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Infrared photometric studies of Be stars

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Summary. The Be stars as a class have been studied. *JHK* (1.2, 1.65, 2.2 μm) magnitudes for 55 Be stars are presented along with L (3.5 μm) magnitudes for 15 of them. For 20 Be stars the observations reported in the present work are new. By geometric considerations it is shown that the energy input to the circumstellar (CS) envelope, by the Lyman continuum flux L_L^0 from the central star, cannot account for the observed continuum luminosity, L_{IR}, of the CS envelope. The bolometric luminosity of the central star, L_*, is found to be correlated to L_{IR}. Selecting Be stars common to our photometric observations and the spectroscopic observations of Andrillat & Fehrenbach, it is shown that $L_{\mathrm{H}\alpha}$, the luminosity of the Hα emission line, is proportional to L_{IR}. By combining the present observations with the previous available data it is shown that in the case of four Be stars significant infrared variations have occurred and that these are accompanied by variations in Hα equivalent widths.

1 Introduction

The distinguishing feature of Be stars is the presence of emission lines superposed on the usual stellar absorption in the optical region; to gain a better understanding of the Be phenomenon it is, however, important to consider other accompanying details associated with the circumstellar (CS) envelopes. In particular, the study of the thermal balance of the CS envelopes appears rewarding. An appreciable portion of the output energy from the CS envelope appears as continuum radiation contributing mainly to the observed flux at infrared wavelengths. The earlier infrared photometric studies of Be stars (Johnson 1967; Woolf, Stein & Strittmatter 1970; Gehrz, Hackwell & Jones 1974, henceforth referred to as GHJ; Neto & Pacheco 1982; Dachs & Wamsteker 1982; Feinstein 1982) have demonstrated their usefulness in delineating the physical conditions prevailing in CS envelopes of Be stars.

In the present work we report (Section 2) *JHK* photometric observations of 55 Be stars. For a few brighter members L band observations are also given. The data set presented in this paper includes new observations for 20 Be stars. In Section 3 an attempt is made to work out details of the energetics of CS envelopes using correlation studies of the infrared excess flux and physical parameters of the central star. The Hα emission line luminosity calculated from the equivalent width data of Andrillat & Fehrenbach (1982) for 18 stars observed by us is found to be correlated with the continuum luminosity of CS envelopes (Section 4). The earlier infrared observations in conjunction with the present ones are used in Section 5 to study the infrared variability of Be stars. In the final section we list the conclusions of the present investigation.

2 The observations

The observations were obtained with 1-m reflectors at the Uttar Pradesh State Observatory, Nainital and the Indian Institute of Astrophysics Observatory, Kavalur, using a liquid nitrogen cooled InSb photometer covering the *JHKL* photometric bands (Kulkarni *et al.* 1979). A few observations of bright programme Be stars were also taken with the 0.5-m reflector at Kavalur. The observations at Nainital were carried out in 1980 April and October and 1981 March and those at Kavalur in 1981 January and February. The data were transformed to the Johnson *JHKL* photometric system by using observations of standard stars (Johnson *et al.* 1966). To minimize the corrections due to atmospheric extinction the programme stars were observed, as far as possible, at zenith angles less than 45°. Also, in most cases, the chosen standard stars were within a few degrees of the programme stars. The typical errors are ±0.07 mag in *JHK* and ±0.1 mag in *L* magnitudes. The observations are presented in Table 1. The programme stars have been divided into two groups. Table 1(a) lists the Be stars observed for the first time by us and Table 1(b) includes the Be stars having previous infrared observations. The HD and HR numbers are given in columns 1

Table 1. (a) Infrared photometry: programme Be stars for which the present observations are new.

Star HD	HR	Spectral type MK	*V*	Date	*J* (1.25 μm)	*H* (1.60 μm)	*K* (2.2 μm)	*L* (3.64 μm)
18552	894	B8 Vn	6.10	b	6.25	6.21	6.28	–
23016	1126	B8 Vn	5.69	b, d	5.76	5.75	5.91	–
29866	1500	B7 IV	6.08	b	5.96	5.87	5.88	–
43285	2231	B5 Vn	6.07	b	6.42	6.46	6.45	–
45995	2370	B2 V	6.14	c	5.99	5.95	5.63	–
54309	2690	B1 V	5.75	c	5.65	5.63	5.58	–
164284	6712	B2 Vn	4.64	a, e	4.43	4.32	4.00	3.6
164447	6720	B8 Vn	6.38	a	6.64	6.78	6.63	–
168717	6873	B3 Vn	6.13	a	6.30	6.49	6.28	6.0
183362	7403	B2 Vn	6.34	a	6.42	6.44	6.15	6.1
187811	7565	B2 V	4.95	a	5.22	5.28	5.19	4.9
189687	7647	B3 IV	5.19	a	5.46	5.54	5.40	5.4
191610	7708	B2 Vn	4.93	a	5.10	5.08	4.92	4.5
192044	7719	B8 Vn	5.92	a	6.06	6.17	6.04	–
193911	7789	B8 III	5.43	a	5.69	5.77	5.74	–
194335	7807	B2 Vn	5.90	a	6.27	6.32	6.35	–
200120	8047	B1.5 V	4.74	a, b	5.18	5.17	5.00	–
203467	8171	B3 III	5.18	a	5.15	5.12	4.91	4.5
208682	8375	B3 V	5.86	a	5.98	6.05	5.72	5.0
214167	8603	B1 V	5.73	b	6.47	6.39	6.72	–

Table 1. (b) Infrared photometry: programme Be stars for which previous infrared observations are available.

