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Infrared and H-alpha emission from Be stars

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Abstract. It was noted earlier by several authors that the infrared excess H_α emission observed from Be stars are not compatible with the idea that both emissions occur from the same optically thin ionised region. We show here that the emissions can be reconciled, if self-absorption of the H_α emission in the ionised region, which is optically thick for H_α emission, is considered. We further show, by using the observed Paschen line intensity, for which the ionised region is optically thin, that *the infrared excess and the hydrogen line emissions do indeed come from the same ionised region* formed around the Be star. We show that the observed infrared emission requires Lyman continuum flux much larger than given by the present model atmosphere calculations. We discuss two possibilities : (i) Be stars emit Lyman continuum fluxes more copiously than given model atmosphere calculation (ii) a binary compact companion to the Be star exists, which supplies the necessary ionising photons. Recent EUVE satellite observations indicate that the first possibility may be correct.

1. Introduction

Infrared excess in the continuum emission from B-emission line stars (Be), compared to normal stars was found by Johnson (1967). This was confirmed by subsequent observations (see Lamers, 1987 for references). Using the spectral nature of the near infrared emission from Be stars, Woolf *et al.* (1970) argued that the excess is free-free emission from the ionised region formed in the gas envelope around the Be star. Ashok *et al.* (1984) obtained the ratio of the energy in the infrared excess and the H_α line emission for Be star of different spectral types. They found this ratio to be about 96 whereas the ratio expected from an ionised region due to

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the free-free process is about 3, suggesting that either the two radiations do not arise from the same ionised volume or that the line radiation does not freely escape the ionised region. The far infrared radiation from Be star observed from the IRAS satellite was used by Cote and Waters 1987 see Lamers, 1987 for other references) to derive the emission measure of the ionised region. Apparao and Tarafdar (1991) used these emission measures to calculate the H_α line flux arising from the ionised region, assuming the region is optically thin for the line radiation. They found that the H_α line emission fluxes obtained using the emission measures obtained from the far infrared emission, are far in excess of the fluxes observed for each of the spectral types. They had entertained the remote possibility that they are usually measured separately, and the incompatibility is due to variability. Apparao *et al.* (1993) measured the near infrared and H_α line emission from several Be star simultaneously with two different telescopes, and found that the discrepancy still exists.

Attempts have been made to reproduce quantitatively the H-alpha and infrared emissions from Be star by Kastner and Mazzali (1989) and by van Kerkwijk *et al.* (1994). Kastner and Mazzali (1989) used a pole-on slab model in their calculations and found that they can reproduce the correlation between the H-alpha emission and infrared excess. Van Kerkwijk *et al.* (1994) have used disk models given by Poeckert and Marlborough (1978) and by Waters (1986). They calculated the H-alpha and infrared correlations. With reasonable choice of parameters they found that the model of Waters (1986) gives too much H-alpha emission while the Poeckert and Marlborough (1978) model gives too little. In all these calculations (Kastner and Mazzali, 1989; Van Kerkwijk, 1994) a temperature was assumed throughout the envelope considered. It needs to be shown that the assumed temperature obtains throughout the envelope, by using the input of Lyman and Balmer continual from the Be star, before the results can be accepted.

In this paper, we first examine the possibility that the ionised region is optically thick to H_α line radiation, by considering the radiation transfer in the ionised region in the envelope around the Be star. The procedure is discussed in section 2. We next use the observed Paschen line observations of Be stars of different spectral types to calculate the implied infrared and H_α line emission, since the ionised region is optically thin to Paschen line radiation. The results are given in section 3. Discussion of the results follows in section 4, with conclusions in section 5.

