SPECTROPHOTOMETRIC OBSERVATIONS AND EVOLUTIONARY STATUS OF TEN Be STARS

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Abstract. The continuum energy distribution data of ten Be stars – namely, HR 1761, HR 1786, HR 1820, σ Ori, ω Ori, OT Gem, β Lyr, HR 7983, ν Cyg, and 59 Cyg – have been presented in the wavelength range $\lambda\lambda$3200–8000 Å. The observed energy distribution curve shows near infrared excess for majority of Be stars and a double Balmer jump for HR 8047 and HR 8146. Empirical effective temperatures of these stars have been estimated by comparing the observed continuum energy distributions with that of computed theoretical models given by Kurucz (1979).

On the basis of an HR diagram with evolutionary tracks for different solar masses the masses of these Be stars have been estimated. Position of these studied stars on the HR diagram suggests that these Be stars may be in the stage of core contraction after exhausting hydrogen at the centre and have undergone hydrogen exhaustion in the thick shell.

1. Introduction

The Be stars have been extensively observed ever since their discovery. The most striking manifestation of the Be phenomenon in the visible spectral region is the existence of emission lines in the Balmer series, in a spectrum which would be classified as type B from its absorption lines. Be stars constitute a peculiar subset of B-type stars. A Be star is a fast rotating hot B star which is surrounded by an extended moving circumstellar envelope. Their peculiarity is manifested in their spectra. Emission lines, particularly the Balmer series of hydrogen, are superposed on the rotationally-broadened lines. The intensities and profiles of these emission lines change on various time-scales. Just like the line spectrum, the continuous spectrum of the Be stars is different from that of normal B stars. A wide range of phenomena takes place in Be stars, such as photometric variations, variations in the line intensity, mass loss due to radiatively driven stellar wind, and change in the Balmer jump. Ultraviolet and infrared excesses, ultraviolet deficiency, variation in emission line strengths, etc., are some of the common features associated with the Be stars.

Continuum energy distribution in the visible region is an important parameter in determining the effective temperatures of early-type stars, since a large amount of energy is radiated by the star in this region. There is one more advantage of studying the continua of early-type stars: since absorption lines are weak, as a result, the apparent absence of serious line blanketing has made their study relatively easier. Convection as a source of energy transport in the stellar atmosphere of the early-type stars is neglected. Thus, a good representation of the variation of temperature and pressure with depth in the atmosphere can be obtained easily to construct models. The continuous spectrum originates at different depths in the photosphere of the star and is modified by the

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frequency-dependent absorption coefficient. So, the emerging continuous spectrum will be related to the physical conditions in the photosphere, while the infrared continuum would be connected to the presence and nature of circumstellar envelope.

The continua of Be stars are peculiar since they display many interesting peculiarities. According to Barbier and Chalonge (1941), the Balmer jump is smaller for Be stars than for normal B-type stars. Mendoza (1958) has concluded that the majority of Be stars have an UV excess. Johnson (1967) has found that the excess is found in infrared too. However, Bottemiller (1972) and Briot (1978) did not find any deficiency or excess in the ultraviolet fluxes.

Since different observers have reported different characteristic features in the continua of Be stars, it becomes relevant and important to keep Be stars under continuous surveillance to understand various facets of the Be phenomenon. The continuum energy distributions are important in order to understand the origin and nature of UV and infrared excesses in the Be stars. The aim of this paper is to make available some more observations which will help us in understanding the various unresolved mystery about Be stars.

2. Observations and Their Reduction

All the programme stars studied in this paper, listed in Table I, were observed through 104-cm reflector of Uttar Pradesh State Observatory using Hilger and Watts monochromator at Cassegrain focus. The stars HR 7106, HR 7983, HR 8047, HR 8146 were observed during November, 1983 and HR 1761, HR 1786, HR 1820, HR 1932, HR 1934, and HR 2817 during February, 1984. The standard stars α Lyr and α Leo were observed alongwith the programme stars. The spectral types and luminosity classes are taken from the compilation of Hoffleit and Jaschek (1982). An exit slot of 0.7 mm, admitting 50 Å of the spectrum onto the photomultiplier, was used for making the observations. Each star was observed four to five times. The reduction techniques were same as used by us earlier (Goraya and Singh, 1985).

