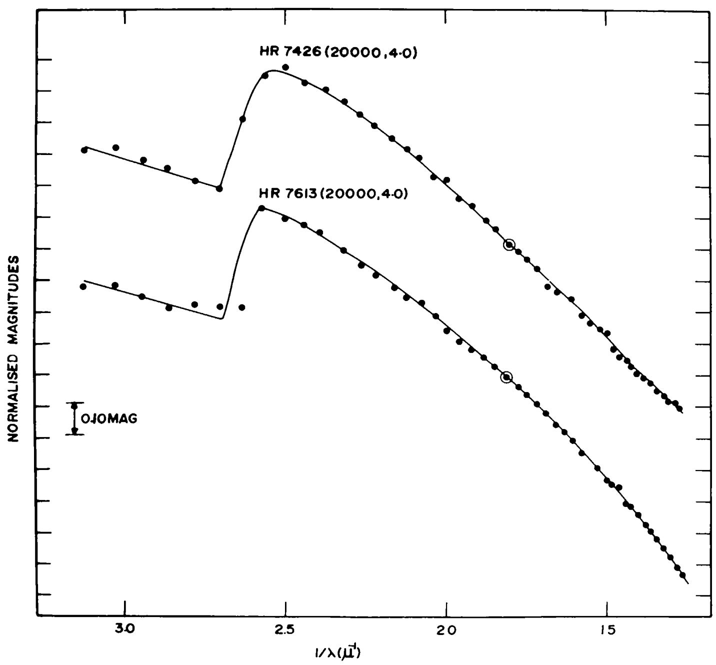

Fig. 2. This figure is the same as Figure 1 but for normal B stars.

composite. As a general rule all the Be stars are variable in line spectrum as well as in their continuous spectrum. Such kind of variability has been observed in a wide range of spectral regions: i.e., from ultraviolet, visible to infrared region. The Balmer jump is seen sometimes in emission and sometimes in absorption. The effective temperature of Be star is highly affected due to high rotation of the star. The high rotation of Be star lowers the effective temperature in geometrical position: i.e., inclination of star also affects the radiation, i.e., decrease in inclination makes an increase in radiation as optical depth through envelope decreases.

In this paper, we have used synthetic spectra constructed by Kurucz (1979) with normal chemical composition for deriving the effective temperatures of stars. The Kurucz models were computed assuming plane-parallel geometry, hydrostatic equilibrium, local thermodynamic equilibrium, no molecules with equation of state and radiative plus convective energy transport. Line blanketing was included by use of statistical distribution function, representation of almost one million atomic lines.

Kurucz model atmospheres with solar abundances and microturbulence velocity of 2 km s^{-1} were superimposed on the observed spectra for deriving effective temperatures, assuming $\log g = 4.0$ for luminosity class IV and V. The model (solid curve) fitted with observations (filled circles) are shown in Figures 1 and 2. The temperatures derived are shown in the same figures. Since the effect of gravity on the effective temperature is small, so the correct value of gravity is not necessary to be known (Nandy and Schmidt, 1975). A change in $\log g = 4$ to $\log g = 2$ would be equivalent to a change in temperature less than 500 K at 10000 K (Kontizas and Theodossiu, 1980).

The uncertainty in temperature due to errors of the observed fluxes is estimated to be $\pm 5\%$ around 25000 K and $\pm 2\%$ around 10000 K. The fit of the computed to the observed fluxes introduces an additional error that varies from ± 500 K for cool star to ± 800 K for hot star.

The energy distribution curves for all the observed stars are shown in Figures 1 and 2. From Figures 1 and 2 it is clear that the observed energy distribution curves of stars fit with models in the Paschen continuum. However, a near infrared excess emission longward of λ6000 Å is seen for the stars HR 7807 and HR 8171 and a double Balmer jump in emission for the star HR 7708 (Figure 1). For the star HR 7927 no excess emission in infrared or in ultraviolet is seen. Near infrared excess emission at visual and near infrared wavelengths have been interpreted by Schild *et al.* (1974) in terms of H^- free-bound emission, first predicted by Milkey and Dyek (1973).

5. Discussion Concerning Individual Be Stars

HR 7708: the star HR 7708 has been an extensively observed star. This star has been observed from 1953 to 1975 which exhibits a B star phase followed by a Be star phase. This star has been discovered to be variable by $0\overset{m}{.}05$ by John Percy in 1976. Also, the photometric study at San Diego State University during July 1978 has shown that this star varies on the order of hours and has an amplitude of $0\overset{m}{.}1$ in U (Mills *et al.*, 1979). A periodogram analysis using the Warner and Roinson method shows a strong $0\overset{d}{.}7$ period for this star. The presence of Balmer discontinuity and a double Balmer jump is a strong indication of the star to be a shell type.

The energy distribution curve of this star is shown in Figure 1. From the figure it is clear that observed curve fits well with computed (Kurucz, 1979) curve. A double Balmer-jump is obvious from the figure.

HR 7807: the star HR 7807 has been observed from 1953 to 1975 which exhibits slight changes in the intensity of the emission 1953 to 1970. Hα was bright and strong and Hβ is a weak emission centrally superposed on a broad hazy absorption. Sharp dark cores due to a shell component are seen on the photospheric Hγ and Hδ lines.

The energy distribution curve of this star is shown in Figure 1. A moderate near-infrared excess emission is seen in this star.

HR 7927: HR 7927, a suspected β Cephei star (Bolton, 1982), was listed as a Be star (Jaschek and Egret, 1981). No significant variation in this star has been observed. A short period variability on the time-scale of about a day or less was suspected but photometric observations made in September 1982 at the University of Toronto (Christopher, 1983) showed no variability.

The energy distribution curve of this star is shown in Figure 1. Its effective temperature seems to be slightly high on account of spectral type.

HR 8171: the star HR 8171 is bright B emission star. Long term spectral variation was discovered for this star by Hubert-Delplace and Hubert (1979) and by Slettebak (1982). Kodaira (1971), on the basis of radial velocity measurements concluded the star to be a spectroscopic binary ($P = 1\overset{d}{.}12215$, $K = 12$ km s^{-1}).

The energy distribution curve for this star is shown in Figure 1. An infrared excess emission observed in this star is seen in the figure.

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