2. Absorption of H-alpha line radiation in an HII region around a Be star

In estimating the enhancement of ionisation in an HII region in the envelope of a Be star by absorption of Balmer continuum from the Be star, Apparao and Tarafdar (1987) considered the radiation transfer of the H_α line radiation in the HII region. They however did not consider the absorption of H_α radiation in the ionised region. The Lyman-alpha line radiation emitted during recombination of an electron with a hydrogen nucleus, is absorbed by the ground state of hydrogen to maintain a population of excited levels (n = 2). These excited levels absorb the H_α line radiation. By introducing the absorption of the H_α radiation by these excited atoms in the radiation transfer, we have calculated the emerging flux of the H_α radiation. As before we considered that the ionisation in the envelope is caused by the Lyman continuum from the Be star and also the enhancement of the ionisation by absorption of the Balmer continuum from the star. The H_α flux has been calculated at a number of frequency points in the line profile using the absorption coefficient $\kappa(\nu, \nu_0)$ at each frequency point ν where, the function $\phi(\nu, \nu_0)$ is the Voigt function (Harris, 1948 ; Finn and Mugglestone, 1965), γ is the inverse lifetime of the upper state, f the oscillator strength and other symbols have their usual meaning. The frequency dependent H_α flux was then integrated over the frequency to determine the total H_α flux. The energy in the H_α flux for the optically thin and thick cases for various spectral types is given in Table 1. The results given in Table 1 are for a spherical geometry ; if the gas disk around the Be star is asymmetric, there will be escape of Lyman-alpha photons and consequently the self-absorption will be less than is indicated in the Table. Also it is likely the gas disk has a rotation velocity component, so that different parts of the disk can have different velocities which can make the self-absorption less. Another factor which will make the self-absorption less is the angle of the line of sight of the observer with respect to the equatorial plane of the Be star. All the effects given above tend to reduce the self-absorption, so that the real value of the observed H_α emission from the disk must be between the values given for the optically thin and the optically thick values. The observed values of H_α emission for each spectral type is shown in the last column of Table 1. It is seen that the observed value for the early type Be star is between the thin and thick cases. Thus self-absorption of H_α in the Be star envelope is possible and therefore the infrared and H_α emission may be reconciled as arising from the same region. In the case of the later type Be star, it was noted earlier (Apparao and Tarafdar, 1987) that the observed H_α emission cannot be accounted for by the ionisation observed H_α emission cannot be accounted for by the ionisation in the Be star envelope due to the Lyman continuum of the Be star obtained from model atmospheric calculations (Kurucz, 1979).

Table 1. Energy in H_α-line radiation from the ionised region in the envelopes of Be stars.

Spectral type	Optically thin case ergs s^{-1}	Optically thick case ergs s^{-1}	Observed$^{@}$ ergs s^{-1}
09.5	2.4 + 36*	5.2 + 33	3.4 + 34
B1	2.8 + 34	8.1 + 32	1.6 + 34
B3	8.3 + 32	1.7 + 32	3.7 + 33
B5	1.3 + 31	5 + 30	8.2 + 32
B8	2.9 + 29	2.2 + 29	4.6 + 32

@ from Ashok *et al.* (1984)

* a+n means a x 10^n in units of ergs s^{-1}

3. Estimates of infrared emission from the gas disk using Paschen line emission

Paschen line emission was observed from several Be star (Briot, 1981; Andrillat, Jaschek and Jaschek, 1988). The lines observed range from P11 to P24 and the emission was observed for spectral types earlier than B5. The gas disk (dimension ~10^{12} cm, see Doazan, 1982) and a density less than 10^{12} H atoms cm^{-3} is optically thin for these Paschen lines, because the number of H atoms in the n = 3 state is very small (we had calculated these numbers for Be stars of various spectral types earlier; Apparao and Tarafdar, 1987). Consequently the observed intensities should give the true emission measure. We have calculated the emission measures for various spectral types using the observations of the Paschen line P17 given by Andrillat, Jaschek and Jaschek (1988). We have used the P17 values because the line appears in emission for a large number of Be stars in the observations of Andrillat, Jaschek and Jaschek (1988). The energy in the Paschen P17 line emission is calculated using the observed equivalent widths, and the continuum level (at the P17 line wavelength) corresponding to the spectral type given by Kurucz (1979). We obtained the emission measure (N_eN_HV, where N_e is the electron density, N_H the proton density and V is the volume) using the observed P17 line emission energy and the coefficient of emission for P17,

$$4\pi J_{17} = 4.7 \times 10^{-28} / N_e N_H$$

in erg cm^3 s^{-1}, obtained by interpolating between the values given for the Paschen lines P15 and P20 given by Osterbrock (1974). We have then calculated the energy in the infrared emission using the free-free emission coefficient ($L_{IR} = 8.9 \times 10^{-25} N_eN_HV$) given by Ashok *et al.* (1984). These values are given in Table 2.

Table 3 gives the observed values of infrared (IR) emission from various spectral types as given by Ashok *et al.* (1984). Also given are the IR emission calculated from the Paschen line emission from Table 2. It is seen that the values of IR emission calculated from the Paschen lines agree well with the observed values (the minor differences can be attributed to time variation of the fluxes), indicating that the *IR emission indeed comes from the ionised region in the envelope of the Be star and it is due to the free-free and free-bound processes*. The free-free emission characteristic of IR emission was earlier indicated by the measured IR spectrum (see references in Lamers, 1987 and Doazan, 1982).

