ENERGY DISTRIBUTIONS OF Be STARS

(Review Paper)

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Abstract. Energy distributions from 0.32 to 1.06 μ for field Be stars having p designations in their spectral types show that stars with Balmer discontinuities in emission do exist. Furthermore, the filling in of the Balmer continuum near the discontinuity is usually observed. The continuum emission showing a peak near 1 μ is a common feature in the energy distributions presented here.

Energy distributions for a number of bright field Be stars are also presented and discussed.

1. Introduction

Why should we study Be star continuum energy distributions? Do they promise to tell us anything about the photospheres or shells around Be stars that we do not already know from 75 years of observations of line spectra? What promise do they offer for new insight into contemporary problems of shell support and acceleration, shell geometry, and stellar evolution?

While it would surely be ambitious to attempt to solve all of the outstanding problems with a single type of observation, I hope to suggest that the study of continuum energy distributions can potentially improve our understanding greatly. This comes about principally because the continuous energy distribution originates in different regions of the star than does the line spectrum. As Woolf *et al.* (1970) have shown, the continuum in the infrared can tell us about the hydrogen density in the shell, while, as we shall see below, the Balmer and Paschen discontinuities may teach us about the photosphere itself.

To summarize what is already known about energy distributions of Be stars, I show in Figure 1 data for stars in the vicinity of h and χ Persei from photoelectric and PbS measurements by Schild *et al.* (1974). It was particularly important to study stars in a region where the interstellar extinction is known, because, as can be seen, the energy distributions are very peculiar and offer, at the outset, little clue of the color excesses, $E(B-V)$, which might be attributed to the interstellar medium. However, comparison of these dereddened energy distributions with stellar models, fitted as shown in Figure 1, shows that the slope of the energy distribution in the λ 4000–5000 Å region probably follows rather well the model continuum, and might profitably be used to deredden stars of unknown $E(B-V)$. Note that the excess emission which appears to peak in the 1 μ region affects the continuum flux at wavelengths as short as V of the UBV system, so that these Be stars have an intrinsic $B-V$ color excess relative to normal stars of the same spectral type.

The excess radiation at visual and near-infrared wavelengths has been interpreted by Schild *et al.* (1974) in terms of the H^- free-bound emission predicted by Milkey and Dyck (1973). The identification is based upon the observation that the excess emission appears to become prominent in the λ 5000 Å region, reach a peak in the 1 μ region, and decline in the 2 μ region. The excess relative to the stellar continuum

A. Slettebak (ed.), Be and Shell Stars, 107–119.

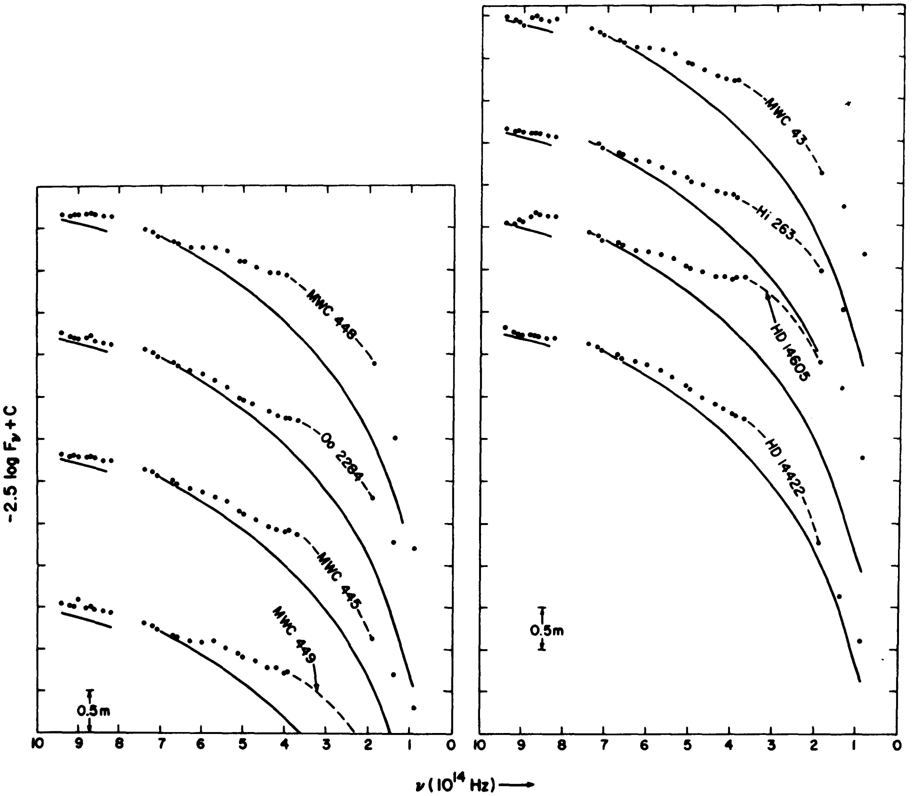

Fig. 1. Energy distributions of Be stars in the h and χ Persei association, corrected for interstellar reddening with $E(B-V)$ estimated from a map of color excesses for stars having UBV photometry.

is shown in Figure 2, where the theoretical H^- free-bound emission spectrum is also shown for comparison. I underscore here the problem with the H^- free-bound interpretation, namely, that the peak of the excess appears to occur at significantly shorter wavelengths than the theoretical curve. The latter results entirely from the physics of the electron–hydrogen interaction and must be considered fixed. As I shall show shortly, newer observations confirm the existence of this discrepancy.

