Optical and infrared excess in radiation from Be stars

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Beryllium stars are observed to emit radiation at several wavelengths—from radio to high-energy gamma rays. In the optical and the infrared, an excess over what is expected from the Be star is observed. I discuss the proposals made to explain this excess and conclude that the excess is not adequately explained.

BERYLLIUM stars are fast-rotating B stars which occasionally show emission lines. The emission lines appear, continue for a period of time, and then disappear. These emission lines are attributed to a gas disk around the Be star[1]. The gas disk is suggested to be ejected from the equatorial regions of the fast-rotating Be star, destabilized either by transport of angular momentum from inside[2] or owing to non-radial oscillations of the Be star[3]. It has also been suggested that the gas disk can be due to accretion of gas from a binary companion to the Be star[4,5]. However, Apparao[6] has shown that this suggestion is not tenable in the case of Be stars from which X-rays are observed, since in these cases the companion is a compact object and cannot supply matter to the Be star. Here we will assume that the gas envelope is ejected by the Be star.

The radiation emitted by the Be stars ranges from radio wavelengths to gamma rays. Here I consider only optical and infrared radiation. This radiation, when the Be star is in the B-stage (that is, without the emission lines implying the lack of a gas envelope), can in general be explained by atmospheric models, using the temperature corresponding to the spectral type. In the Be-stage, the optical radiation shows Balmer, HeI and several metallic emission lines along with an increase in the continuum radiation also. Sometimes there is a delay in the appearance of the optical enhancement and X-ray emission. Infrared continuum excess (we define excess as that over the expected radiation from the B-star of corresponding spectral type) and line radiation are also observed in the Be-stage. Several suggestions were made to explain the optical and infrared excess and I discuss these below.

Optical radiation

Line radiation

Line emission from Be stars, as mentioned earlier, appears and disappears and this is linked to the appearance and disappearance of the gas envelope. The lines most commonly observed are the Balmer lines, HeI and singly charged metallic lines. These lines are presumed to be emitted by the ionized matter in the gas envelope. The ionization is presumed to occur due to the radiation from the Be star. Apparao and Tarafdar[7] examined whether this explanation is correct in the case of the Balmer line radiation. They used the radiation from Be star of different spectral types; for a given spectral type, the corresponding surface temperature was used. The amount of Lyman radiation was obtained using the atmospheric models of Kurucz[8]. The emission measure was obtained using the case-B situation and a density in the gas envelope $N_H = 10^{12}$ cm^{-3}. Using these emission measures the amount of H_α emission was calculated, and the values for different spectral types are given in Table 1. The maximum value of the observed H_α radiation for each spectral type is also given in Table 1. A comparison of the calculated and observed values shows that the Lyman continuum

Table 1. H_α line emission from Be stars.

					Calculated H_α emission	
Spectral type	Temperature (K)	Lyman photons* (log $Q_L s^{-1}$)	Balmer photons* (log Q_B s^{-1})	Observed H_α em.† (erg s^{-1})	Lyman photons (erg s^{-1})	Lym + Balm (erg s^{-1})
B1	25000	45.78	48.37	2.5×10^{34}	8.2×10^{33}	2.7×10^{34}
B3	20000	44.24	47.83	4×10^{33}	2.4×10^{32}	5.8×10^{32}
B5	16000	42.42	47.12	8×10^{32}	3.6×10^{30}	8.3×10^{30}
B8	13000	40.71	46.53	5×10^{32}	7×10^{28}	1.7×10^{29}

*Thompson[25], using Kurucz atmosphere.
†from Ashok *et al.*[22]

photons are not sufficient to produce the requisite ionization. Apparao and Tarafdar[7] further examined if the absorption of Balmer continuum by excited states of hydrogen can enhance the ionization. The values of the H_α emission for different spectral types with the enhanced ionization are given in Table 1. While this can explain the H_α emission from Be spectral types earlier than B3, it still fails for later spectral types. It seems that additional ionizing photons are needed, the origin of which is unknown at present.

