IV. INFRARED OBSERVATIONS

SPECTROSCOPIC OBSERVATIONS OF Be STARS ESPECIALLY IN THE INFRARED

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Since the time of I.A.U. Colloquium n° 70, new data have been obtained in the infrared, far less however than in the ultraviolet or in the visible. Few line spectra have been recorded but numerous results have been published in the field of spectrometry of the continuum. It is however neither easy nor very useful to report on the infrared wavelength range alone, and therefore we shall consider when appropriate other spectral regions in this review. After all, the astrophysicist nowadays has the advantage to seek for information in a spectrum which encompasses a fantastic frequency range of about 10 dex, from $\nu = 10^8 s^{-1}$ up to $\nu = 10^{18} s^{-1}$. This means that a contemporary astronomer will have to become familiar with a somewhat larger span of phenomena than with the rather narrow one he has been accustomed to for the last 40 or 50 years.

The fields of photometry and polarimetry in the infrared have been reviewed earlier during this symposium respectively by E.E. Mendoza and G.V. Coyne.

Among recent works on line spectroscopy in the infrared, we would like first to mention the stellar atlas published by the late H.L. Johnson (1977) and based on spectra obtained via Fourier transform spectroscopy. This atlas contains namely the spectra of γ Cas, P Cygni and ϕ Per, from about Hβ to 10,300 A. The fluxes have been normalised to give a constant value per unit frequency interval. The reduction procedure allows a resolution of 1.93 A at 5000 A, but the instrument is capable of a much higher resolution (0.13 A at 5000 A).

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Work at Haute Provence and Asiago allowed to observe several lines up to 11,200 A, revealing in peculiar Be stars the Paschen lines up to P6, the He I 10830 and 10913 A lines, the C I multiplet around 10690 A, the [S II] lines at 10284, 10318 and 10336 A, [S III] lines at 9069 and 9532 A, [Fe III] lines at 8838, 9960, 10433 and 10504 A. Several lines remain however unidentified.

The infrared spectrum of ζ Tau has been obtained between 1.5 and 4.7 μm by Smith, Thronson, Larson and Fink (1979) using Fourier spectroscopy. The outstanding features in this range are the Brackett lines. Bα is in emission at 4.05 μm but from B(4-10) to B(4-25), around 1.6 μm, these lines appear in absorption. This behaviour is unlike that of the Brackett series in γ Cas, in which all lines are in emission. In addition to the Brackett lines, the Pfund line Pβ(5-7) and some Humphreys lines (6-11 and 6-10) are detected in emission. Typical line width is around 130 km/s, i.e. about 40 A at 4 μm, which is much less than v sin i ∿ 310 km/s measured from emission features in the visible. The equivalent width of the Brackett α line is about 33 A, while its width (FWMH) is 47.2 A. It is suggested by the authors that therefore Bα is optically thick and originates in a small rapid rotation hot region close to the star, while the absorption lines arise from a cooler and more extended atmosphere.

It has been known since 1924 that the bright O I line at 8446 A should be due to a fluorescence mechanism pumping Ly β photons. However the line at 11287 A, which precedes 8446 A in the cascade towards the ground level has not been reported in emission. More curious still is the fact that the resonance multiplet at 1302 A has not been observed either in several Be stars where the 8446 A line appears as a strong emission (as reported by Oegerle, Polidan and Peters (1979)). In HD 50138, where λ 8446 is the strongest feature in the near infrared, we have been unable to detect any emission at λ 1302 on high dispersion I.U.E. spectra. Of course, it is well known that strong interstellar absorption is present in this line but a broad and strong emission should be easily detectable.

We shall come back on infrared lines later but we would like to report now about important observations of the infrared continuum. Garrison (1978) has extended his observations of Herbig Ae/Be stars to the near infrared, covering the λ 3400 to λ 8300 range.