4. Discussion

In Table 3 we have given the highest value of IR emission derived from Paschen line emission for Be stars of different spectral types (column 2). We have also given (column 4), for various spectral types, values of IR emission from an ionised region formed due to the Lyman continuum of a Be star of that spectral type, calculated using the number of Lyman continuum photons given by Thompson (1984) and the coefficient for infrared emission by the free-free process given by Ashok *et al.* (1984). [The values given correspond to complete absorption of the Lyman photons of the star, so that these are the maximum values possible; if for example the gas envelope is not spherically symmetric, as is shown by many observations, the calculated values have to be reduced by a solid angle factor]. The number of Lyman continuum photons given by Thompson (1984) is for the luminosity class V, and the values for luminosity class III and IV are to be obtained by multiplying the values for the luminosity class V, by about 6 and 2.5 respectively; the calculated values for IR emission should also be multiplied by the same factors. The observed values of IR emission are also given in column 3 of the table. A comparison of the values of IR emission produced by the Lyman continuum from the Be stars, with either the observed IR emission or the IR emission derived from Paschen line observation, clearly shows that the Lyman continuum from Be stars is not adequate to explain the observations. In the case of late type Be stars, it was indicated earlier (Apparao and Tarafdar, 1991), that the Lyan continuum is not enough to explain either the IR emission or the Hα emission. Now it seems that even in the case of the early type Be stars the Lyman continuum is not enough to explain the IR emission. Three possibilities exists : (1) Be stars emit Lyman continuum more copiously than given by the atmospheric calculations. (2) additional ionising photons are supplied by a companion compact star (He star, white dwarf or neutron star, see Apparao and Tarafdar, 1993, 1994). (3) ionisation is enhanced by absorption of Balmer photons. We will discuss these possibilities below.

Table 2 . Infrared emission of Be stars calculated from Paschen Line P17 emission.

HD No.	Spectral type	Equivalent width (A)$^+$	E_{p17} ergs s^{-1}	E_{IR} ergs s^{-1}
4180	B5 IV	0.44	4.4 + 31*	8.3 + 34
5394	B0.5 IV	1.77	8.1 + 32	1.5 + 36
10516	B1.5 V	1.63	2.3 + 32	4.4 + 35
109387	B5 III	0.77	2 + 32	3.8 + 35
148184	B1.5 IV	3.0	7 + 32	1.3 + 36
164284	B2 V	2.94	2.1 + 32	4 + 35
183362	B2 V	1.58	1.1 + 32	2.1 + 35
187567	B2 IV	2.26	3.8 + 32	7.2 + 35
194335	B2 III	1.36	7.2 + 32	1.4 + 36
202904	B2.5 V	3.23	2.4 + 32	4.5 + 35
208682	B2 V	0.47	3.4 + 31	6.3 + 34
212571	B1 III-IV	1.86	1.35 + 33	2.6 + 36
212076	B2.5 V	0.57	4.2 + 31	8.0 + 34
19243	B1 III-IV	0.7	5.1 + 32	9.7 + 35
24560	B1.5 V	0.52	1.2 + 32	2.3 + 35
32243	B3 V	1.74	9.8 + 31	1.9 + 35
32991	B3 V	0.73	4.1 + 31	7.8 + 34
32988	B2 III	0.61	3.2 + 32	6.1 + 35
36576	B1.5 V	0.98	1.4 + 32	2.7 + 35
37967	B3 V	0.91	5.1 + 31	9.7 + 34
38010	B1 V	1.50	2.2 + 32	4.2 + 35
50083	B2 V	0.80	5.5 + 31	1.1 + 35
52721	B2 V	0.35	2.4 + 31	4.5 + 34
53367	B0 IV	1.11	7.29 + 32	1.4 + 36
58050	B2 V	0.97	6.7 + 31	1.3 + 35
65079	B2 V	0.56	3.9 + 31	7.4 + 34
65176	B0 II	0.59	1.1 + 33	2.1 + 36
65875	B2 V	0.69	4.7 + 31	8.9 + 36
193009	B1 IV	1.58	5 + 32	9.5 + 35

+ from Andrillat, Jaschek and Jaschek (1988).

* a+n means a x 10^n ergs s^{-1}

Table 3. Infrared emission from the ionised region around Be stars.