Star HD	HR	Spectral type MK	V	Date	J (1.25 μm)	H (1.60 μm)	K (2.2 μm)	L (3.64 μm)	References
5394	264	B0.5 IV	2.47	b	2.30	2.24	2.08	–	1, 3, 5, 6, 11
10516	496	B1 V	4.07	b	3.94	3.82	3.54	–	1, 3, 5, 6, 11
20336	985	B3 Vn	4.84	b	5.03	5.07	5.00	–	1
22192	1087	B4 V	4.23	b, c	4.30	4.24	4.04	–	1, 3, 8, 11
23302	1142	B6 III	3.70	c, d	3.90	3.88	3.95	–	3, 5
23480	1156	B7 III	4.18	c, d	4.25	4.22	4.28	–	3, 5
23630	1165	B7 III	2.87	c, d	2.95	2.99	2.94	–	3, 5
23850	1178	B8 III	3.63	c, d	3.74	3.75	3.77	–	3, 5
23862	1180	B8 V	5.09	c, d	5.22	5.31	5.13	–	5
32343	1622	B3 V	5.08	b	5.20	5.13	5.00	–	1, 8
32990	1659	B2 Vp	5.50	d	5.53	5.47	5.51	–	9
35439	1789	B1 IV	4.95	b, c, d	4.98	4.90	4.76	–	1, 2
37202	1910	B2 III	3.00	d	3.25	3.13	3.00	–	3, 5, 8, 11
37490	1934	B3 III	4.57	b, c	4.78	4.79	4.76	–	2, 3, 5
37795	1956	B8 V	2.64	d	2.77	2.79	2.87	–	2, 3, 5
45542	2343	B6 III	4.15	b, c	4.47	4.43	4.47	–	3, 9
50013	2538	B2 V	3.95	d	3.78	3.64	3.61	–	2, 3
56014	2745	B3 III p	4.66	c, d	4.88	4.82	4.82	–	5
56139	2749	B3 V	3.85	c, d	4.39	4.42	4.48	–	1, 2, 4, 5
58343	2825	B3 IV	5.33	d	5.00	4.89	5.04	–	2, 8, 9
58715	2845	B8 Vn	2.90	c	3.00	3.10	2.99	–	3, 5
63462	3034	B0 Vp	4.52	c, d, e	4.34	4.25	4.08	3.6	1–3
68980	3237	B1.5 III	4.78	d	4.89	4.72	4.59	–	5
83953	3858	B6 V	4.77	b, c	4.90	4.90	4.72	4.4	1–3
109387	4787	B5 IV	3.87	a, e	3.94	3.95	3.84	3.6	1, 3, 5, 11
138749	5778	B6 Vn	4.14	a, c, d	4.44	4.49	4.48	4.5	1, 3, 8
142983	5941	B4 III	4.88	a, d, e	4.90	4.84	4.71	4.3	1–3, 6, 7
148184	6118	B1 V	4.42	a, d, e	3.40	3.18	2.88	2.5	1–3, 6–8, 10
174638	7106	B7 V	3.45	a	3.37	3.29	3.15	2.9	3, 5
202904	8146	B2 V	4.43	a, b	4.40	4.39	4.16	–	8
209409	8402	B6 V	4.69	b	4.82	4.84	4.85	–	3, 5
212076	8520	B2 V	5.01	b	5.29	5.38	5.42	–	3
212571	8539	B1 V	4.66	b	4.46	4.07	3.82	–	1, 3, 6
217050	8731	B3 III	5.43	b	5.34	5.30	5.16	–	1, 6
217891	8773	B6 III	4.53	b	4.67	4.81	4.84	–	1, 3, 8

Notes:

(1) Date: a, April 1980; b, October 1980; c, January 1981; d, February 1981; e, March 1981. a, b, e at Nainital and c, d at Kavalur.

(2) References in column 10 are:
1. Allen (1973). 2. Dachs & Wamsteker (1982). 3. Gehrz *et al.* (1974). 4. Glass (1974). 5. Johnson *et al.* (1966). 6. Jones (1979). 7. Neto & Pacheco (1982). 8. Schild (1973). 9. Smyth & Nandy (1978). 10. Whittet & van Breda (1980). 11. Woolf *et al.* (1970).

and 2. The MK spectral types and V magnitudes of the programme stars listed in columns 3 and 4 are taken mainly from Jaschek *et al.* (1980). The month and year of the observations are given in column 5. Observed *JHKL* magnitudes appear in columns 6–9. In Table 1(b) references to earlier infrared studies are also included (column 10).

3 Correlation studies of the continuum luminosity, L_{IR}, of the CS envelope with the central star's parameters

3.1 CALCULATION OF L_{IR}

The most widely accepted explanation for the infrared excess exhibited by the majority of the Be stars invokes free–free and bound–free emission originating in the ionized CS envelopes (GHJ; Scargle *et al.* 1978). We also adopt the free–free and bound–free emission mechanisms for the calculation of the continuum luminosity of the CS envelopes of the Be stars. The knowledge of emission mechanisms makes it possible to estimate L_{IR} from the flux measurement at a given wavelength.