TABLE I

Ephemerides of the programme Be stars

HR	Star	Sp. type	m_V	T_{eff}	Log g	$E(B-V)$
1761	–	B5Ve	$6\overset{m}{.}57$	18000	4.0	$0\overset{m}{.}04$
1786	–	B4IVe	6.32	17000	4.0	0.03
1820	–	B2Ve	6.41	25000	4.0	0.05
1932	σ Ori	B2Ve	6.70	30000	4.0	0.05
1934	ω Ori	B3IIIe	4.57	22500	3.5	0.08
2817	OT Gem	B2Ve	6.30	22500	4.0	0.07
7106	β Lyr	B7Ve	3.40	13000	4.0	0.03
7983	–	B4Ve	6.33	18000	4.0	0.05
8146	ν Cyg	B2Ve	4.43	25000	4.0	0.06
8047	59 Cyg	B1IVe	4.74	30000	4.0	0.06

The nightly extinction coefficients were applied for each star using standard star observations. Transformations of observations to absolute flux values were carried out with the help of the absolute calibration of α Lyr and α Leo given by Taylor (1984). The absolute monochromatic magnitudes extracted at every 100 Å interval between λλ3200–8000 Å corrected for interstellar reddening have been normalised to λ5500 Å. These are listed in Table II. The standard deviation of the measurements does not exceed $\pm 0\overset{m}{.}03$ in the entire wavelength region.

3. Corrections for Interstellar Reddening

The determination of interstellar reddening for Be star is complicated due to their high-rotational velocities which introduces an intrinsic reddening for rapidly rotating Be stars. A neglect of this effect yields an overestimate of interstellar reddening which in turn, yield an over-correction of ultraviolet fluxes in spurious ultraviolet excess. So the normal Q method of colour excess determination of Johnson and Morgan (1953) cannot be applied for 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. The details of the method of reddening corrections are given in our previous papers (Singh, 1985, 1986). The colour excesses $E(B - V)$ determined through this method are also given in Table I. 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).

4. Discussions of the Result

The energy radiated from Be stars comprise of stellar radiation, radiation from circumstellar envelope and scattered radiation. In such a way the radiation received from these stars is composite, variability in line spectrum as well as in the continuum is found practically for every Be star. Such kind of variability has been observed over a wide range of electromagnetic radiation: i.e., from ultraviolet, visible, infrared to radio 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 geometrical position of the star also affects its effective temperature (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.

Kurucz model atmospheres with solar abundances and microturbulence velocity of 2 km s^{-1} were superimposed on the observed spectra in order to derive effective temperatures assuming $\log g = 4$ for luminosity classes IV and V and $\log g = 3.5$ for luminosity class III. Continuum fits to stellar models are considered only in the wavelength region λλ4000–5500 Å since this region is free from ultraviolet and near-