The most remarkable characteristic feature is the heavy reddening of these objects and a much smaller Balmer discontinuity than that observed in stars with an analogous spectral type. This is shown on fig. 1, where the spectrum is however dereddened using model atmosphere fluxes for stars of similar effective temperatures. It is also apparent that some stars show an infrared excess with respect to the model fluxes.

Garrison explains the small Balmer jump by free-bound emission and establishes a means of computing the "Balmer excess" for an optically thin model

$$\Delta D_B = -2.5 \log \frac{4\pi R_*^2 \pi F_\nu}{4\pi R_*^2 \pi F_\nu + 4\pi \int_{V_s} j_{\nu_{bf}} \, dV_s}$$

where

F_ν is the flux from the star shortward of $1/\lambda = 2.7\ \mu m^{-1}$.

$j_{\nu_{bf}}$ is the volume emission for the free-bound H transitions,

V_s being the volume of the emitting region.

$$j_\nu = 1.88\ 10^{-34}\ T_s^{-3/2}\ N_e N_i \text{ cgs}$$

where T_s is the shell temperature; then an idea of the shell emission called the "emission measure" and defined as

$$\varepsilon = \frac{\int_V N_e N_i \, dV}{R_*^2}$$

can be computed.

But

$$\int_V j_{\nu_{bf}} \, dV = 4\pi R_*^2\ \pi F_\nu\ (10^{0.4\ \Delta D_B} - 1)$$

hence

$$1.88\ 10^{-34}\ T_s^{-3/2} \int_V N_e N_i \, dV = 4\pi R_*^2 \pi F_\nu\ (10^{0.4 \Delta D_B} - 1)$$

and

$$\varepsilon = \frac{4\pi^2 F_\nu}{1.88} (10^{0.4\Delta D_B} - 1)\ 10^{34}\ T_s^{3/2}$$

can be deduced from ΔD_B, T_s and F_ν taken from a model atmosphere.

The emission measure can also be used to predict the Paschen excess due to Paschen free-bound and free-free emission. The excess in magnitude is given by

$$\Delta m_{ir} = -2.5 \log \frac{4\pi R_*^2\ \pi F'_\nu}{4\pi R_*^2 \pi F'_\nu + 4\pi \int j_{\nu_{bf+ff}}\ dV_s}$$

F_ν' meaning here the theoretical stellar flux at some point in the Paschen continuum. The emissivity for free-free transitions is

$$4\pi j_{\nu_{ff}} = 7.39\ 10^{-38}\ T^{-1/2} e^{(-1.44\ 10^4 \lambda^{-1}/T_s)}\ N_e N_i$$

and Δm_{ir} may then be computed for various T_s in order to give a best fit with the observed energy distribution. These temperatures are given on fig. 1.

The reliability of these models is based on the assumption that the shell is optically thin in the continuum. The optical depth for free-free absorption, bound-free absorption and electron scattering are discussed by Garrison taking into account a model where the density drops off at a rate

$$N = N_o \left(\frac{r_o}{r}\right)^n$$

for realistic values of r_o and N_o at the stellar surface. The conclusion is that the shell is optically thin for free-free absorption and electron scattering, while this might not be true for bound-free absorption at the Balmer continuum. Garrison concludes also that the Paschen reemission alters only very slightly the flux below 5000 A, so that the dereddening procedure is not affected. This in our opinion is a very important point that should be examined with caution in each case since it affects all the results. The dereddening procedure has thus to be confined in a small region between 5000 and say 4000 A where the reddening is assumed to be truly interstellar.