3.1.1 Programme stars in present investigation

The fractional contribution of the CS envelope to the observed flux increases as one goes to longer wavelengths in the 1–5 μm region. To minimize the effect of observational errors in the calculation of L_{IR} it is therefore advisable to use observations at the longest wavelength available. Since L band observations are not available for all of our programme stars, K band observations have been utilized to calculate L_{IR}.

The interstellar reddening corrections were done using the visual data; observed $(B-V)$ colours and spectral types are taken mainly from Jaschek *et al.* (1980) and intrinsic colours from Johnson (1966). First, A_V, the extinction at V is estimated assuming that only interstellar reddening contributes to the $(B-V)$ colour excess $E(B-V)$,

$$A_V = RE(B-V) \tag{1}$$

where $R = 3.1$ (Barlow & Cohen 1977).

A_K, the extinction at K, is then calculated from the standard van de Hulst extinction curve (Johnson 1968) which gives

$$A_K = 0.089\,A_V. \tag{2}$$

The dereddened magnitues V_0 and K_0 are then given by

$$V_0 = V - A_V \tag{3a}$$

$$K_0 = K - A_K \tag{3b}$$

where V and K are the observed magnitudes.

The dereddened flux corresponding to K_0 contains contributions from the central star's photosphere and its CS envelope. The expected stellar magnitude K_* is estimated using the intrinsic colour $(V-K)_{\mathrm{i}}$ corresponding to the spectral type of the star (Johnson 1966) and assuming that the contribution of the CS envelope is negligible in the V band:

$$K_* = V_0 - (V-K)_{\mathrm{i}}. \tag{4}$$

The CS envelope flux in the K band is calculated using the parameter $\Delta K = (K_* - K_0)/2.5$ and adopting the zero magnitude flux value given by Johnson (1966). Hence

$$F_K = 3.9 \times 10^{-7}(10^{\Delta K} - 1)/(2.5119)^{K_*} \qquad \mathrm{erg\ s^{-1}\ cm^{-2}\ \mu m^{-1}}. \tag{5}$$

The CS envelope luminosity at 2.2 μm, L_K, is calculated using the distance D to the source. Therefore

$$L_K = 4\pi D^2 F_K \qquad \mathrm{erg\ s^{-1}\ \mu m^{-1}}. \tag{6}$$

The distance D is obtained by normalizing the model (blackbody) photospheric flux at V to the observed photospheric flux; the radius and temperature of the central star needed in this calculation have been taken from Collins (1974).

As noted in the beginning of this subsection the total continuum luminosity, $L_{\rm IR}$, is calculated on the basis of the free–free and bound–free emission mechanisms. The free–free and bound–free volume emission coefficients are given by (Tucker 1975)

$$j_{\lambda\,\rm ff} = 1.633 \times 10^{-24}\,\lambda^{-2} Z^2 g T^{-1/2} N_{\rm e} N_{\rm i} \exp(-c_2/\lambda T) \qquad \text{erg s}^{-1}\ \text{cm}^{-3}\ \text{sr}^{-1}\ \mu\text{m}^{-1} \tag{7a}$$

and

$$j_{\lambda\rm bf} = \sum_{\rm n} j_{\lambda\rm n}, \tag{7b}$$

$$j_{\lambda\rm n} = 4.3 \times 10^{-23}\,\lambda^{-2} Z^4 g T^{-3/2} N_{\rm e} N_{\rm i} n^{-3}$$

$$\exp\left[\frac{c_2}{T}\left(\frac{1}{\lambda_{\rm Ln}} - \frac{1}{\lambda}\right)\right] \qquad \text{erg s}^{-1}\ \text{cm}^{-3}\ \text{sr}^{-1}\ \mu\text{m}^{-1} \tag{7c}$$

where λ is the wavelength of emission in μm, Z is the charge, g is the Gaunt factor, T is the temperature, $N_{\rm e}$ and $N_{\rm i}$ are electron and ion densities and $\lambda_{\rm Ln}$ is the wavelength of the nth series limit in μm.

In the following calculations $T = 1.4 \times 10^4$ K (GHJ), $Z = 1$ (most of the material is hydrogen) and $g = 1$ are taken and Menzel–Baker case B is adopted. Integration of equation (7a) over the whole wavelength range gives

$$j_{\rm ff} = 1.142 \times 10^{-28}\, T^{1/2} N_{\rm e} N_{\rm i} \qquad \text{erg s}^{-1}\ \text{cm}^{-3}\ \text{sr}^{-1}. \tag{8a}$$

In the case of the bound–free volume emission coefficient the wavelength integration of equation (7c) followed by summation over n of equation (7b) results in the relation given below,

$$j_{\rm bf} = 5.938 \times 10^{-24}\, T^{-1/2} N_{\rm e} N_{\rm i} \qquad \text{erg s}^{-1}\ \text{cm}^{-3}\ \text{sr}^{-1}. \tag{8b}$$

Substituting $\lambda = 2.2\ \mu$m (K band effective wavelength) in equations (7a) and (7b) and comparing them with equations (8a) and (8b) one gets

$$j_{\rm ff} = 7.56\, j_{K\rm ff}, \tag{9a}$$

$$j_{\rm bf} = 47.94\, j_{K\rm bf}. \tag{9b}$$

The total volume emission coefficient is

$$j_{\rm tot} = j_{\rm ff} + j_{\rm bf}. \tag{9c}$$

At 2.2 μm the relative contributions of free–free emission and bound–free emission to the total emission are 63 and 37 per cent respectively. Hence

$$j_{\rm tot} = 22.5\, j_K. \tag{9d}$$

The continuum luminosity of the CS envelope (assumed to be optically thin) is obtained by integrating the emission throughout its volume V, i.e.

$$L = 4\pi j V \qquad \text{erg s}^{-1}. \tag{10}$$

From equations (9d) and (10) one then obtains

$$L_{\rm IR} \equiv L_{\rm tot} = 22.5\, L_K. \tag{11}$$

Table 2. (a) Total continuum luminosity of the circumstellar envelope and its relation to continuum luminosity shortward of the Lyman limit and central star luminosity: programme Be stars of the present work.