TABLE II

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

λ (Å)	$1/\lambda$ (μ^{-1})	HR 1761	HR 1786	HR 1820	HR 1932	HR 1934	HR 2817	HR 7106	HR 7983	HR 8146	HR 8047
3200	3.13	−0.488	−0.431	−0.900	−0.925	−0.575	−0.502	+0.303	−0.103	−0.674	−0.862
3300	3.03	−0.301	−0.361	−0.852	−0.891	−0.499	−0.455	+0.322	−0.175	−0.522	−0.869
3400	2.94	−0.201	−0.281	−0.813	−0.802	−0.450	−0.374	+0.322	−0.203	−0.558	−0.763
3500	2.86	−0.165	−0.235	−0.753	−0.822	−0.401	−0.325	+0.372	−0.051	−0.475	−0.688
3600	2.78	−0.100	−0.151	−0.652	−0.725	−0.343	−0.350	+0.350	−0.125	−0.386	−0.428
3700	2.70	−0.250	−0.200	−0.600	−0.751	−0.242	−0.225	+0.261	−0.025	−0.350	−0.350
3800	2.63	−0.385	−0.320	−0.555	−0.703	−0.322	−0.325	+0.292	−0.176	−0.300	−0.272
3900	2.56	−0.462	−0.410	−0.592	−0.703	−0.377	−0.452	+0.114	−0.325	−0.342	−0.252
4000	2.50	−0.492	−0.462	−0.652	−0.750	−0.505	−0.482	−0.130	−0.465	−0.625	−0.678
4100	2.44	−0.462	−0.425	−0.622	−0.700	−0.475	−0.601	−0.275	−0.431	−0.552	−0.581
4200	2.38	−0.431	−0.403	−0.556	−0.653	−0.455	−0.390	−0.302	−0.402	−0.532	−0.543
4300	2.33	−0.367	−0.356	−0.496	−0.598	−0.390	−0.374	−0.278	−0.375	−0.508	−0.486
4400	2.27	−0.362	−0.341	−0.482	−0.571	−0.375	−0.357	−0.250	−0.325	−0.511	−0.442
4500	2.22	−0.326	−0.297	−0.487	−0.548	−0.325	−0.309	−0.248	−0.302	−0.412	−0.391
4600	2.17	−0.313	−0.243	−0.383	−0.451	−0.295	−0.278	−0.175	−0.272	−0.378	−0.383
4700	2.13	−0.235	−0.210	−0.353	−0.406	−0.275	−0.242	−0.153	−0.250	−0.298	−0.304
4800	2.08	−0.168	−0.192	−0.279	−0.325	−0.225	−0.179	−0.143	−0.225	−0.270	−0.289
4900	2.04	−0.167	−0.153	−0.277	−0.311	−0.231	−0.169	−0.108	−0.175	−0.224	−0.247
5000	2.00	−0.132	+0.117	−0.239	−0.266	−0.210	−0.133	−0.098	−0.150	−0.212	−0.201
5100	1.96	−0.089	−0.082	−0.145	−0.210	−0.175	−0.092	−0.141	−0.135	−0.174	−0.175
5200	1.92	−0.093	−0.090	−0.142	−0.150	−0.100	−0.082	−0.035	−0.102	−0.131	−0.116
5300	1.89	−0.063	−0.052	−0.097	−0.100	−0.075	−0.073	−0.027	−0.035	−0.047	−0.113
5400	1.85	−0.026	−0.016	−0.003	−0.054	−0.025	−0.021	+0.015	−0.013	−0.013	−0.223
5500	1.82	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5600	1.79	+0.002	+0.022	+0.018	+0.022	+0.050	+0.221	+0.003	+0.061	+0.074	+0.017
5700	1.75	+0.041	+0.044	−0.052	+0.047	+0.075	+0.048	+0.027	+0.092	+0.081	+0.040
5800	1.72	+0.052	+0.059	+0.100	−0.051	+0.112	+0.101	−0.065	+0.073	+0.113	+0.093
5900	1.69	+0.072	+0.075	+0.150	+0.096	+0.135	+0.133	−0.118	+0.102	+0.141	+0.138
6000	1.67	+0.102	+0.104	+0.205	+0.135	+0.150	+0.208	−0.118	+0.095	+0.128	+0.104
6100	1.64	+0.175	+0.110	+0.214	+0.157	+0.153	+0.252	−0.126	+0.162	+0.226	+0.117
6200	1.61	+0.198	+0.125	+0.253	+0.184	+0.175	+0.303	−0.129	+0.162	+0.244	+0.197

Table II (continued)