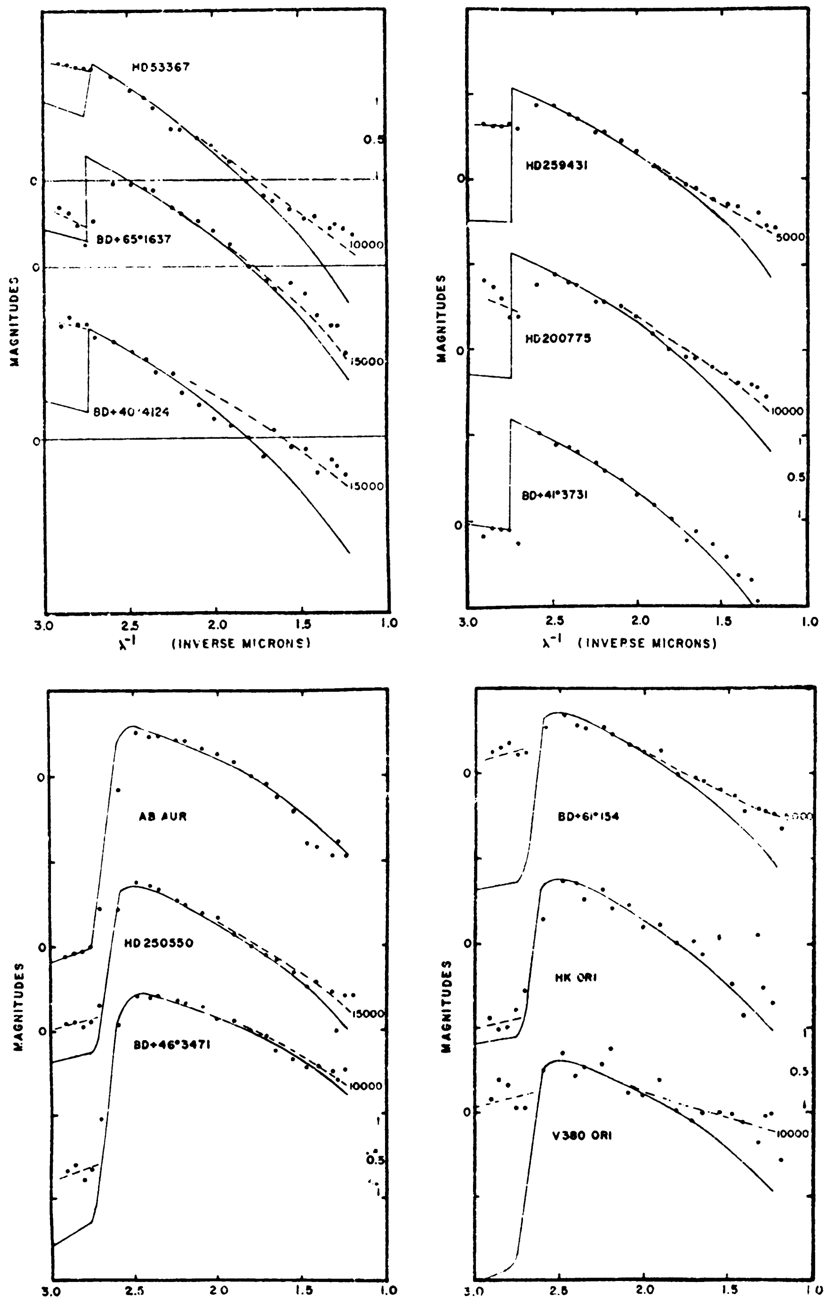


Figure 1. Dereddened spectral energy distributions, plotted as colour m(λ) − m(5556 A), versus 1/λ (μm). The solid lines represent model atmospheres appropriate to the spectral types. Dashed lines indicate model fluxes plus optically thin emission from a circumstellar shell. Numbers to the right of each curve give the temperature of the shell yielding the best fit with the observations (L.M. Garrison, Jr. The Astrophysical Journal, 224, pp. 540-541, 1978).

The infrared excess up to 5 μ has been computed in the same way as for the Paschen excess, using Johnson's results for the reddening curve below 1 μ. The results show that all the IR excess cannot be attributed to free-free and bound-free emission including n = 4 and 5 levels.

A thermal component is thus necessary also to explain a peak in the blackbody function around 3 μ, hence linked to temperatures of T = 2,890/λ(μm) or about 1000°K. These results are also in agreement with the emission measures derived from the Balmer excess.