Star HR	Spectral type MK	$(B-V)$	L_{IR}‡ (erg s^{-1})	L_{IR}/L_L^0	L_{IR}/L_*‡
264	B0.5 IV	−0.15	1.29 E 36	0.07	0.86 E −2
3034	B0 Vp	−0.05	8.39 E 35	0.04	0.57 E −2
496	B1 V	−0.04	8.99 E 35	0.21	2.50 E −2
1789	B1 V	−0.20	1.11 E 36	0.24	3.06 E −2
2690	B1 V	−0.18	9.64 E 35	0.21	2.68 E −2
6118	B1 V	+0.28★	2.39 E 36	0.54	6.67 E −2
8047	B1 V	−0.05	†	–	–
8539	B1 V	−0.03	1.45 E 36	0.33	4.05 E −2
8603	B1 V	−0.15	†	–	–
1659	B2 Vp	+0.06	†	–	–
2370	B2 V	−0.08	5.15 E 35	0.63	5.09 E −2
2538	B2 V	−0.23	7.80 E 35	0.92	5.27 E −2
6712	B2 Vn	−0.03	5.03 E 35	0.60	3.39 E −2
7403	B2 Vn	−0.14	3.87 E 35	0.45	2.62 E −2
7565	B2 V	−0.14	1.05 E 35	0.12	0.71 E −2
7708	B2 Vn	−0.13	2.37 E 35	0.27	1.61 E −2
7807	B2 Vn	−0.20	8.42 E 34	0.09	0.57 E −2
8146	B2 V	−0.11	3.84 E 35	0.45	2.59 E −2
8520	B2 V	−0.13	†	–	–
985	B3 Vn	−0.15	1.12 E 35	0.68	1.79 E −2
1622	B3 V	−0.08	1.29 E 35	0.77	2.08 E −2
2749	B3 V	−0.17	†	–	–
2825	B3 IV	−0.05	1.86 E 35	1.13	2.98 E −2
6873	B3 Vn	−0.04	†	–	–
7647	B3 IV	−0.17	1.15 E 35	0.68	1.85 E −2
8375	B3 Vn	−0.06	1.30 E 35	0.80	2.08 E −2
1087	B4 V	−0.06	1.21 E 35	2.02	2.68 E −2
2231	B5 Vn	−0.13	†	–	–
4787	B5 IV	−0.13	1.04 E 35	5.57	3.75 E −2
3858	B6 V	−0.12	8.60 E 34	9.26	4.14 E −2
5778	B6 Vn	−0.13	†	–	–
8402	B6 V	−0.06	†	–	–
1500	B7 IV	+0.06	†	–	–
7106	B7 V	0.00	5.39 E 34	11.67	3.93 E −2
894	B8 Vn	−0.06	†	–	–
1126	B8 V	−0.01	†	–	–
1180	B8 V	−0.08	1.90 E 34	22.56	2.44 E −2
1956	B8 V	−0.12	†	–	–
2845	B8 Vn	−0.09	1.64 E 34	19.55	2.11 E −2
6720	B8 Vn	−0.06	†	–	–
7719	B8 Vn	−0.11	1.29 E 34	15.42	1.67 E −2

★$E(B-V) = +0.35$ adopted from Snow (1975).

† No detectable IR excess.

‡$x\mathrm{E}y \equiv x \times 10^{y}$.

1984MNRAS.211..471A

Table 2. (b) Total continuum luminosity of the circumstellar envelope and its relation to continuum luminosity shortward of the Lyman limit and central star's luminosity: Be stars from Gehrz *et al.* (1974).

Star name	HR	L_{IR} (erg s^{-1})	L_{IR}/L_L^0	L_{IR}/L_*
γ Cas	264	8.23 E 35	0.07	1.01 E – 2
π Aqr	8539	5.60 E 35	0.31	1.62 E – 2
χ Oph	6118	1.77 E 35	0.75	1.48 E – 2
ζ Tau	1910	2.67 E 25	1.13	2.23 E – 2
HD 217050		3.16 E 35	1.34	2.63 E – 2
ω Ori	1934	3.06 E 35	3.17	4.10 E – 2
ϕ Per	469	3.12 E 35	4.23	5.45 E – 2
48 Lib	5941	1.53 E 35	14.43	6.22 E – 2
β Psc	8773	4.24 E 24	4.0	1.72 E – 2

L_{IR} calculations have been done only for the programme Be stars of luminosity class IV and V and listed in Table 2(a). Table 2(b) contains L_{IR} values for Be stars observed by GHJ (Section 3.1.2). Also included in Table 2(a) and (b) are the observed $(B-V)$ colours utilized to estimate the interstellar reddening corrections and the ratios L_{IR}/L_L^0 (Section 3.2) and L_{IR}/L_* (Section 3.3).