λ (Å)	$1/\lambda$ (μ^{-1})	HR 1761	HR 1786	HR 1820	HR 1932	HR 1934	HR 2817	HR 7106	HR 7983	HR 8146	HR 8047
6300	1.59	+0.231	+0.135	+0.271	+0.212	+0.200	+0.325	+0.150	+0.171	+0.255	+0.345
6400	1.56	+0.252	+0.155	+0.291	+0.229	+0.252	+0.353	+0.160	+0.165	+0.275	+0.347
6500	1.53	+0.281	+0.179	+0.322	+0.277	+0.300	+0.375	+0.175	+0.201	+0.357	+0.362
6600	1.51	+0.305	+0.200	+0.362	+0.281	+0.331	+0.403	+0.181	+0.215	+0.395	+0.392
6700	1.49	+0.320	+0.225	+0.403	+0.312	+0.375	+0.425	+0.195	+0.245	+0.442	+0.408
6800	1.47	+0.333	+0.257	+0.423	+0.291	+0.401	+0.453	+0.201	+0.240	+0.371	+0.411
6900	1.45	+0.340	+0.289	+0.424	+0.284	+0.425	+0.504	+0.213	+0.250	+0.439	+0.467
7000	1.43	+0.353	+0.305	+0.422	+0.280	+0.400	+0.525	+0.225	+0.265	+0.475	+0.502
7100	1.41	+0.362	+0.326	+0.425	+0.312	+0.385	+0.548	+0.212	+0.270	+0.530	+0.535
7200	1.39	+0.375	+0.342	+0.430	+0.325	+0.382	+0.556	+0.193	+0.250	+0.525	+0.537
7300	1.37	+0.385	+0.350	+0.450	+0.346	+0.375	+0.577	+0.201	+0.275	+0.548	+0.555
7400	1.35	+0.402	+0.363	+0.475	+0.360	+0.369	+0.611	+0.218	+0.269	+0.634	+0.622
7500	1.33	+0.422	+0.306	+0.485	+0.375	+0.375	+0.594	+0.225	+0.282	+0.646	+0.577
7600	1.31	+0.450	+0.313	+0.490	+0.400	+0.405	+0.672	+0.236	+0.290	+0.676	+0.679
7700	1.29	+0.470	+0.334	+0.501	+0.422	+0.425	+0.717	+0.240	+0.301	+0.623	+0.687
7800	1.27	+0.490	+0.351	+0.515	+0.450	+0.423	+0.703	+0.245	+0.313	+0.786	+0.899
7900	1.26	+0.510	+0.299	+0.525	+0.470	+0.420	+0.635	+0.175	+0.319	+0.804	+0.610
8000	1.25	+0.515	+0.163	+0.533	+0.480	+0.430	+0.650	+0.165	+0.325	+0.994	+0.728

infrared excess emissions. The observed energy distribution with Kurucz (1979) model (solid curve) line is shown in Figures 1 and 2. Since the effect of gravity on the effective temperature is small, it is not necessary to know the correct value of gravity (Nandy and Schmidt, 1975). A change in $\log g = 4$ to $\log g = 2$ would be equivalent to a change in temperature of less than 500 at 10000 K (Kontizas and Theodossiu, 1980).

The uncertainty in the temperatures due to errors of the observed fluxes is estimated to be $\pm 5\%$ around 25000 K and $\pm 2\%$ around 10000 K. The fitting of the computed to the observed fluxes introduces an additional error that varies from $\pm$ 500 K for cool stars to $\pm$ 1000 K for hot stars. The temperatures derived here are plotted on the