Spectral type (1)	IR from Paschen (2)	IR from Obs[*]. (3)	IR from Calc[@]. (4)
09.5	—	1.0 + 36[+#]	7.2 + 36[#]
B1	2.6 + 36	2.4 + 36	8.4 + 34
B3	1.9 + 35	1.9 + 35	2.5 + 33
B5	3.8 + 35	1.0 + 35	3.9 + 32
B8	—	1.9 + 34	8.7 + 30

[*] Highest values observed for the spectral type (from Ashok *et al.*, 1984)

[@] IR emission calculated from the ionisation due to the Lyman continuum of the star (see text)

[+] Observed value from X-Per, when it is not at its peak emission (see Roche *et al.*, 1993).

[#] a+n means a x 10^n in units of ergs s^{-1}

Observations of ε CMa in the extreme ultraviolet range have been made by Cassinelli *et al.* (1995) using the EUVE satellite. They find the EUVE flux observed is about thirty times that given by atmospheric calculations. Modification of the atmospheric calculations so far have not explained the observations, and the origin of the extra flux remains obscure. It remains to be seen if other B stars and also Be stars give EUVE flux more copiously than is given by atmospheric calculations. If this is true, then the observed infrared and H_α fluxes from Be stars can be easily explained.

The presence of a compact object (He star, white dwarf or a neutron star) in binary motion around a Be star can result in a supply of ionising photons. In the case of He stars, the surface temperature is high and the size is large enough to supply sufficient amounts of ionising photons (Cox and Salpeter, 1964), to explain the IR and H_α emission (Apparao and Tarafdar, 1994). In the case of white dwarf stars or neutron stars, matter accretion has to taken place on to these stars, in order that they emit sufficient amounts of ionising photons. Matter accretion can take place when the gas envelope around the Be star reaches the compact object as is indicated by x-ray emission by some Be stars. Thus the presence of a compact object in binary motion around the Be star can explain the IR and H_α emission. However, this then would mean that all Be stars are binaries; even though this is a possibility, suggested earlier by many authors (Harmanec, 1982), there is no evidence of binarity of all Be stars. We wish to point out that the observed helium line emission in the case of Be stars with spectral type later than B1.5, and the observed H_α emission for Be stars later than B5 can be explained by using ionised photons from a binary companion (Apparao and Tarafdar, 1993, 1994. The enhancement of ionisation in the gas envelope of the Be stars by absorption of the Balmer continuum is an attractive alternative, since there is enough energy in the Balmer continuum to explain the IR and H_α emission. Apparao and Tarafdar (1987) have calculated this enhancement by considering the radiative transfer in the gas envelope around the Be star. The enhancement of ionisation is by about a factor of three in the case of B1 spectral type, decreasing with the increase of spectral type number. Hoflich (1988) has considered a model in which the gas envelope is an extension of the atmosphere of the Be star. The Balmer continuum absorption results in increased emission of Half line. Hoflich (1988) thus had been able to explain the observed H_α emission from Be stars. This however does not account for the IR emission as the emission measure produced is not adequate. The model also uses spherical symmetry for the envelope, while there is evidence for the asymmetry of the gas envelope around Be stars. Considering the asymmetry will lead to lower values of emission of both H_α and IR emission.

In the above discussion we have been comparing the maximum observed and calculated values of IR and H_α emission, so that the conclusions drawn, namely that a binary compact companion supplies the ionising photons required, or that Balmer photon absorption enhances the ionization, pertains to those Be stars with the maximum values given. It is possible that the Be stars with lower values of emission do not need either of the adjustments suggested.

Large infrared excesses have been detected in the case of Bp and B[e] stars (see Doazan, 1982). These excesses have been successfully interpreted as due to emission from dust around the stars (see Doazan, 1982 for references). The above considerations obviously do not apply to these stars.

5. Conclusions

i) We have calculated the infrared emission from the ionised region around Be stars using the observed Paschen line emission. This calculated value agrees with the observed values indicating that the IR and hydrogen line emission comes from the same ionised region.

ii) The discrepancy between the observed infrared and H_α emissions can be due to self absorption of the H_α emission in the ionised region.

iii) The observed IR emission cannot be explained as from an ionised region around the Be star formed by the Lyman continuum from the Be stars. Additional ionising photons are required. These may be provided by a compact binary companion. Absorption of Balmer continuum and the resulting enhancement of ionisation is also a possible explanation. However the proposed methods in the literature for this enhancement are not adequate at present. Recent EUVE flux measurements of B star ϵ CMa (B2II) have shown that the flux is about thirty times that given by theoretical atmospheric calculations. If this is valid for Be stars also, then the observed infrared and H_α fluxes from Be stars can be explained.

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