X-ray emission from Be stars has been observed (see ref. 9 for a review), indicating that these Be stars are binary systems containing a compact object (neutron star or white dwarf). Accretion of matter from the gas envelope on to the compact star produces X-rays. These X-rays ionize the gas in the envelope which then emits line radiation. The H_α emission from such X-ray ionization for different luminosities and spectra is given by Apparao[10] and is presented in Table 2. This emission can adequately explain the observed values of H_α emission from Be stars of different spectral types for sufficient intensity of X-rays. While the X-ray ionization can explain H_α emission from some Be stars, it is difficult to claim that all Be stars of later spectral types are binaries with compact objects. Therefore a source of ionizing photons is still required. Possible sources of this radiation are (i) X and EUV radiation from a corona, and (ii) shocks in the gas envelope. These sources have to be examined critically.

FeII lines are ubiquitous in emission spectra of Be stars. These lines cannot originate in the ionized gas of the envelope, because at the temperature ($\sim 10^4$ K) found in this region, most of the iron atoms are in highly ionized states. Apparao and Tarafdar suggest that the FeII radiation arises in the cooler regions of the envelope, which is outside the ionized region away from the Be star. The sub-Lyman ultraviolet radiation is absorbed by this region to produce low ionization states of many elements, especially carbon and iron. This region is called the CII region. The observed FeII emission is adequately explained by calculating the emission from the CII region.

Table 2. Optical emission from Be-star HII region.

Spectral type	Temperature (K)	Δm_v (magnitude)	Δm_b (magnitude)
B0	30000	0.21	0.025
B1	25000	0.03	0.017
B3	20000	0.012	0.008
B5	16000	0.006	0.001
B8	13000	0.007	0.0009

Continuum radiation

Optical variability is a characteristic of Be stars. Periodic variability in the magnitude range 0.01 to 0.1 and time-scales of hours to days is attributed to non-radial pulsations of the Be star[3]. Long-term increases, up to about 2 magnitudes, on time-scales of months to years, are also observed. These increases are accompanied by increases in H_α emission in many Be stars, but there are instances where the optical increase is not associated with any increase in H_α emission. The optical increases may be due to: (i) emission from the HII region formed in the gas envelope around the Be star by the Lyman continuum photons from the star, (ii) emission from the HII region formed in the gas envelope by X-rays and EUV radiation emitted by an accreting compact companion to the Be star, and (iii) emission from an accretion disk around the compact companion to the Be star. Apparao[10] has examined these three processes. In obtaining the optical emission from the first, he used the Lyman continuum given by Kurucz[8] for a given spectral type. The Balmer continuum absorption was also taken into account. The results are given in Table 2. In the visual the maximum increase possible is about 0.2 magnitude. As mentioned in the earlier section, some Be stars have compact companions, which accrete gas from the Be star gas envelope, and emit X- and EUV radiation. This produces an HII region which emits optical radiation. In estimating this the calculations of Kallman and McCray[12] were used. Kallman and McCray obtained the ionization structure of the HII region for various values of intensity of X-rays and different spectra. The results, in Table 3, show that large changes in the visual magnitude of the system are possible. These increases are accompanied by emission of H_α line. The emission from an accretion disk around a compact companion of a Be star, for reasonable values of accretion rates, is small compared to the luminosity of Be stars, and cannot account for the optical continuum increases[10].

Table 3. Optical emission from X-ray-induced HII region.