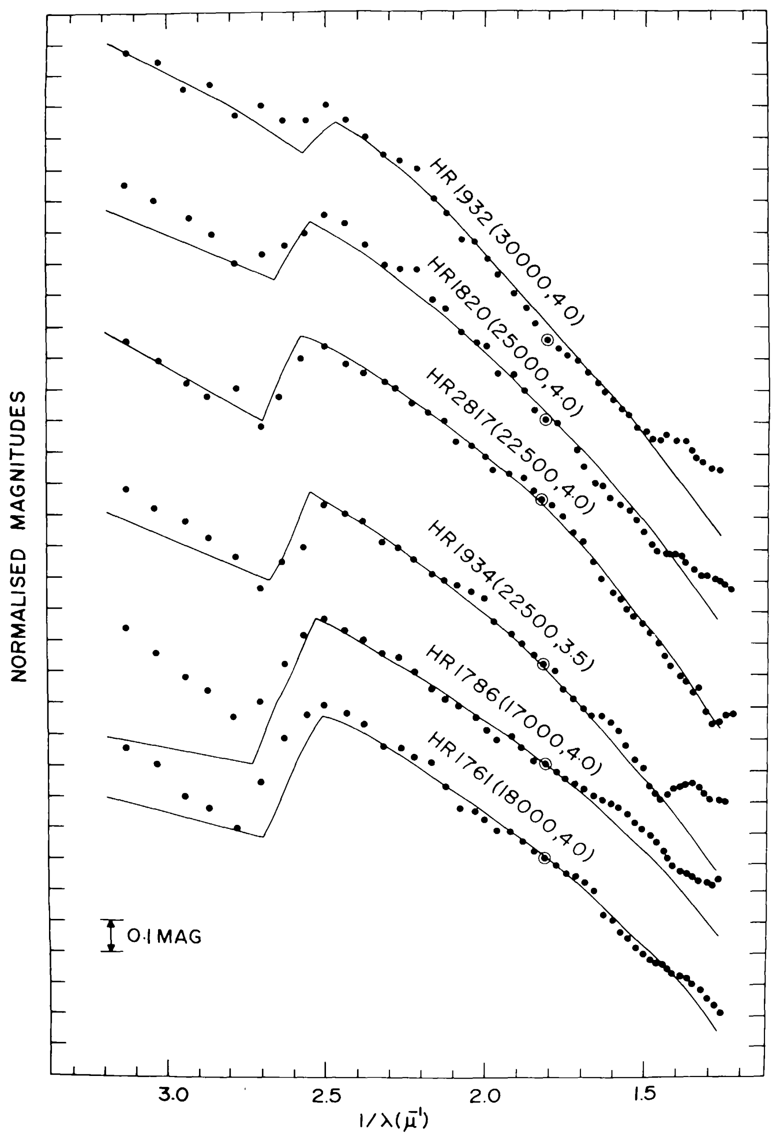

Fig. 1. Normalised de-reddened energy distribution curves of Be stars (filled circles) superimposed by best fitting models (solid continuous curves). The normalisation has been done at λ5500 Å which is denoted by a filled circle surrounded by an open circle. The matching has been done by eye.

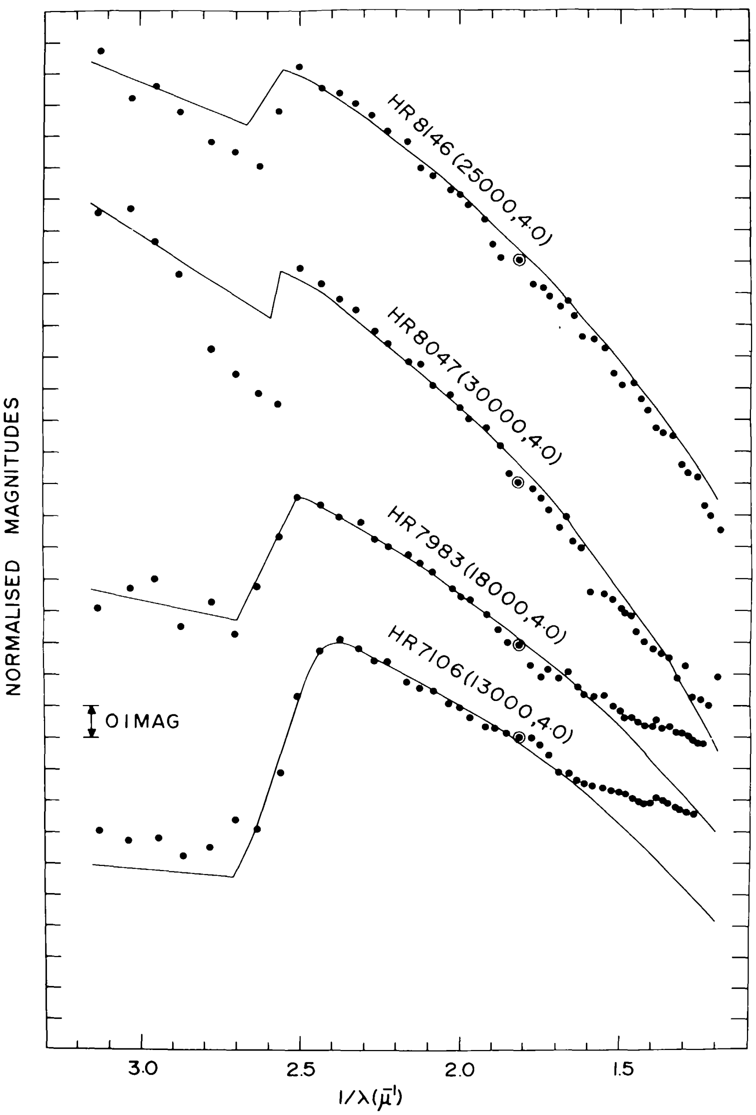

Fig. 2. This figure is the same as Figure 1.