Using the characteristic velocity derived from the H_α profile and integrated intensities from the Balmer excess, the mass flow rate is derived.

For spherical symmetry and constant density

$$\varepsilon = \frac{4\pi R_s^3 \, N_e^2}{3R_*^2}$$

assuming complete ionization and taking no account of the star's volume and occultation. R_s is the radius of the shell. Then

$$\frac{dM}{dt} = \dot{M} = 4\pi R_s^2 \, N_H \mu \, m_H \, \frac{dR}{dt}$$

If Hα and the Balmer excess are formed at about the same R_S,

$$\dot{M} = (3\varepsilon)^{2/3} R_*^{4/3} \, 4\pi \, \mu m_H \, v_s \, N_e^{-1/3}$$

Thus to know the massflow rate when the velocity v_s and ε are known, one needs to estimate the electron density and the stellar radius. Massflow rates are of the order of 10^{-6} to 10^{-7} $M_\odot y^{-1}$. General properties of the shells are deduced from all available data.

Scargle, Erickson, Witteborn and Strecker (1978) have studied the infrared spectrum of γ Cas. Observations, carried out aboard the Kuiper Airbone Observatory cover a region from 1.12 to 4.1 μm. Main results are summarised on fig. 2. Various stellar models are proposed by the authors. The flux F_ν is decomposed into star and shell contributions

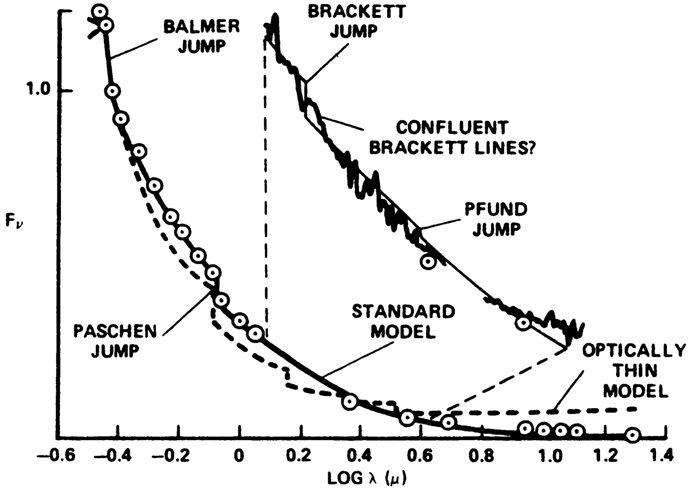


Figure 2. The spectrum of γ Cas, on a linear scale, corrected for a reddening corresponding to E(B-V) = 0.1. The points ⊙ are broad band data. The smooth solid line is the flux for a slab geometry model with T_e = 28,000°K and T_{shell} = 17,540°K. The dashed line represents the flux of an optically thin model which is clearly inadequate. The inset shows the dereddened data obtained by Scargle, Erickson, Witteborn and Strecker (from the Astrophysical J., 224, p. 528, 1978).

$$F = (1 - f)\psi_\nu + f\phi_\nu$$

$$= (1 - f)\, F^*_\nu \exp(-\tau^*_\nu) + f\phi_\nu(\tau^s_\nu)$$

where F_ν is the stellar flux, attenuated by an optical thickness τ^*_ν For the isothermal slab model, the function ϕ_ν, which represents the flux emitted by the shell,is

$$\phi_\nu(\tau) = B_\nu(T_s)(1 - e^{-\tau})$$

The parameter f represents the fraction of the total radiation contributed by the shell at the long wavelength side of the Balmer discontinuity; it is depending on the size of the shell relative to the stellar photosphere. f is determined by forcing the model Balmer jump to equal the observed one.

It is found that the IR excess in the case of γ Cas is due mostly to free-free and bound-free emission from a shell of gas at T_S = 18,000°K, with an optical depth $\tau(1\ \mu m) = 0.5$. Disk models for the shell give the best fit with $N_e = 10^{12} cm^{-3}$ and a size of 2.10^{12}cm.

