# PHOTOGRAPHIC INFRARED SPECTROSCOPY AND NEAR INFRARED PHOTOMETRY OF Be STARS

(*Review Paper*)

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## 1. Introduction

As the title indicates two topics will be tackled in this presentation: spectroscopy and photometry. Let us therefore define first what 'infrared' means for these two subjects. I chose the following definitions:
– photographic infrared spectroscopy: wavelengths $H\alpha \leq \lambda < 1.2\ \mu$
– near infrared photometry: wavebands: $1.6\ \mu \leq \bar{\lambda} \leq 20\ \mu$

## 2. Near Infrared Photometry

As pointed out by Allen (1973): "That emission lines in the spectrum of a star are evidence of an extended stellar atmosphere is well established. If the density of material in that atmosphere is sufficiently high, its presence should additionally be manifested by radiation mostly at longer wavelengths than that of the underlying star. We therefore seek to explain the infrared excess of the early type emission-line stars in terms of the circumstellar material we believe to lie in clouds around them". This of course implies that infrared excesses have been observed from Be stars, which indeed is the case. For publications prior to the summer of 1971 I refer to an excellent review paper given that year by J. C. Pecker at the Liège Symposium. What I plan to do here is to show that there is a gradation in the excesses observed in classical Be, less classical Be, and peculiar Be stars. For this matter I rely mainly on the surveys published up to 3.5 $\mu$ by Allen (1973) and up to 20 $\mu$ by Gehrz *et al.* (1974) (referred to as G-H-J).

### 2.1. Classical Be stars

It appears that the most likely mechanism for the production of the observed excess infrared radiation in classical Be stars (see e.g. $\beta$CMi, Figure 3 of G-H-J) is free-free radiation (remaining optically thin to 20 $\mu$) from proton-electron scattering in a hot ($T_{\rm shell} \geq 10\,000$ K) ionized circumstellar plasma. The preliminary result of Woolf *et al.* (1970) and the survey by Allen (1973) strongly suggested this mechanism although their data did not include spectral detail in the 4.9–19.5 $\mu$ region. The optical hydrogen emission lines, and thus presumably the excess infrared radiation, originate in a circumstellar gas shell, or extended atmosphere, that is formed from material ejected from the equatorial regions of a star near the limit of rotational stability (G-H-J, 1974).

*A. Slettebak (ed.), Be and Shell Stars*, 219–225. 

## 2.2 Less classical Be stars (shell stars?)

As examples of stars of this class I suggest $\phi$ Per and $\zeta$ Tau. G-H-J indicate in the caption to their Figure 2 that $\phi$ Per is a typical example of Be stars whose infrared excess is fitted by a pure free-free model in which the shell becomes optically thick at long wavelengths. The infrared energy distribution of $\zeta$ Tau (see Figure 6 of G-H-J) can be reproduced by adding either a 1200 K black body spectrum or a 14 000 K free-free spectrum (under some conditions, i.e. $\tau_s = 1$ at 8.7 $\mu$) to the hot stellar continuum. In any case the circumstellar flux makes a negligible contribution to the total emitted energy shortward of 2.3 $\mu$.

For these two subclasses of Be stars, G-H-J derive that "a typical Be star shell, assuming a shell radius-to-thickness ratio of 5, is characterized by an electron density of $3.7 \times 10^{11}$ cm$^{-3}$, a radius of $\sim 4\ R_*$ and a Thomson optical depth of 0.16; the infrared excess in Be stars tends to decrease as spectral type becomes late; a number of the survey stars were tested for infrared variability with negative results".

## 2.3. Peculiar Be stars (B[e] stars)

The prototype for these B[e] stars is, of course, HD 45677 whose energy distribution in the visible and near infrared is given in Swings and Allen (1971), and in Allen (1973) together with a series of objects exhibiting considerable infrared excesses. Starting in 1971 there has been a little debate concerning the mechanisms for producing the color indices of the stars of category D (Allen, 1973), i.e. those with prominent infrared excess. The mechanisms that were suggested and subsequently ruled out were:

(i) the presence of a cool companion to the Be star;
(ii) $H^-$ free-free, and free-free radiation in the H II region surrounding the stars;
(iii) free-free radiation in an ionized metal region around both the star and its H II region.