3.1.2 Be stars observed by Gehrz, Hackwell & Jones (1974)

GHJ have studied the spectral characteristics of CS envelope continuum emission. They could obtain more definitely the parameters of CS envelopes because of the extended wavelength coverage from 2.3 to 19.5 μm. To check the consistency of our method for calculating L_{IR} from K band observations, a comparative study is done for nine Be stars observed by GHJ. For these stars various parameters have been listed in table 5 of their paper by GHJ. The CS envelope continuum luminosity, L_{IR}, is obtained using equations (8a), (8b) and (10) as

$$L_{IR} = 1.435\times10^{-27}\,T_s^{1/2}N_e^2\,V_s + 7.463\times10^{-23}\,T_s^{-1/2}N_e^2\,V_s \qquad \text{erg s}^{-1}. \tag{12}$$

In the above equation N_i is taken equal to N_e since most of the CS envelope material is hydrogen and T_s is the CS envelope temperature. The CS envelope volume, V_s, is calculated assuming a disc geometry (GHJ),

$$V_s = \pi R_s^2 H_s \text{ cm}^3 \tag{13}$$

where R_s and H_s are the disc radius and thickness respectively. The typical value of $R_s/5$ was taken for H_s (GHJ) to calculate L_{IR} values listed in Table 2(b).

3.2 DEPENDENCE OF L_{IR} ON L_L^0, THE CONTINUUM LUMINOSITY SHORTWARD OF THE LYMAN LIMIT

The ionization of CS envelope material, necessary for free–free and bound–free emission mechanisms to be operative, is done by the Lyman continuum radiation from the central star. GHJ have noted that the infrared excess in Be stars increases as spectral type becomes earlier and ascribe it to the increased stellar luminosity shortward of the Lyman limit, L_L^0. GHJ also observe that infrared excess does not increase in direct proportion with L_L^0; they interpret their result as an indication that there is a limited amount of material in the envelope available for ionization. In this subsection the quantitative dependence of L_{IR} on L_L^0 is studied. To begin with, the expected value of L_{IR}/L_L^0 is estimated from geometrical considerations.

For disc geometry the fractional solid angle Ω subtended by the CS envelope at the central star is

$$\Omega = \frac{2\pi R_\mathrm{s} H_\mathrm{s}}{4\pi R_\mathrm{s}^2} = \frac{1}{2}\frac{H_\mathrm{s}}{R_\mathrm{s}}. \tag{14}$$

The typical value of $H_\mathrm{s}/R_\mathrm{s}$ is given as 1/5 by GHJ. Hence

$$\Omega \sim 0.1. \tag{15}$$

This means that only 10 per cent of the central star's radiation is intercepted by the CS envelope. Assuming that all of L_L^0 is absorbed by the envelope and radiated as the free–free and bound–free continuum flux one obtains

$$\frac{L_{\mathrm{IR}}}{L_L^0} \sim 0.1. \tag{16}$$

It should be noted that this value, 0.1, is an upper limit since the CS envelope also loses energy in the form of optical emission lines. The Be stars as a class are fast rotators resulting in flattening of the polar regions and in non-uniform surface-gravity and temperature distributions. The polar region temperatures would be higher and relatively more continuum radiation would be emitted from the polar regions than from the equatorial regions. Since the CS envelopes are flattened and mainly confined to the equatorial region, the polar region ultraviolet flux is not utilized to ionize the CS envelope material. So the disc type geometry of the CS envelope, aided by preferential emission of stellar flux shortward of the Lyman limit from the polar region sets an upper limit for L_{IR}/L_L^0.

For calculating the observed L_{IR}/L_L^0 ratio, L_L^0 is obtained by using the relation

$$L_L^0 = 4\pi R_*^2 \int_{\nu_0}^{\infty} \mathscr{F}_\nu(T_*)\, d\nu \qquad \mathrm{erg\ s^{-1}} \tag{17}$$

where R_* is the stellar radius, ν_0 is the frequency at the Lyman limit and $\mathscr{F}_\nu(T_*)$ is the emittance per unit frequency range of a blackbody with temperature T_*, the effective stellar temperature.

An inspection of Table 2(a) and (b) shows that the observed values of L_{IR}/L_L^0 are greater than 0.1 for the majority of the Be stars. In particular, for Be stars of later spectral types the ratio L_{IR}/L_L^0 exceeds 1. These observations point out the inadequacy of the Lyman continuum flux for supplying input energy to the CS envelope. We note here that in the above calculations the stellar Lyman continuum luminosity was calculated assuming that the star radiates as a blackbody. However, in reality the strong absorption edges near the Lyman limit reduce the available Lyman continuum luminosity (Kurucz 1979) and make the actual L_{IR}/L_L^0 ratio even higher. Therefore we conclude that apart from the energy input by Lyman continuum flux an additional energy source is necessary to explain the higher values of the ratio L_{IR}/L_L^0.