Also evident in Figure 1 is an excess of continuum emission below the Balmer discontinuity. This excess causes the energy distribution of the stars in Figure 1 to be nearly continuous across the Balmer jump. Schild *et al.* (1974) also presented energy distributions of 10 field stars and found that several had Balmer jumps too small for their spectral types. While the interpretation of this fact, in terms of the temperature gradient in the Be star atmosphere, is not clear, it is probably safe to say that the U color of the UBV system will be affected, so that the relationship between spectral type and $B-V$ or $U-B$ for normal stars will be invalid for Be stars. A similar conclusion has been reached, on the basis of UBV photometry, by Feinstein (1968), who also noted variability in $(U-B)$.

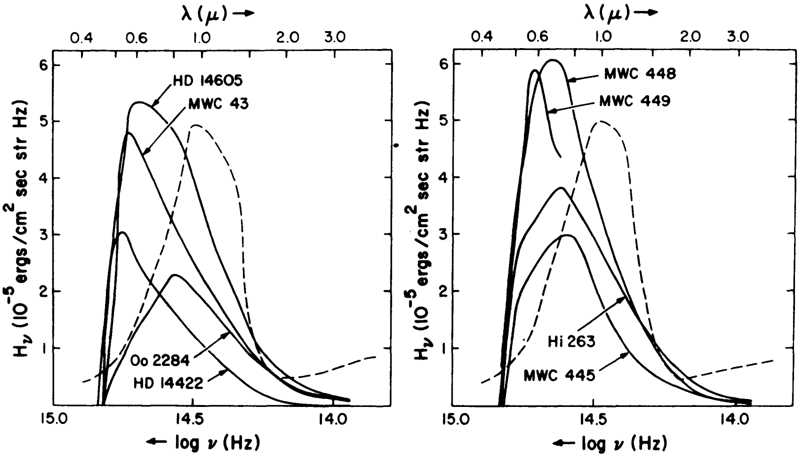

Fig. 2. The 1 μ feature, shown from heavily smoothed data for the stars in Figure 1, but with the continuum of a normal B1 star, HD 13900, subtracted off. The normalized curve for an isothermal shell of 3000 K is shown as a dashed line.

The effects of the excess continuum radiation in the visual to near-infrared and below the Balmer jump are shown schematically in the two-color diagram, Figure 3. The excesses in both colors, $(B-V)$ and $(U-B)$, cooperate to cause reddening to be overestimated when conventional dereddening procedures are followed. Because no correlation of the intrinsic $(B-V)$ or $(U-B)$ excesses with other measurable

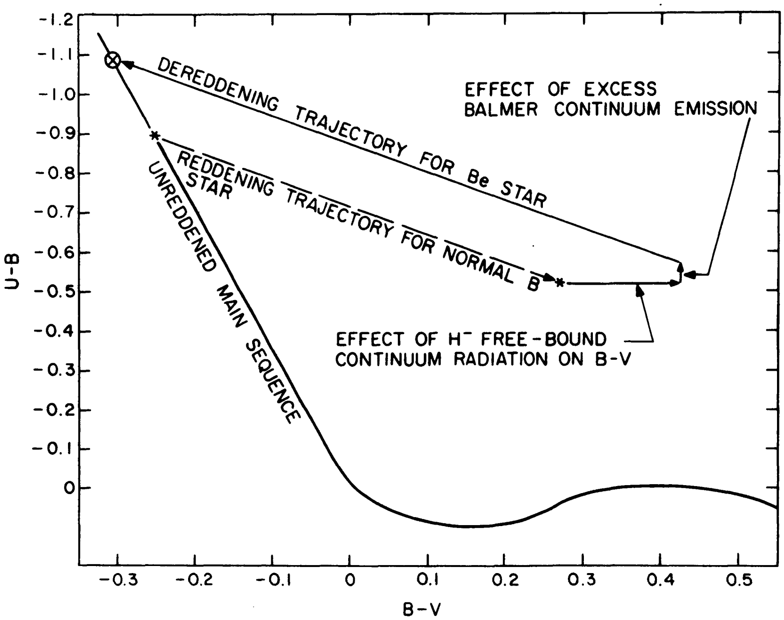

Fig. 3. Schematic two-color diagram, to show the effects of continuum emission below the Balmer jump and in the near infrared. Relative to a normal reddened B star, the Be star would be dereddened to a color too blue for its photospheric temperature.

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parameters, such as Hα emission line strength, are yet known, the only way to determine the color excess due to interstellar reddening is to fit the continuum to stellar models in the λ 4000–5000 Å region. Infrared observations are affected by free-free emission to the extent that they do not help specify the interstellar color excess.