$\theta_{\rm eff}$-spectral type relation in Figure 3. From Figure 3 we see that there exists a fairly good correlation between $\theta_{\rm eff}$ and spectral type for Be stars. From Figures 1 and 2 we see that energy distribution fits well with the model in the wavelength region $\lambda\lambda$4000–5500 Å. However, there is an excess emission longward of λ6000 Å for most of the Be stars. For Be stars HR 8047 and HR 8146 a double Balmer jump is seen. In shell stars the presence of a second Balmer jump is a common feature. These two Balmer jumps are produced in two different regions of the stellar atmosphere: the photosphere and the extended atmosphere where the pressure is much lower.

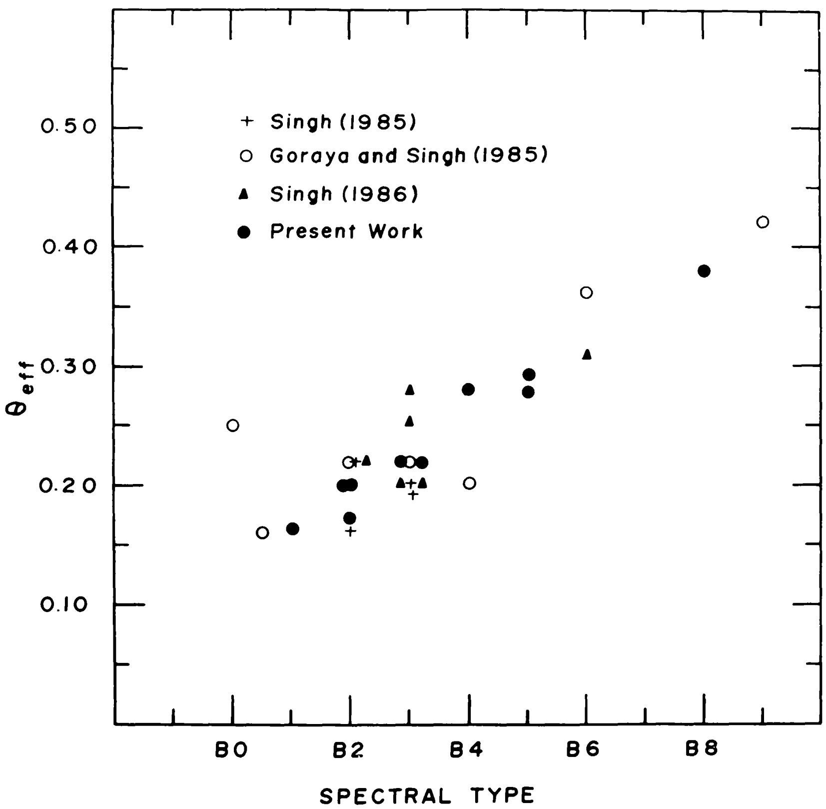

Fig. 3. A plot of θ_{eff}-spectral type relation for Be stars.

5. Evolutionary Status of Be Stars

The evolutionary status of Be stars is not yet known completely. According to Schmidt-Kaler (1964) and Crampin and Hoyle (1969), all Be stars are in the secondary contraction phase followed by hydrogen exhaustion in the core. Thus the shrinking of the stellar core decreases the moment of inertia, thereby causing it to spin faster to conserve total angular momentum. The high rotation might be brought to critical speeds in this way to produce extended atmosphere or envelope. The correct position of Be stars on the HR diagram is not clearly defined. Some investigators like Bidelman (1947), Mendoza (1958), Schild (1965), Meisel (1968), and Slettebak (1968) suggested that on the average, Be stars are located 0.5–1.0 mag above the Main Sequence. Contrary to above, Bond (1973), Schild and Romanishin (1976), Abt and Levato (1977) have shown that Be stars in clusters do not lie above the Main Sequence but also found near the Zero-Age Main Sequence. In order to study the evolutionary status of our programme Be stars and their mass determinations, we have plotted positions of these stars in the $\log(L/L_{\odot})$ versus $\log(T_{eff})$ HR diagram shown in Figure 4. The HR diagram with evolutionary tracks for different solar masses has been taken from Novotny (1973). The boundaries of the Main Sequence are shown by dashed lines.