The authors attract attention on the fact that the shell adds radiation to that of the star and also substracts radiation from the star. In certain situations, the net effect may be zero and shell is invisible at some wavelengths in the continuum.

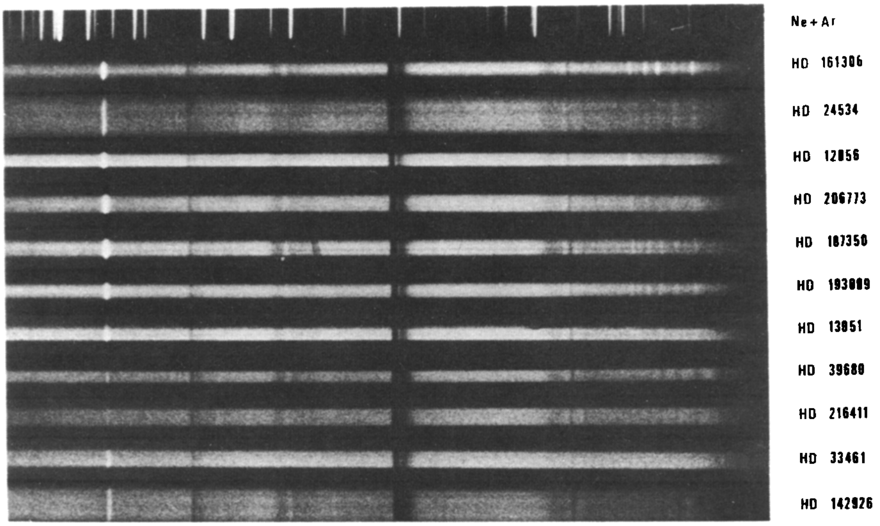
A study of HD 200775 has been carried out by Altamore et al. (1980) using data available in all frequency ranges. In the infrared, new photometric observations have been made from 2.3 to 12.6 µm. No variability in the IR magnitudes has been found. Extinction due to interstellar matter has been estimated at 0.25 m, in contrast to E(B-V) = 0.57 - 0.70 as derived from ground based photometry. The stellar continuum fits a 16,000°, log g = 4 atmosphere, especially in the UV. Also in the case of this star, a discontinuity of -0.36 magnitude for the shell is found. The authors ascribe most of the IR excess to thermal radiation while an outflow of material is found to be

$$\frac{\dot{M}}{v_{es}} = 2.3\ 10^{-9}\ M_\odot\ yr^{-1}/km\ s^{-1}$$

where v_{es} is the escape velocity.

On the photometric side, Whittet and van Breda (1980)