2. New Data

To provide a basis for further exploration of energy distributions, I have measured energy distributions for 60 Be stars. The observing list consists of all the stars north of declination 0° having BD numbers and having the *pe* classification in Hiltner's (1956) catalogue. This selection of spectral type is expected to yield a large number of stars with strong continuum emission. Not all stars were measured in the near infrared (0.8 to 1.0 μ), and I present at this time energy distributions of only those stars for which full energy distributions from 0.32 to 1.06 μ are available. Some questions which we might ask of these energy distributions are:

(i) how common are the infrared excesses which peak at 1 μ?

(ii) do stars with negative Balmer jumps exist?

Before these questions can be answered, the energy distributions must be corrected for interstellar reddening. Three special problems arise in this connection:

(i) the problem of determining the color excesses, $E(B-V)$;

(ii) the variation of the shape of the interstellar reddening curve with galactic longitude;

(iii) the shape of the interstellar reddening curve for our shortest wavelengths, 0.32 to 0.34 μ.

Problem (i) has been dealt with by plotting the energy distributions for eight choices of $E(B-V)$, and fitting a Kurucz *et al.* (1974) model in the λ 4000–5000 Å region to achieve a best fit. Problem (ii) has arisen recently with the recognition from OAO II data (Bless and Savage, 1972) that the far ultraviolet reddening law has important longitude variations, and from the results of Hayes *et al.* (1973) that smaller differences also affect visible energy distributions, especially in the 0.4 to 0.5 μ region. Because many of our stars are heavily reddened, with several $(B-V)$ color excesses of one magnitude, it is important to allow for these longitude variations. We have done this by using an average of Radick's (1973) curves 1 and 2 for $18^{\mathrm{h}} \leq \alpha < 1^{\mathrm{h}}$, curve 3 for $1^{\mathrm{h}} \leq \alpha \leq 5^{\mathrm{h}}$, and curve 4 for $\alpha > 5^{\mathrm{h}}$. Problem (iii), the shape of the interstellar extinction curve at λ 3200 Å remains vexing because of the difficulty of getting accurate energy distributions of heavily reddened stars at the shortest wavelengths. The Radick's (1973) data which show the longitude dependence of interstellar reddening extend to only 0.3448 μ, but are simply extrapolated to 0.32 μ for the present work. It seems likely that the intrinsic Be star energy distributions are too peculiar to derive the interstellar reddening law from the present data.

In Figure 4a, b, c, d, and e we show the new energy distributions corrected for interstellar extinction. They are arranged in a sequence of increasing Balmer discontinuity. All energy distributions shown here are on the calibration system of