So, all in all, it is believed that the strong infrared excesses are to be explained by the presence in the circumstellar environment of solid particles (therefore the expression 'dust shell') which absorb the ultraviolet and visible radiations and degrade them to infrared wavelengths. In the case of the prototype HD 45677 one then gets a physical model such as that described by Swings (1973a) where a dust shell of radius about 30 AU optically thick at 5 $\mu$ (Swings and Allen, 1971) surrounds the peculiar Be star and its extended atmosphere, ring, and forbidden line regions. Of course, among bright early-type shell stars HD 45677 is an extreme example. In 1952 Paul W. Merrill noted that it "is not a typical shell star, but rather an object intermediate between an ordinary Be star and a planetary nebula. Perhaps it can be thought of as a shell star whose outer atmosphere is extraordinarily extended and brilliant". This possible connection between evolved Be's and young planetary nebulae leads me to introduce an interesting color-color diagram on which one may plot the position of the stars we have been talking about in sections 2.1, 2.2, and 2.3: the $H(1.6\ \mu) - K(2.2\ \mu)$ vs $K - L(3.5\ \mu)$ diagram (see also Allen and Swings, 1972a; Allen, 1973; Swings, 1973b). On such a diagram one sees immediately that the colors of peculiar Be stars and young and dense planetaries are very similar: it is interesting to note that

https://doi.org/10.1017/S0074180900011384 Published online by Cambridge University Press

the spectra of most of those objects reveal low excitation emission lines of e.g. [O I], [S II] and [Fe II]. Knowing that such a correlation does exist, Allen and Swings (1972b) suggested that infrared photometry could be a rapid and effective method of making a first order classification of Be stars and in particular of isolating those with unusual spectral properties. First applied to the visible part of the spectrum (cf. a review by Allen and Swings, 1976, and references therein) this method gives equally good results in the photographic infrared (λ 8200–11 200 Å) as we shall see later on the basis of very recent data obtained by Mrs Andrillat and myself.

## 3. Photographic Infrared Spectroscopy of Be Stars

Since, in the context of this Symposium, we are dealing mainly with new observation techniques I shall not speak of what is done, or has been done, with I-N or I-Z plates except for the work of Andrillat and Houziaux. On the contrary I wish to present a few recent results obtained with the help of some new devices that are becoming more and more used, and useful, in many observatories around the world.

As for part one of this presentation we shall proceed from classical Be stars to peculiar Be stars.

### 3.1. Classical and less classical Be stars

In a Bulletin of the American Astronomical Society report written by the 'chair-creature' of U.C.L.A. we read that "G. Peters and R. Polidan have continued a spectroscopic study of Be, Be-shell, and binary stars in the visual and near-infrared portions of the spectrum. They obtained approximately 750 plates of more than 150 different objects brighter than $7\overset{m}{.}0$ at Lick Observatory's Coudé auxiliary telescope with a Varo image tube . . ."

"As an initial step toward understanding the envelopes of Be stars, G. Peters and R. Polidan are attempting to set up a meaningful classification scheme (Peters, 1974). The spectral line which appears to be the most promising is λ 7774 Å of O I. They have found that the appearance of λ 7774 Å allows them to distinguish three groups of Be stars: (1) Be stars with enhanced λ 7774 Å absorption (the classical shell stars); (2) Be stars with weak λ 7774 Å absorption (Be stars with relatively weak Hα emission); and (3) Be stars with λ 7774 Å in emission (Be stars which as a rule also show Fe II emission and strong Hα emission with no conspicuous structure)". These conclusions are pertinent to Be stars earlier than B6 (Peters, 1975). It is interesting to introduce here a report of the work by Andrillat and Houziaux (1975) who obtained conventional 230 Å $mm^{-1}$ spectrograms in the photographic infrared of 68 'normal' Be stars (of magnitudes between 7 and 9). According to Andrillat and Houziaux, emission appears in the Paschen lines, O I lines and in the Ca II triplet. It is usually confined to spectral types earlier than B5. On the basis of statistics on the HD spectral types (MK types were unavailable for most of the stars), the following percentages of line emission are obtained using the data in Merrill and Burwell

https://doi.org/10.1017/S0074180900011384 Published online by Cambridge University Press

Catalogues of Be and Ae stars:

TABLE I
HD stars ($m_v < 9.0$) (Andrillat and Houziaux, 1975)

| HD spectral type | Total number | % Hα emiss. | % Pasch. emiss | % O I emiss. 8446 Å | % Ca II emiss. |
|---|---|---|---|---|---|
| B0–B1 | 364 | 19 | 8.6 | 8.6 | 3.4 |
| B2 | 305 | 21 | 14 | 12.6 | 6.3 |
| B3 | 902 | 15 | 1.8 | 4.4 | 1.8 |
| B4–B5–B6 | 1021 | 9 | 1.1 | 1.1 | 4 |
| B7–B8 | 2318 | 3 | – | – | – |
| B9 | 4096 | 1 | – | – | – |
| A0 | 11184 | 0.3 | – | – | – |
| A2 | 8734 | 0.2 | – | – | – |