Luminosity (erg s^{-1})	Spectrum	H_α emission (erg s^{-1})	Optical emission (erg s^{-1})	Δm_v B0	B1	B3	B5	B8
10^{38}	10 keV Brems	6×10^{36}	1.04×10^{36}	1.3	2.08	3.09	4.04	4.75
10^{37}	10 keV Brems	2×10^{35}	3.4×10^{34}	0.08	0.19	0.5	0.93	1.4
10^{37}	2 keV Brems	7×10^{35}	1.2×10^{35}	0.27	0.55	0.79	1.71	2.41
10^{36}	10 keV Brems	5.9×10^{33}	1.02×10^{33}	0.0025	0.0059	0.019	0.043	0.082
10^{35}	10 keV Brems	2×10^{32}	3.4×10^{31}	8×10^{-5}	2×10^{-4}	6×10^{-4}	1.5×10^{-3}	0.003
4×10^{36}	40 eV BB	1.6×10^{35}	2.7×10^{34}	0.066	0.15	0.41	0.79	1.22

The processes considered above can account for optical continuum increases accompanied by increases in the H_α-line emission. Examples of these are the Be star X-ray sources γCas (ref. 13) and A0535+26 (refs. 14, 15), both of which are of spectral-type B0. However, as mentioned earlier, optical continuum increases are observed for some Be stars without a corresponding increase in H_α emission, e.g. 4U0115+63 (ref. 16), which is not explained. This optical increase precedes X-ray emission by about 50 days, which makes it all the more puzzling.

Infrared radiation

Line radiation

Near-infrared line emission was observed in many Be stars. Lines of HI (Paschen series), OI (7772–74–75, 8446 Å), CaII (8542, 8662, 8498 Å), FeII (7712, 9997 Å) and NI (8686–83–80, 8719–12–03, 8629 Å) were observed, some of which appear as blends. To my knowledge no quantitative accounting for these lines has been attempted, except for the CaII triplet by Apparao and Tarafdar[17]. They noted that these lines cannot arise in the HII region formed by the absorption of Lyman continuum radiation from the Be star by the gas envelope, because, at the temperature existing in the HII region, most of the calcium is in higher ionization states. Recombination of CaIII in the HII region does not yield sufficient intensity to explain the observations. It is suggested that the CaII radiation arises in the cooler parts of the envelope (CII region) where absorption of sub-Lyman ultraviolet radiation leads to CII and CaII ions. Excitation of the CaII ions by further absorption of ultraviolet radiation and re-emission by cascading leads to the observed CaII triplet infrared radiation. By considering the radiative transfer, Apparao and Tarafdar[17] could account for the equivalent widths of the radiation observed as also the relative strengths of the radiation. The OI λ8446 Å radiation is suggested to arise by the Bowen mechanism due to the coincidence of levels of Lβ with one of the excited states of OI. However, no quantitative estimates are available. A detailed study of all the near-infrared line emission is yet to be made.

Continuum radiation

A review of the observations of the infrared continuum from Be stars was given by Lamers[18]. Woolf *et al.*[20] suggested that the excess infrared radiation might be due to free–free emission from the ionized circumstellar envelope around the Be star. Based on the observations of the infrared spectra of several stars between wavelengths 2.3 μm and 19.5 μm, Gehrz *et al.*[21] concluded that the infrared excess is not due to emission from dust around the Be star, and the spectrum can be explained by a simple model of an equatorial shell. Since this observation, many ground-based observations of the near-infrared excess of Be stars were made (see Lamers[18], for references). Observations at wavelengths of 12, 25, 60 and 100 μm were made by the IRAS satellite and analysed by Waters and his collaborators (see Lamers[18], for references).