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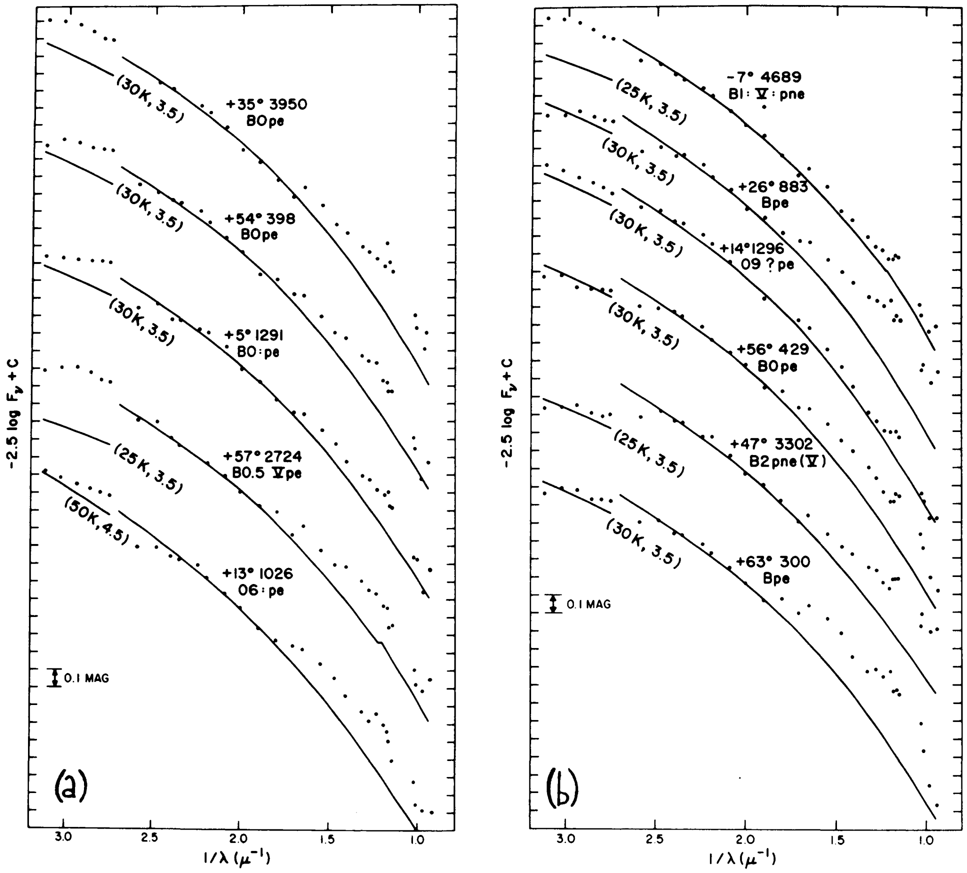
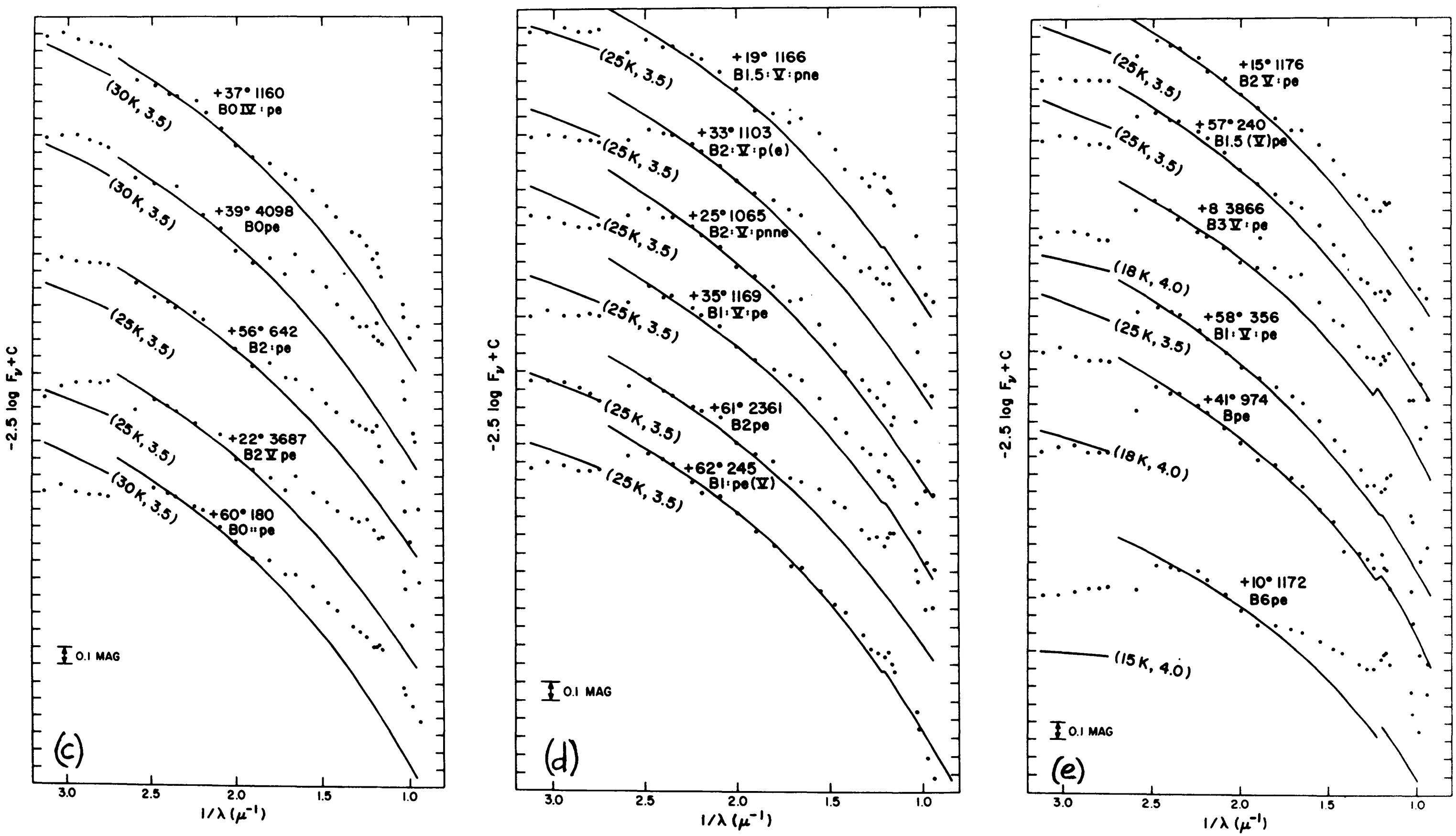


Fig. 4a–e. Field Be star energy distributions, corrected for reddening and fitted to models with temperatures appropriate to the spectral types. (For Figure 4c–e see next page.)

Hayes and Latham (1975), because this has a more positive Balmer discontinuity than the calibration of Oke and Schild (1970). Thus, our conclusions regarding the existence of Balmer discontinuities in emission are conservative.

In Figure 4a, we show energy distributions of five stars in which the Balmer discontinuities are in emission by 0.05 mag. or more. These stars tend to be the Be stars of earliest spectral type, B0pe, and are not confined to any one region of the sky. The existence of emission Balmer discontinuities had already been noted by Barbier and Chalonge (1949), for the bright star γ Cas, which is also of spectral type B0. The existence of Balmer discontinuities in emission is of interest because it implies that scattering is not the dominant source of opacity in the Be star envelope, and that continuum emission from the envelope is also likely to be important on the long wavelength side of the Balmer discontinuity. This in turn implies that line profiles are diluted by continuous emission from the Be star envelope, and cannot be safely used to estimate surface gravities or $v \sin i$.