For plotting our observed points on $\log(L/L_{\odot})$ versus $\log(T_{eff})$ HR diagram the

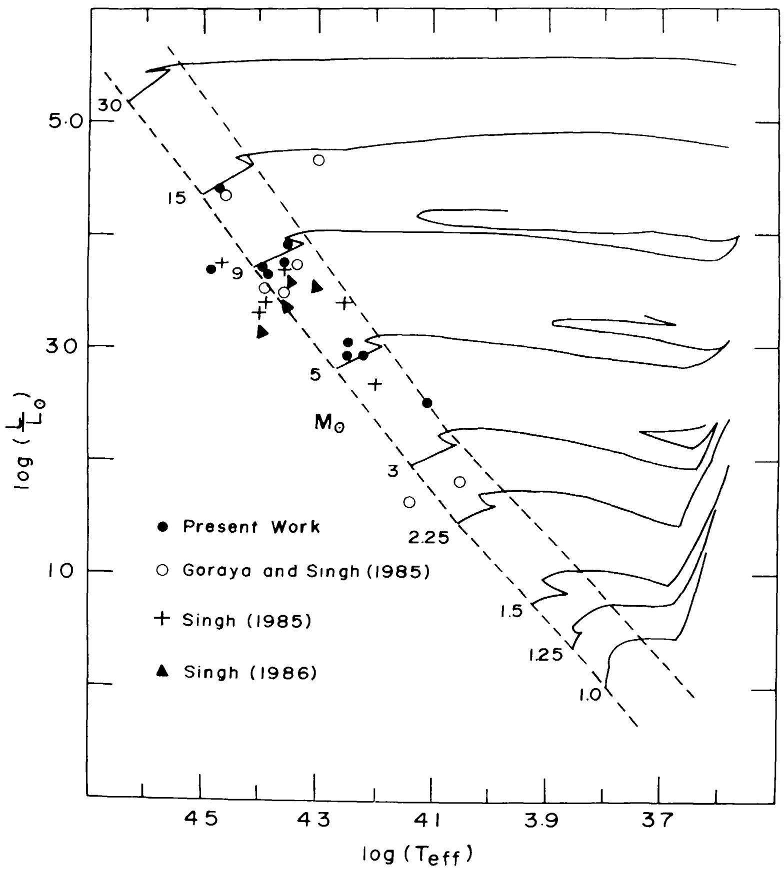

Fig. 4. Positions of the programme Be stars on HR diagram with adopted evolutionary tracks for different solar masses. This figure has been taken from Novotny (1973).

values of effective temperatures have been taken from our observations. For luminosity determinations, we have taken the values of absolute magnitudes (M_V) from Hirshfeld and Sinnott (1982). By use of bolometric corrections taken from Schmidt-Kaler (1982), bolometric magnitudes ($M_{\rm bol}$) were determined. From the bolometric magnitudes and luminosity relations the values of luminosities were calculated for individual stars. We have plotted our previous observations (Goraya and Singh, 1985; Singh, 1985, 1986) also on the $\log(L/L_\odot)$ versus $\log(T_{\rm eff})$ HR diagram.

From Figure 4, we see that majority of Be stars are lying well above the Main Sequence of the HR diagram near the turning points of evolutionary tracks. This suggests that these stars may be in a stage of core contraction after exhaustion of hydrogen at the centre and have undergone hydrogen exhaustion in the thick shell. However, a few stars are seen to lie just below the Main Sequence of the HR diagram. It is possible that due to error in effective temperature and luminosity determinations these stars may be lying below the Main Sequence. It is also clear from Figure 4 that majority of stars are lying between 5 $M_\odot$ to 9 $M_\odot$ evolutionary tracks.

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