3.3 DEPENDENCE OF L_{IR} ON L_*, THE BOLOMETRIC LUMINOSITY OF THE CENTRAL STAR

To gain an understanding about other possible energy input mechanisms, the bolometric luminosity of the central star, L_*, is compared with L_{IR}. L_* is obtained by using the

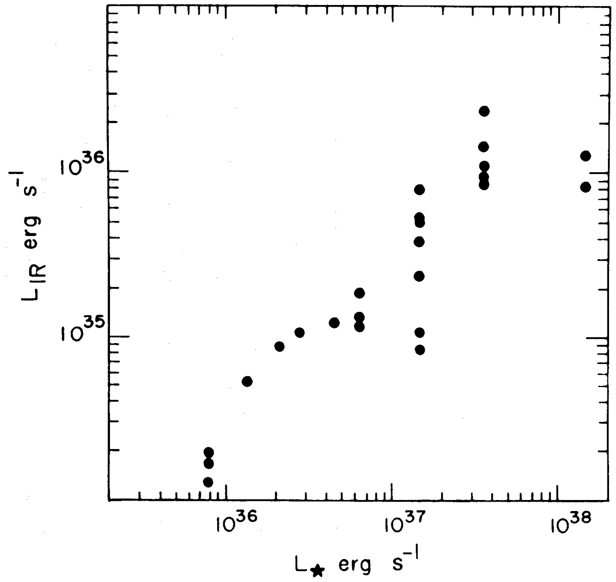

Figure 1. The continuum infrared luminosity, L_{IR}, of circumstellar envelopes of Be stars as a function of central star's bolometric luminosity, L_*.

relation

$$L_* = 4\pi R_*^2 \sigma T_*^4 \qquad \mathrm{erg\ s^{-1}} \tag{18}$$

where σ is the Stefan-Boltzmann constant.

In Fig. 1 L_{IR} values of our programme stars have been plotted against corresponding L_*. It is seen from this figure that from B0 to B8 L_{IR} increases in proportion with L_*. The physical implications of correlation between L_{IR} and L_* are not clear. However, it is interesting to note that mass-loss rates of early-type stars depend on their bolometric magnitudes (Lamers 1981).

4 Correlation of infrared excess with Hα emission

In Be stars the hydrogen recombination lines and infrared excess emission originate in the same CS envelope. As a result it is interesting to see whether any correlation exists between the infrared continuum radiation and the emission lines. For such a study it is desirable to have simultaneous infrared photometric and visual spectroscopic data. The Hα equivalent widths obtained by Andrillat & Fehrenbach (1982), sufficiently close in time to our observations, have been taken for this correlation study. For 18 of our programme stars Hα equivalent widths are available. We have considered only the Hα line as it is the most prominent spectral feature that distinguishes a Be star. Assuming that the underlying continuum, in terms of which the equivalent widths are measured, arises from a star radiating as a blackbody at temperature T_* with radius R_*, one can write for the line luminosity the following equation (Burbidge & Burbidge 1953)

$$L_{\mathrm{H}\alpha} = \frac{c_1}{\lambda^5} \frac{10^{-8}}{\exp(c_2/\lambda T_*) - 1} W_\alpha 4\pi R_*^2 \qquad \mathrm{erg\ s^{-1}}, \tag{19}$$

where c_1 and c_2 are radiation constants, λ the wavelength of the Hα line in cm and W_α the observed equivalent width in Å.

Table 3. Total continuum luminosity of the circumstellar envelope and Hα emission line luminosity of programme Be stars.

Sar HR	Infrared data★ Date	$L_{\rm IR}$ (erg s^{-1})	Hα data‡ Date	W_α (Å)	$L_{\rm H\alpha}$ (erg s^{-1})	$L_{\rm IR}/L_{\rm H\alpha}$
264	1980 October 15/16	1.29 E 36	1980 December 26	−21.3	1.21 E 34	107
496	1980 October 15/16	8.99 E 35	1980 December 26	−49.7	2.47 E 34	36
1789	1980 October 16 1981 January 25/29 1981 February 15	1.11 E 36	1980 December 28	−8.4	4.17 E 33	266
6118	1980 April 23/24/26 1981 February 15 1981 March 16	2.39 E 36	1980 March 1	−32.8	1.63 E 34	147
8539	1980 October 15	1.45 E 36	1980 December 30	−31.9	1.58 E 34	92
2370	1981 January 11	5.15 E 35	1980 December 26	−30.1	7.04 E 33	73
6712	1980 April 23/24/27 1981 March 16	5.03 E 35	1980 April 4	−44.0	1.03 E 34	49
8520	1980 October 15/16	†	1980 December 28	−18.3	4.28 E 33	–
985	1980 October 15	1.12 E 35	1980 December 30	−5.5	8.36 E 32	134
1622	1980 October 16	1.29 E 35	1980 December 26	−24.2	3.68 E 33	35
2825	1981 February 9	1.86 E 35	1980 December 30	−8.5	1.29 E 33	144
1087	1980 October 16 1981 January 10	1.21 E 35	1980 December 25	−41.0	5.25 E 33	23
2231	1980 October 16	†	1981 February 12	−1.6	1.44 E 32	–
4787	1980 April 24 1981 March 16	1.04 E 35	1980 December 30	−9.1	8.20 E 32	127
5778	1980 April 24/26 1981 January 11 1981 February 15	†	1980 December 30	5.6	–	–
894	1980 October 15	†	1980 December 29	−18.9	7.22 E 32	–
1180	1981 January 24 1981 February 14	1.90 E 34	1981 February 12	−12.0	4.58 E 32	41
2845	1981 January 25	1.64 E 34	1980 December 26	−6.0	2.29 E 32	72

★ Infrared data from present work.