-2.5 log F_ν + C
+37° 1160
B0 IV: pe
(30K, 3.5)
+39° 4098
B0pe
(30K, 3.5)
+56° 642
B2: pe
(25K, 3.5)
+22° 3687
B2 V pe
(25K, 3.5)
+60° 180
B0:: pe
(30K, 3.5)
0.1 MAG
(c)
3.0
2.5
2.0
1.5
1.0
$1/\lambda$ (μ^{-1})
-2.5 log F_ν + C
+19° 1166
B1.5: V: pne
(25K, 3.5)
+33° 1103
B2: V: p(e)
(25K, 3.5)
+25° 1065
B2: V: pnne
(25K, 3.5)
+35° 1169
B1: V: pe
(25K, 3.5)
+61° 2361
B2pe
(25K, 3.5)
+62° 245
B1: pe(V)
(25K, 3.5)
0.1 MAG
(d)
3.0
2.5
2.0
1.5
1.0
$1/\lambda$ (μ^{-1})
-2.5 log F_ν + C
+15° 1176
B2 V: pe
(25K, 3.5)
+57° 240
B1.5 (V)pe
(25K, 3.5)
+8 3866
B3 V: pe
(18K, 4.0)
+58° 356
B1: V: pe
(25K, 3.5)
+41° 974
Bpe
(18K, 4.0)
+10° 1172
B6pe
(15K, 4.0)
0.1 MAG
(e)
3.0
2.5
2.0
1.5
1.0
$1/\lambda$ (μ^{-1})

Fig. 4 (*cont.*)

At the shortest wavelengths below the Balmer discontinuity, data for all of our stars often show a slope inconsistent with the model continuum. At present we must consider this an effect of the uncertainty in the interstellar reddening law at these wavelengths.

Turning next to the near infrared, we note that all of the stars in Figure 4a have moderate to large excesses, of the order of 0.2 mag., which peak in the 0.8 to 0.9 μ region and which are significantly diminished at 1.06 μ. We also note the lack of evidence for a Paschen discontinuity in emission or absorption for these very hot Be stars.

As we pass to increasingly cool stars, in Figures 4b, c, d, e, we see the Balmer discontinuity becoming longer, the spectral type becoming later, and, possibly, evidence for emergence of the Paschen discontinuity. Although the data in the infrared are noisy, I have the impression that the Paschen discontinuities are larger than the model prediction.

The existence of infrared continuum emission has been recognized in many southern Be stars by Feinstein (1968) from *UBVRI* photometry. Feinstein (1970) also has reported variability in V magnitude and $B-V$ color, which suggest that the near infrared emission is probably variable in at least some stars.

3. I.A.U. Symposium 70 Stars

I wish now to pass on to the IAU Symposium 70 stars. As most of you know, the organizers of this symposium announced a consensus of early symposium participants that intensive observations of four stars, γ Cas, ϕ Per, ζ Tau, and 28 Tau, be made by all available observational techniques to permit a synthesis of their many properties. I show in Figure 5 the energy distributions from 0.32 to 1.06 μ for these four stars.

The B0 p star γ Cas is seen to have a continuous energy distribution across the Balmer jump, and a moderate excess in the near infrared. Chalonge and collaborators (Arnulf *et al.*, 1938) have found the Balmer discontinuity strongly in emission in 1937, and significantly variable on a time scale of six months. Thus we conclude that the shell in γ Cas was relatively thin when our observations were made in October 1974.

The B1 p star ϕ Per is also nearly continuous across the Balmer jump, and also has a moderate excess in the near infrared. We note here that the energy distributions follow the extrapolated Paschen continuum and parallel the Balmer continuum of the Kurucz *et al.* (1973) models quite well, which suggests that the fainter stars in Figure 4 still have systematic errors in the dereddening at the shortest wavelengths, as discussed in Section 2. The Balmer discontinuity of ϕ Per given by Chalonge and collaborators appears to be constant and near zero, in agreement with the October 1974 measurement.

For the B2 IV p star ζ Tau I was unable to decide on the correct color excess, and have plotted energy distributions for two choices. The first choice fits well in the λ 4000 Å region and in the infrared, but has a moderate trough in the λ 5000 Å region, which is usually an indication that the star has been overcorrected for