These results are comparable to those of Peters and Polidan (Abell, 1975) who find that for 120 different objects the infrared calcium triplet emission appears to be rare in Be stars: only 10% of their sample shows Ca II triplet emission. Ca II triplet emission does not appear to correlate strongly with any other spectral feature in the region surveyed by Peters and Polidan; however, the incidence of emission is very high among Be stars which are confirmed or suspected interacting binaries. On the basis of Table I however there seems to exist some correlation between the percentages of appearance of Hα, Paschen lines, O I λ 8446 Å and Ca II. According to Briot (1976) the infrared excess is greater for those stars showing emission in the Paschen lines than for those whose spectra exhibit a Paschen series in absorption: it is likely that both the Paschen emissions (and Balmer as well) and the free-free radiation originate from the H II region surrounding the Be star. Concerning emitting zones around Be stars, Peters (1975) feels that 'early-type Be stars which show O I λ 7774 Å emission must have more extended envelopes than early-type shell stars'. However it seems reasonable to her that 'late type shell stars can have very extended envelopes (>20 $R_*$) and not show λ 7774 Å emission due to the scarcity of far ultraviolet radiation needed to ionize the O I atom. All O I emission stars are earlier than B6'. G. Peters thus feels that O I λ 7774 Å (whose lower level is metastable) emission is simply a result of recombination in an extended, low density ($10^{10}$–$10^{11}$ cm$^{-3}$) envelope.

Infrared line profiles can be studied in detail when the Be stars are bright enough to give a fair signal to noise ratio: for example a spectrum of γ Cas has been obtained at 4 cm$^{-1}$ resolution over the spectral region 1–1.6 μ with a $S/N$ of 31 in the spectrum at 8050 cm$^{-1}$. This spectrum was obtained with a Michelson interferometer located at the coudé focus of the 2.72 meter telescope at McDonald Observatory (Texas). The strongest feature in the spectrum is the He I λ 10 830 Å line; in addition, the hydrogen lines $P_\alpha$, $P_\beta$, and $P_\gamma$, are quite prominent in emission and faint emission is evident in the Brackett series. The line profiles show no reversal at the center of the line (Morgan and Potter, 1975).

### 3.2. Peculiar Be's

Much less has been done in this field essentially because, on the average, the B[e] stars are much fainter than the other Be stars. Near infrared I-N spectra of objects such as HD 50138 and HD 45677 were obtained more than a decade ago. However the B[e] stars started being frequently observed beyond H$\alpha$ only very recently after such marvelous gadgets as Varo tubes, image tubes, image intensifiers, and multichannel spectrophotometers were made available to the astronomers. Also those B[e] stars that sounded a bit old-fashioned, that were almost forgotten for 20 years, became fashionable again after their prominent infrared excess radiation was discovered. Spectra from H$\alpha$ to $\lambda$ 8600 Å, or even from $\lambda$ 8000 to 11 000 Å were obtained in various parts of the world: U.S.A. (Lick Observatory for example), Chile, Italy (Asiago), Israel (Mitzpeh Ramon), France (Haute Provence). Astronomers from Asiago have published recently some interesting low dispersion data, up to $\lambda$ 11 000 Å, of a few BQ[] stars, in which some late type molecular features are detectable (Ciatti and Mammano, 1975a, b; Ciatti *et al.*, 1974). Before describing some very recent, and quite spectacular, spectra it should be mentioned that near infrared data may also be obtained via the use of multichannel spectrometers, such as the one developed by Dr Oke for the Palomar 200-in. telescope. Using that equipment the author gathered data at resolutions between 20 and 80 Å for about 20 B[e] stars that are presently being analysed and that will be joined to the 7 Å resolution spectrograms of August 1975 acquired at the Haute Provence Observatory in the same spectral region. These were obtained by Mrs Andrillat and myself with the Roucas grating spectrograph attached to the Cassegrain focus of the O.H.P. 77-in. telescope. The equipment has its highest efficiency around 1 $\mu$, and covers the spectral region $\lambda$ 7500–12 000 Å with a dispersion of 230 Å $mm^{-1}$. The receiver is a cooled two-stage image-tube equipped with an S1 photocathode; 103-aD film is used behind the fiber optics output. The aim of our observations was to detect not only the Paschen series, but mainly the emission lines due to permitted and forbidden transitions. It is indeed well known, as I explained earlier in this presentation, that there exists for peculiar Be stars a correlation between the presence of an infrared excess and the existence in their spectrum of emission lines of e.g. [O I], [S II], [Fe II]. Andrillat and Swings (1976) give a table of the identification of the main emissions although some strong lines remain unidentified (e.g. $\lambda$ 9999 Å): the strongest features are due essentially to lines of the Paschen series, of the Ca II triplet, and of He I $\lambda$ 10 830 Å, O I $\lambda$ 8446 Å, [S III] $\lambda\lambda$ 9069 and 9532 Å, and [Fe III] $\lambda$ 10 540 Å. The Ca II triplet is strong when O I $\lambda$ 8446 Å is weak, and vice-versa (except for Minkowski's footprint M1–92, studied also by Herbig, 1975). It is to be mentioned that spectra of a few stars revealing virtually no infrared excess were obtained with the same equipment: no emission line was detected in 88 Her (B8q; $H-K\sim0$), BD +61°40 (B2e; $H-K\sim0.2$) and BD −11°4747 (Be[]; $H-K\sim0.2$). On the contrary it was shown above that the richness in emission lines becomes remarkable for the objects whose $H-K$ index becomes important and especially for those with $H-K$ greater than unity. Therefore the value $H-K\sim1.0$ which had been considered by Allen and Swings (1972b) as a limit between objects with weak- (free-free) and strong- (dust thermal radiation) infrared excess appears in