The near-infrared flux from Be stars is dependent on the spectral type of the star and is variable. It ranges from about 10^{34} to 10^{36} erg s^{-1}. The infrared excess is found to be approximately proportional to the bolometric luminosity of the star. It is also found to be proportional to the H_α flux. It is this last fact that prompted some observers to suggest that they arise from the same ionized region and that the infrared radiation is from free–free and free–bound emission. However, Ashok *et al.*[22] have shown that the ratio of the infrared luminosity and the H_α luminosity is about 3, if they arise owing to free–free and free–bound processes in the same ionized region, while the observed value is ~ 96. Waters[23] and Waters *et al.*[24] have interpreted the infrared emission spectrum as arising from free–free emission in gas disk around the Be star. They obtained the emission measure (EM) needed to explain the infrared excess (see Lamers[18]). Apparao and Tarafdar[19] used the EM given in Lamers[18] and calculated the expected H_α emission. These fluxes are given in Table 4. Also given in the table are the observed fluxes. It is seen that the observed fluxes are smaller than the expected fluxes. Table 4 gives the ratio of the infrared luminosity to the Lyman continuum luminosity for different spectral types. It is seen that the Lyman continuum luminosity, which produces the ionization in the gas disk is not enough to account for the infrared luminosity for later spectral types. It seems that the infrared excess may not arise from free–free and free–bound emission. In column 6 of Table 4 is given the ratio of the infrared luminosity to that of the bolometric luminosity for different spectral types. It is possible that the infrared emission occurs by absorption of the ultraviolet and optical radiation of the star. This aspect needs to be explored.

Table 4. Infrared and H_α line emission from Be stars.

Spectral type	Log(EM)* (cm^{-3})	Log $E(H_\alpha)$ (calc.) (erg s^{-1})	Log $E(H_\alpha)$ (obs.) (erg s^{-1})	$L_{IR}/L_L^\dagger$	$L_{IR}/L_*^\ddagger$ ($\times 10^{-2}$)
B0–B1.5	60.6–61.1	36–36.5	33.6–34.4	0.04–0.54	0.57–6.67
B2–B3	59.4–60.4	34.8–35.8	33.1–34.0	0.09–1.13	0.57–5.27
B4–B5	59.2–59.9	34.6–35.3	32.2–33.7	2.02–5.57	2.68–3.75
B6–B7	58.2–59.5	33.6–34.9	32.1–33	9.26–11.67	3.53–4.14
B8–B9	57.7–58.2	33.1–33.6	32.4–32.8	15.42–22.56	1.67–2.44

*From Lamers[18]

†See Ashok *et al.*[22]

Discussion

I have discussed the attempts made to explain the optical and infrared line and continuum radiation from Be stars. In the case of optical line emission, the flux produced by the HII region formed by absorption of the Lyman continuum of the Be star is not enough to explain the observed flux; additional ionizing radiation is needed. Alternatively, there could be heating processes occurring in the gas envelope, for example heating produced by shocks, which could result in the needed ionized gas. These processes need to be explored. The optical continuum is adequately explained by the emission from HII regions produced either by the radiation from the Be star or by radiation produced by an accreting compact binary companion. However, excess optical radiation produced in some Be stars, without accompanying H_α emission, is not explained by the emission from the HII regions and remains unaccounted for.

The infrared line emission from Be stars seems to arise in the cooler regions of the gas envelope outside the HII region; but only the CaII triplet emission is accounted for quantitatively. The location of and the processes leading to the emission of the other infrared lines need to be explored. The infrared continuum excess was suggested to be from the ionized regions due to the free–free and free–bound processes. However, the H_α emission implied by this is not observed. In addition, the Lyman continuum from Be stars of later spectral types is not adequate to produce the requisite ionization. Thus the source of the infrared continuum excess from Be stars remains unidentified.

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Search for dark-matter particles

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Experiments performed over the last two years have been very successful in drastically reducing the number of viable elementary particles that could possibly constitute the dark matter that dominates the large-scale gravitational dynamics of astronomical systems. The candidates that survive are the light neutrinos, the axion, and a supersymmetric particle with carefully chosen parameters called the neutralino. Baryonic dark matter, which might contribute not insignificantly over small scales, is perhaps present in the form of brown dwarfs, and a search for these is under way. In this article I first review the astrophysical studies which bear on the density and the phase-space structure of the dark-matter particles; then discuss the implications of the various direct and indirect searches for these particles; and, finally, point out alternative suggestions for the candidates and directions for further searches.

The fascination and the challenge of the search for the constituents of dark matter stem from the connection it bears with astronomy, astrophysics and cosmology on the one hand and with nuclear and particle physics on the other. Dark-matter particles are the only relicts that still survive from the epochs prior to the primordial