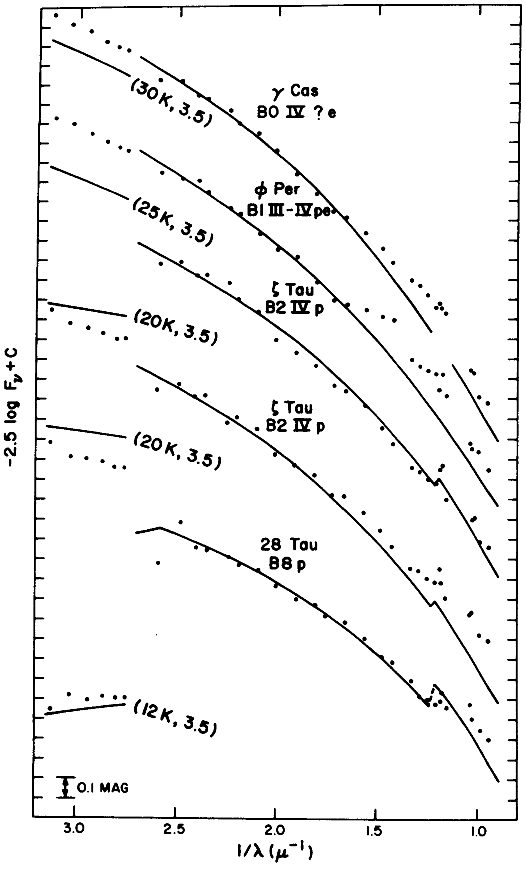


Fig. 5. Energy distributions of IAU Symposium 70 stars, fitted to models appropriate to the spectral types. The data for ζ Tau are shown for two choices of color excess, $E(B-V)$.

reddening. A better fit at the λ 4000–5000 Å region is obtained for the second choice of color excess, which gives a mild excess in the near infrared. Note, however, that the infrared excess does not peak in the 0.8 μ region, but instead appears to increase monotonically with wavelength, unlike the stars in Figures 4a, b, c, d.

Finally, we note that the fit of 28 Tau to the (12 K, 3.5) model is quite good, except that the observed Paschen discontinuity appears to be somewhat too large, as was noted for the cooler stars in Figure 4.

4. Energy Distributions of 'Pole-on' Stars

In this section we discuss the two groups of 'pole-on' stars which were investigated by means of infrared data and other techniques by Schild (1973). At the time I made the present observations, I expected all of the original pole-on stars to show the 1 μ excess.

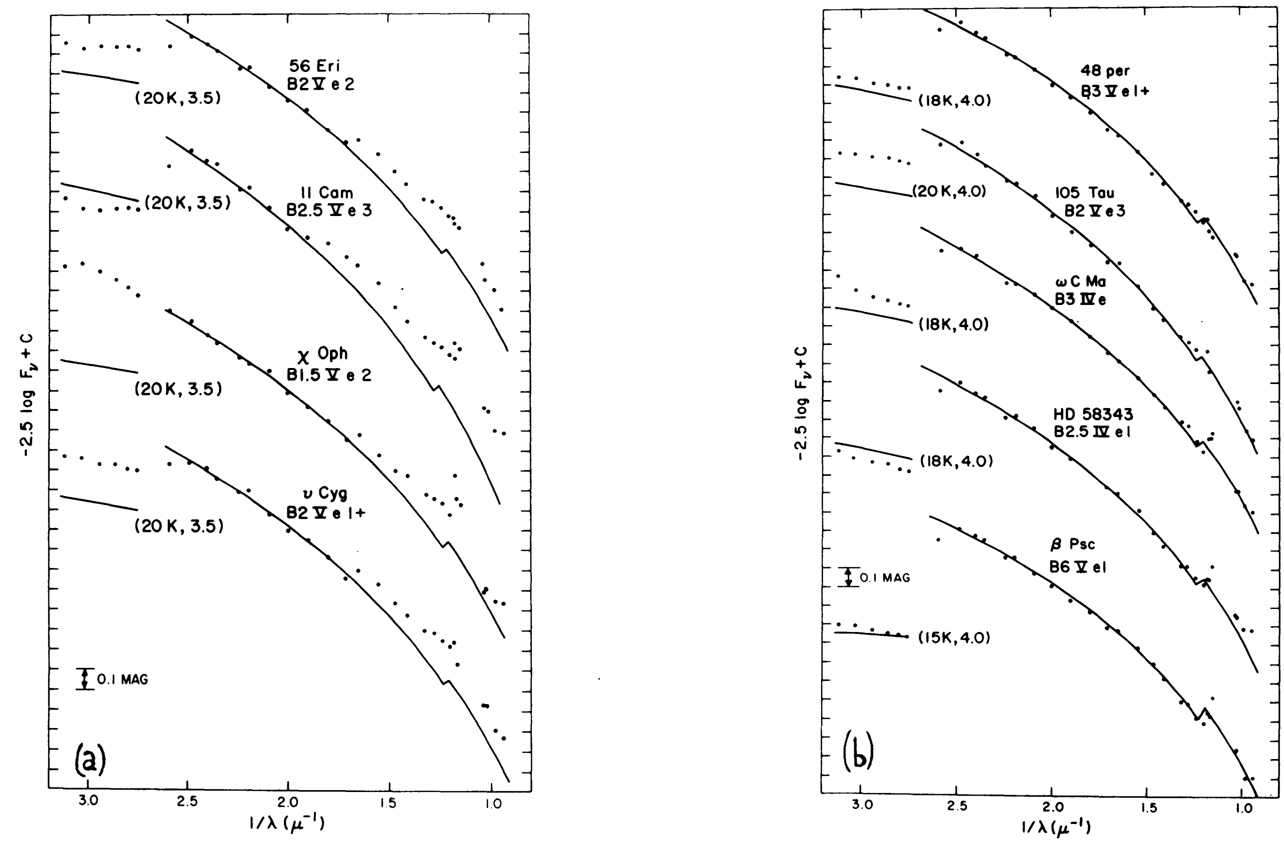


Fig. 6. Energy distributions for the classic 'pole-on' stars.