‡ Hα emission line data from Andrillat & Fehrenbach (1982); $W_\alpha < 0$ for emission lines and $W_\alpha > 0$ for absorption lines.

† No detectable IR excess.

Table 3 lists the $L_{\rm H\alpha}$ values along with dates of observation and Hα equivalent widths. Fig. 2, a plot of $L_{\rm IR}$ against $L_{\rm H\alpha}$, shows that a significant correlation exists between them. The correlation coefficient of the linear regression curve of log $L_{\rm IR}$ and log $L_{\rm H\alpha}$ is 0.9. This result from the present investigation is in agreement with the conclusions of Neto & Pacheco (1982) and Dachs & Wamsteker (1982).

To understand the physical processes responsible for the observed correlation of infrared excess and line emission from the Be stars the details of line formation are considered. Adopting the analytical expression given by Tucker (1975) for the emissivity of a Balmer H*n* line as a function of temperature we obtain the following expression for Hα emission line luminosity,

$$L_{\rm H\alpha} = 1.29 \times 10^{-23} \int T_{\rm s}^{-1/2} \ln\,(h\nu_0/kT_{\rm s})\, N_{\rm e} N_{\rm i}\, dV_{\rm s} \qquad \text{erg s}^{-1}. \tag{20}$$

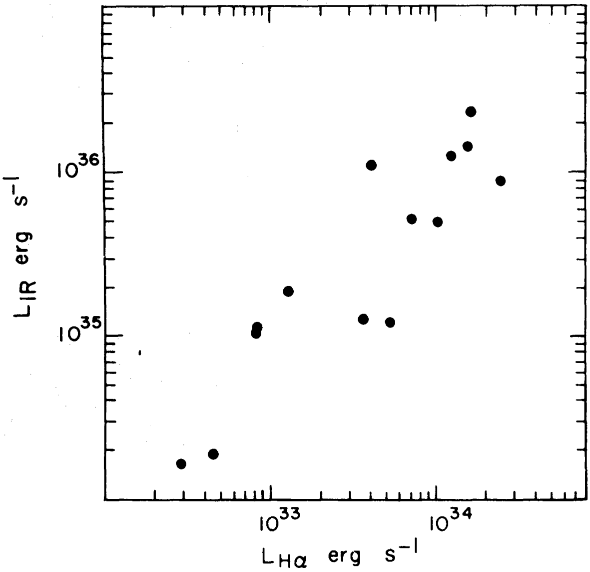

Figure 2. The continuum infrared luminosity, L_{IR}, of circumstellar envelopes of Be stars as a function of Balmer Hα line luminosity, $L_{\mathrm{H}\alpha}$.

Comparison of equation (20) with equations (8), (10) and (11) shows that both L_{IR} and $L_{\mathrm{H}\alpha}$ have the same functional dependence on the product $N_{\mathrm{e}} N_{\mathrm{i}}$ apart from the weak dependence on temperature. Consequently the existence of correlation between L_{IR} and $L_{\mathrm{H}\alpha}$ is understandable.

Table 3 shows that out of 18 stars listed, four do not have measurable infrared excesses. This could be explained as follows. The Be stars show infrared variability (Section 5) and for a given Be star the infrared excess will be present only when there is sufficient material in the CS envelope. Depletion of material in the envelope results in the absence of an infrared excess. From the previous discussion in this section it is also implied that the absence of an infrared excess should be accompanied by a smaller Hα equivalent width or even the absence of Hα line emission. This is corroborated by spectroscopic observations of two of the stars, viz. HR 2231 and 5778. The 1.6 Å Hα equivalent width of HR 2231 is the lowest of all the 18 stars; in the case of HR 5778, Hα is in absorption. The other two stars – HR 894 and 8520 – that do not have infrared excess, however, do have appreciable Hα equivalent widths. This apparent contradiction may be due to the variations (Section 5) in the physical conditions of the CS envelope in the two months separating the infrared and Hα observations.

Examination of Table 2(a) shows that out of 41 stars, in addition to the four stars discussed above, a further 10 Be stars do not exhibit infrared excess during our observations. The reason for the absence of infrared excess appears to be the absence of Be episodes at the time of the infrared observations. It will be interesting and valuable to confirm this inference drawn from infrared observations.

It is instructive to do a quantitative comparison between the observed and theoretically estimated ratio of L_{IR} to $L_{\mathrm{H}\alpha}$. For theoretical estimation, from equations (8), (10), (11) and (20) we obtain

$$\frac{L_{\mathrm{IR}}}{L_{\mathrm{H}\alpha}} = \frac{\int (1.435 \times 10^{-27} T_{\mathrm{s}}^{1/2} + 7.463 \times 10^{-23} T_{\mathrm{s}}^{-1/2}) N_{\mathrm{e}} N_{\mathrm{i}} \, dV_{\mathrm{IR}}}{\int 1.29 \times 10^{-23} T_{\mathrm{s}}^{-1/2} \ln (h\nu_0/kT_{\mathrm{s}}) N_{\mathrm{e}} N_{\mathrm{i}} \, dV_{\mathrm{H}\alpha}} . \tag{21}$$

In the above expression $dV_{\rm IR}$ and $dV_{\rm H\alpha}$ are the volume elements emitting continuum infrared radiation and Hα line emission respectively. Assuming that the temperature is uniform throughout the CS envelope ($T = 1.4 \times 10^4$ K, GHJ) the above expression reduces to

$$\frac{L_{\rm IR}}{L_{\rm H\alpha}} \simeq 3 \frac{\int N_{\rm e} N_{\rm i}\, dV_{\rm IR}}{\int N_{\rm e} N_{\rm i}\, dV_{\rm H\alpha}}. \tag{22}$$

From Table 3 it is seen that the average value of the observed ratio $L_{\rm IR}/L_{\rm H\alpha}$ is ~ 96, significantly different from the theoretical estimate of 3 if the emission measures were the same for continuum and line radiation. The large observed value of $L_{\rm IR}/L_{\rm H\alpha}$ shows that the effective emitting volumes are not identical and line radiation probably does not escape freely all through the envelope.