https://doi.org/10.1017/S0074180900011384 Published online by Cambridge University Press

Andrillat and Swings (1976) to distinguish the objects with rich emission spectra (groups 2 and 3 in Allen and Swings, 1976) from the others (group 1).

## 4. Infrared Observations of Be Stars in the Future

Although it is clear that the sophisticated infrared photometer that may be put on board the Large Space Telescope would provide valuable information, it is my impression that the best piece of equipment to rely upon in the coming decade will be the Large Infrared Telescope to be put on Spacelab (L.I.R.T.S.). Thus, to conclude this presentation, I shall simply reproduce an excerpt of the abstract of the report on the mission definition study for the L.I.R.T.S. (Jennings *et al.*, 1974). "Developments in infrared techniques during the last few years have resulted in the discovery of a very high number of astronomical objects which radiate predominantly at infrared wavelengths. These are generally cool objects at temperatures between 3 K and 3000 K, and range from the planets of our own solar system to external galaxies. Infrared observations are providing valuable information also about objects which are intrinsically much hotter (e.g., early type stars) but whose energy is degraded by visibly obscuring dust clouds. The peak emission from many important classes of object, however, lies in the 20 $\mu$–300 $\mu$ region which is inaccessible to ground-based observations due to the opacity of the Earth's atmosphere. Information in this region of the spectrum has been limited so far to mainly photometric data obtained with relatively small telescopes flown on aircraft, balloons and rockets. The future development of this very exciting field requires high sensitivity measurements, with high spatial and spectral resolution, and thus the use of large telescopes operating in space, free from the restrictions imposed by the selective atmospheric absorption. The advent of Spacelab in the next decade offers just such a possibility to infrared astronomy. One of the major infrared facilities required on Spacelab is conceived to be a large uncooled telescope which could be used for a wide range of infrared observations. Its unique advantages, however, lie in its capability of carrying out high sensitivity photometry with high spatial resolution and of studying a wide range of astrophysical problems through measurements of atomic and molecular lines in the far infrared. The telescope considered is a 2–3 meter classical Cassegrain-type configuration with uncooled optics. Modulation is provided by rocking the secondary mirror. Its suggested focal plane instrumentation consists of a multi-band photometer, a polarimeter, a Michelson interferometer, and a heterodyne receiver allowing for multi-band mapping and polarimetry, and high and very high resolution spectroscopy. Compared to existing telescopes on ground, balloons and aeroplanes, this telescope will provide more than one order of magnitude greater sensitivity and, most important, a higher spatial resolution in the far infrared".

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## DISCUSSION

*Polidan:* (1) Regarding the *HKL* color diagram and free-free emission: Three stars in Allen's list (AX Mon, HD 218393, and HR 894) are all listed as showing only a free-free excess. Yet in each case we see a K-type secondary at λ 8500. Indeed, in AX Mon the K-type star contributes over half the light at this point. From this one would conclude that one cannot distinguish between a K-type companion and free-free emission. (2) Regarding the Andrillat and Houziaux statistics on Ca II emission, we have extended the survey to later type Be stars and find the same percentages as for the early types. So apparently no correlation exists between Ca II triplet emission and spectral type.

*Swings:* With regard to your first comment, this fact was noticed by Swings and Allen in their near infrared photometric survey of symbiotic and VV Cephei stars (*Pub.. Astron. Soc. Pacific* **84**, 523, 1972).