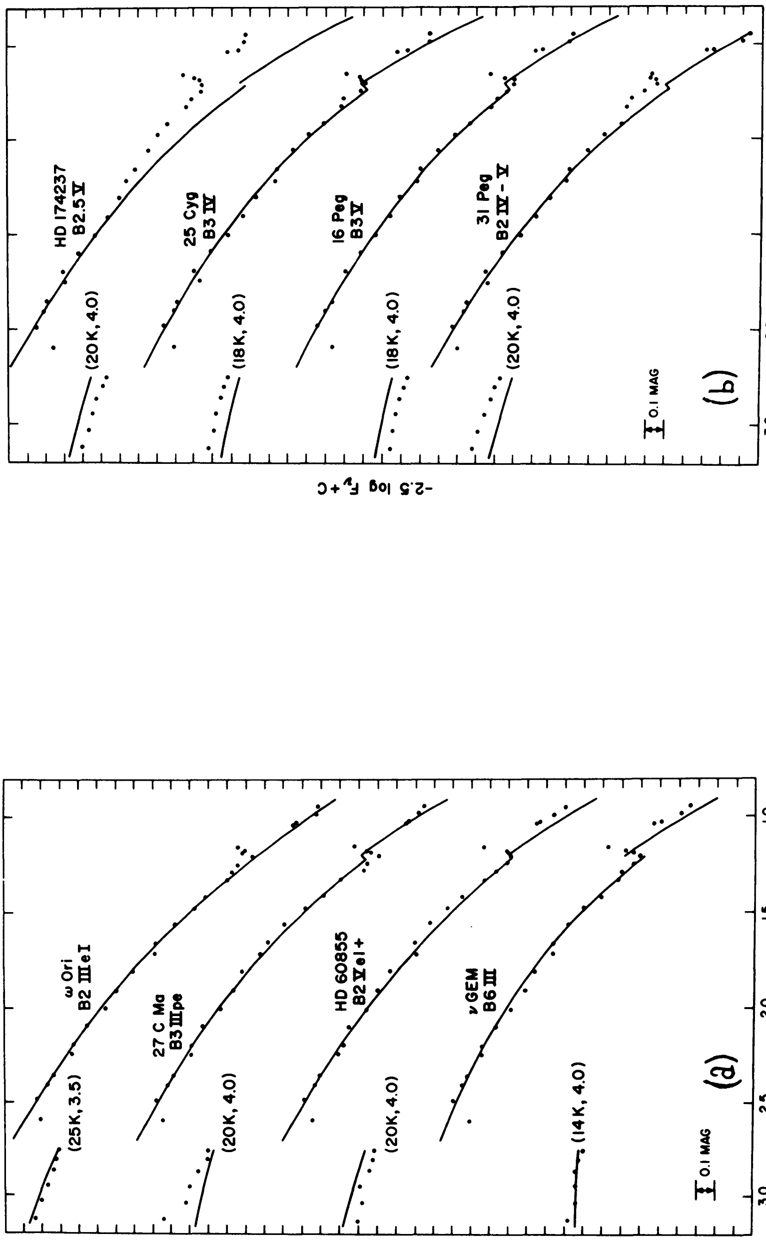


Fig. 7. Energy distributions for the group of stars identified by Schild (1973) as true pole-on stars.

Figure 6a shows energy distributions of the classic pole-on stars which do show the 1 μ excess. We note that χ Oph appears to be nearly constant across the Balmer discontinuity, much as was found by Barbier and Chalonge (1941). In Figure 6b we have energy distributions for the five remaining pole-on stars. These appear to be quite normal for their spectral types, which are on the average only slightly later than the stars in Figure 6a. We may note that the Balmer jumps for stars having an infrared excess are systematically smaller than for those lacking the 1 μ excess.

One of the stars in Figure 6b, 105 Tau, may have a weak excess in the near infrared. When stars having such an excess are fitted to continuum models by overestimating the color excess $E(B-V)$, the fitted energy distribution shows a slight excess in the λ 4000 Å region and a moderate deficiency in the λ 5000 Å region. This is faintly seen for 105 Tau as seen in Figure 6b and has also been discussed in the preceding section with regard to ζ Tau, where two choices of the reddening are given. We have adopted here the conservative value of $E(B-V)$ in plotting our data for 105 Tau, so a good fit to the model is obtained in the near infrared.

It is not yet clear why some of the stars in Figures 6a and b have the near infrared excess whereas others lack it. We note, however, that the stars in Figure 6b which lack the excess appear systematically to be cooler than the stars in Figure 6a. This is particularly true if the ambiguous case 105 Tau is allowed for.