5 Infrared variability

The existence of a correlation between $L_{\rm IR}$ and $L_{\rm H\alpha}$ suggests that the Be stars should exhibit infrared variability since the Hα line strength of Be stars exhibits temporal variations.

Table 4. Be stars showing infrared variability.

Star HR	Infrared data Date	J (1.25 μm)	H (1.60 μm)	K (2.2 μm)	L (3.64 μm)	Ref*	Hα data† Date	W_α (Å)
1789	1971–72	–	5.44	5.47	–	1	1975 December	−3.78
	1979 February	5.15	5.16	5.16	4.97	2	1976 November	2.87
	1980–81	4.98	4.90	4.76	–	PW	1977 January	0
1934	1965	4.75	–	4.82	4.81	5	1974 October	−12.5
	1972–73	–	–	4.32	4.01	3	1975 December	−13.1
	1979 February	4.53	4.51	4.51	–	2	1976 November	−10.5
	1980–81	4.78	4.79	4.76	–	PW	1977 January	−7.8
							1978 January	−4.8
							1978 October	−7.6
							1978 November	
							1979 February	−7.0
							1979 March	
2749	1965	4.32	–	4.28	–	5	1978 January	−14.2
	1971–72	–	4.06	3.89	3.48	1	1978 February	
	1972–73	4.17	4.12	3.99	–	4	1978 October	−12.9
	1979 February	4.21	4.26	4.30	4.20	2	1978 November	
	1981	4.39	4.42	4.48	–	PW		
6118	1970	–	3.43	3.15	2.92	8	1972 May	−66.7
	1971–72	–	3.68	3.42	2.79	1	1976 May	−45.4
	1972–73	–	–	3.60	3.14	3	1977 June	−42.8
	1976	3.42	–	3.03	–	6	1977 July	−44.0
	1976–77	3.50	3.29	3.04	2.71	9	1978 February	−41.3
	1979 February	3.33	3.20	2.97	2.56	2	1978 October	−39.4
	1980 May	3.46	–	2.89	2.28	7	1979 March	−36.9
	1980–81	3.40	3.18	2.88	2.5	PW	1980 May	−33.7

* References in column 7 are:
PW, present work; others same as in Table 1(b).
† Hα data from Dachs *et al.* (1981); $W_\alpha < 0$ for emission lines and $W_\alpha > 0$ for absorption lines.

Systematic infrared photometric studies of Be stars to look for infrared variability have not been done. The data of Woolf *et al.* (1970) hinted at infrared variability of Be stars. However, GHJ reported that during their observational period of one year they did not find any evidence of infrared variability in Be stars. Elias, Lanning & Neugebauer (1978) have reported infrared variability correlated with variations in the Balmer emission lines in the Be star o Cas. Similar findings for μ Cen and χ Oph have been reported by Dachs & Wamsteker (1982).

The present set of programme stars contains 35 Be stars for which already published infrared data exist. The *JHKL* magnitudes for these stars available in the literature and obtained in the present investigation have been pooled together to obtain a data set spanning the time period from 1965 to 1981. This combined data set reveals that in the case of four of the programme stars the infrared magnitudes have significantly varied. The maximum change Δm_K in K magnitude lies in the range 0.5 to 0.8 mag. For these stars all the available *JHKL* magnitudes along with our observations are listed in Table 4. It is also seen from Table 4 that the infrared variations are accompanied by changes in the Hα emission line equivalent widths.

6 Conclusions

Infrared photometric studies of Be stars have been carried out. *JHK* magnitudes of 55 Be stars are presented. For 15 of these Be stars L magnitudes are also given. For 20 of the Be stars the infrared photometric observations reported in this paper are new. The new results that have emerged from the present investigation are listed below.

(1) For a large number of our programme Be stars the observed infrared continuum luminosity, L_{IR}, of the CS envelopes exceeds the energy input from the Lyman continuum luminosity, L_L^0, of the central star. Consequently there is a necessity for an additional energy source to maintain the thermal balance of CS envelopes.

(2) The existence of a correlation between L_{IR} and the bolometric luminosity of the central star, L_*, is demonstrated. Over almost two orders of magnitudes L_{IR} varies in proportion to L_*. This correlation suggests that L_* plays an important role in deciding the energetics of CS envelopes.

(3) L_{IR} is also correlated to the Balmer Hα emission-line luminosity $L_{\mathrm{H}\alpha}$.

(4) The effective volumes emitting Hα emission line and infrared continuum emission are different.

(5) Four of our programme Be stars – 25 Ori, ω Ori, ω CMa, χ Oph – have shown infrared variability. The amplitude of the variation ranges from 0.5 to 0.8 mag in the K band with a time-scale of a few years.

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