In Figures 7a, b we show energy distributions of stars identified by Schild (1973) as 'true pole-on stars'. They have been fitted to Kurucz *et al.* (1973) models appropriate to their spectral types. In general, the fit to the continuum is good except that the Balmer discontinuities are, on the average, too small. One star, HD 174237, shows evidence for the 1 μ infrared excess. Since there is no tendency for the spectral types of the true pole-on stars to be different from those of the classical pole-on stars, there may be some slight evidence for a greater incidence of 1 μ excess emission among the latter group of stars.

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DISCUSSION

Peters: (1) I doubt whether continuous emission from the envelope contributes significantly in the blue portion of the spectrum in most cases. The maximum measured equivalent widths of the He I features in Be stars are comparable to the maximum values measured for non-Be stars. Specifically, in many cases we measure equivalent widths of 1.3 Å or higher for the stronger He I features (i.e. $\lambda\lambda$ 3819, 4026, 4471).

Schild: Our models do not yet completely reproduce the continuum so I cannot yet be sure of the contribution of the shell. My stars were selected to have strong emission, and are not typical.

Peters: Can you be sure that your infrared magnitudes are free from Paschen line emission?

Schild: The infrared bands were chosen to be free of the Paschen lines, except for one which was chosen to measure emission from a single Paschen line.

Peters: What T_{eff} and log g did you obtain for ϕ Per?

Schild: The energy distribution of ϕ Per is so nearly continuous across the Balmer jump that it would imply a temperature in excess of 50 000 K if fitted to a plane parallel model in static equilibrium. Such a temperature is completely incompatible with the absorption line spectrum.

Snow: If the infrared excesses in these stars are due to H^- free-bound emission, then the amount of excess flux is an indication of the formation rate of bound H^- in the circumstellar shell. H^- has predicted discrete transitions in the far-ultraviolet, and *Copernicus* data have been used to show that H^- is probably not present in the amount inferred from the infrared excess in at least two cases (χ Oph: Snow, *Astrophys. J.* **198**, 361, 1975, and υ Cyg, unpublished) of Be stars which show the kind of infrared excess which you attribute to H^- free-bound emission. This implies that these infrared excesses are not due to H^- free-bound emission, although it should be pointed out that, because it is a very difficult laboratory experiment, the expected discrete transitions in bound H^- have yet to be observed, and at present nearly all that is known about them is based on theoretical calculations.

Schild: There is a strong line just shortward of the wavelength of the predicted H^- feature (λ 1129.6 Å) in the spectrum of χ Oph, and I suggest that this is the H^- feature, shifted due to expansion in the circumstellar shell.

Snow: The feature you refer to is identified as Si IV λ 1128.34, and is strong in all early B-stars observed with *Copernicus*. It may be possible that the H^- feature is present and is shifted so that it is superposed on the Si IV line and therefore is not seen, but this seems unlikely for two reasons: (1) it is somewhat ad hoc to assume that the line is present but shifted by just the right amount so that it can't be seen, especially since more than one star is under consideration, and (2) in χ Oph the numerous shell lines due to Fe II and Fe III in the vicinity of λ 1130 Å are not noticeably more shifted than the stellar rest frame, so it is difficult to see why the H^- feature should be.

Slettebak: You stated that you chose stars having a '*p*', or peculiar, designation. In what sense were these stars peculiar?

Schild: These stars were taken from Hiltner's 1956 list (*Astrophys. J. Suppl. Ser.* **2**, 389) and the peculiarity was not stated. My selection inclined to favor stars with strong infrared excesses, however.

Feinstein: With respect to the near infrared excess of the Be stars, I showed some years ago (*Z. Astrophys.* **68**, 29, 1968) that when one makes two-color diagrams with the *UBVRI* measures (for example, $V-I$ vs $B-V$), the Be stars appear above the main sequence. This gives evidence of the near infrared excess of these stars, in agreement with Schild's paper.

Cowley: Have you considered the effects of cool companions in your work?

Schild: I would not expect the energy distributions to reach a maximum and then go down again in the cool companion model. I once tried to add cool energy distributions to hot energy distributions in an attempt to synthesize the observed ones, but the synthesized energy distributions always level off to longer wavelengths instead of receding as observed.

Feinstein: In several bright southern Be stars, we found no infrared excess in *JHKL* photometry.

Haight: Cassinelli and I constructed very extended model atmospheres taking into account the radiative transfer and spherical geometry, and we found that practically all of our models have the Balmer discontinuity in emission. Only the very coolest stars with effective temperatures of 16 000° or 17 000° have Balmer discontinuities in absorption.

Schild: Have these results been published?

Haight: No. These are essentially scaled down versions of a Wolf-Rayet model which was constructed in connection with work on polarization.

Hutchings: Have you concluded that the pole-on stars show infrared excesses?

Schild: I've concluded that half the pole-on stars do and half don't. But if we are talking about the stars defined by Slettebak in 1949, they tend to be somewhat cooler than the stars selected from the Hiltner catalogue which I observed. Therefore it may be that when you get to the cooler stars the frequency of occurrence of this phenomenon is lower. If indeed the interpretation of infrared excess as H^- free-bound continuum emission is correct it takes an enormous big shell at a temperature of about 3000°, of the order of 1000 stellar radii, to generate the amount of emission that we found here. It may be that the stars of later spectral type do not sustain such a large shell at the required temperature.