BOe B1e



B2e

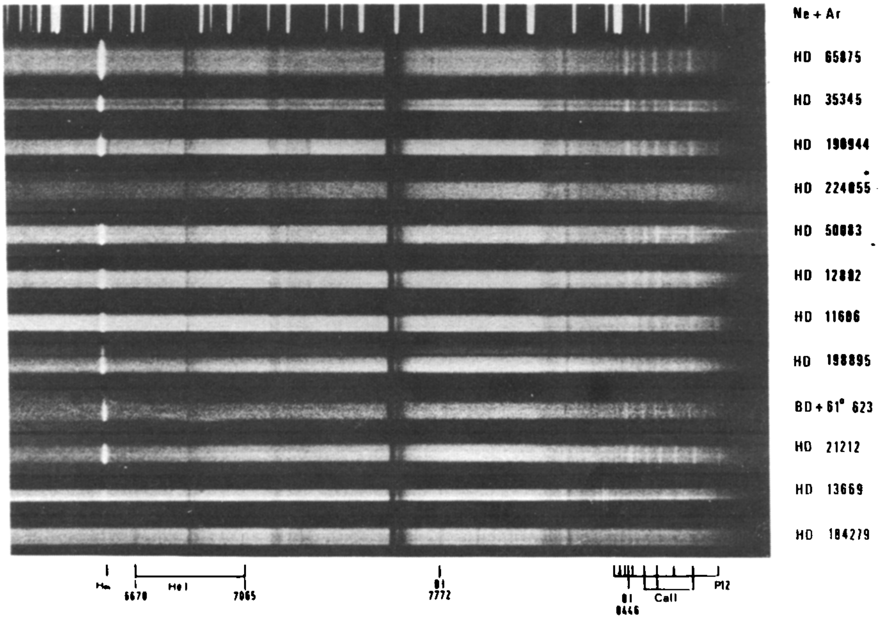
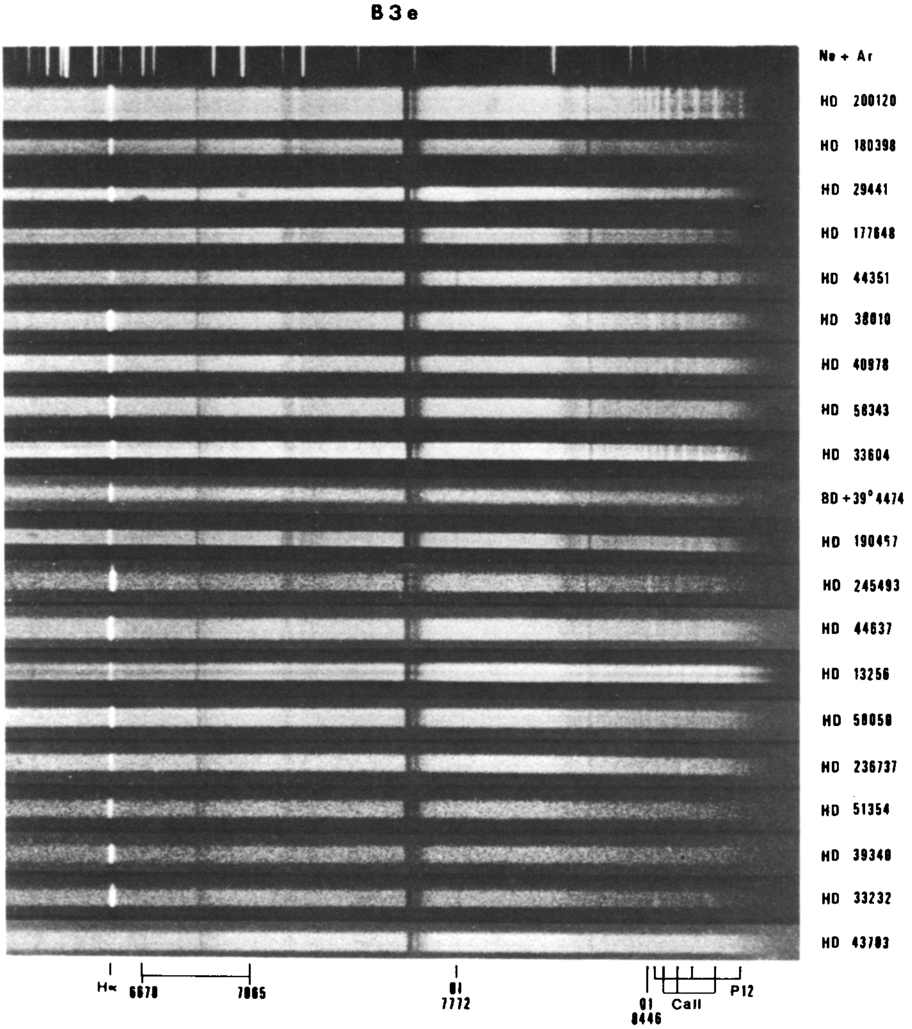


Plate 1


B3e
Ne + Ar
HD 200120
HD 180398
HD 29441
HD 177648
HD 44351
HD 38010
HD 40978
HD 58343
HD 33604
BD +39° 4474
HD 190457
HD 245493
HD 44637
HD 13256
HD 58050
HD 236737
HD 51354
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HD 43703
Hα
6678
7065
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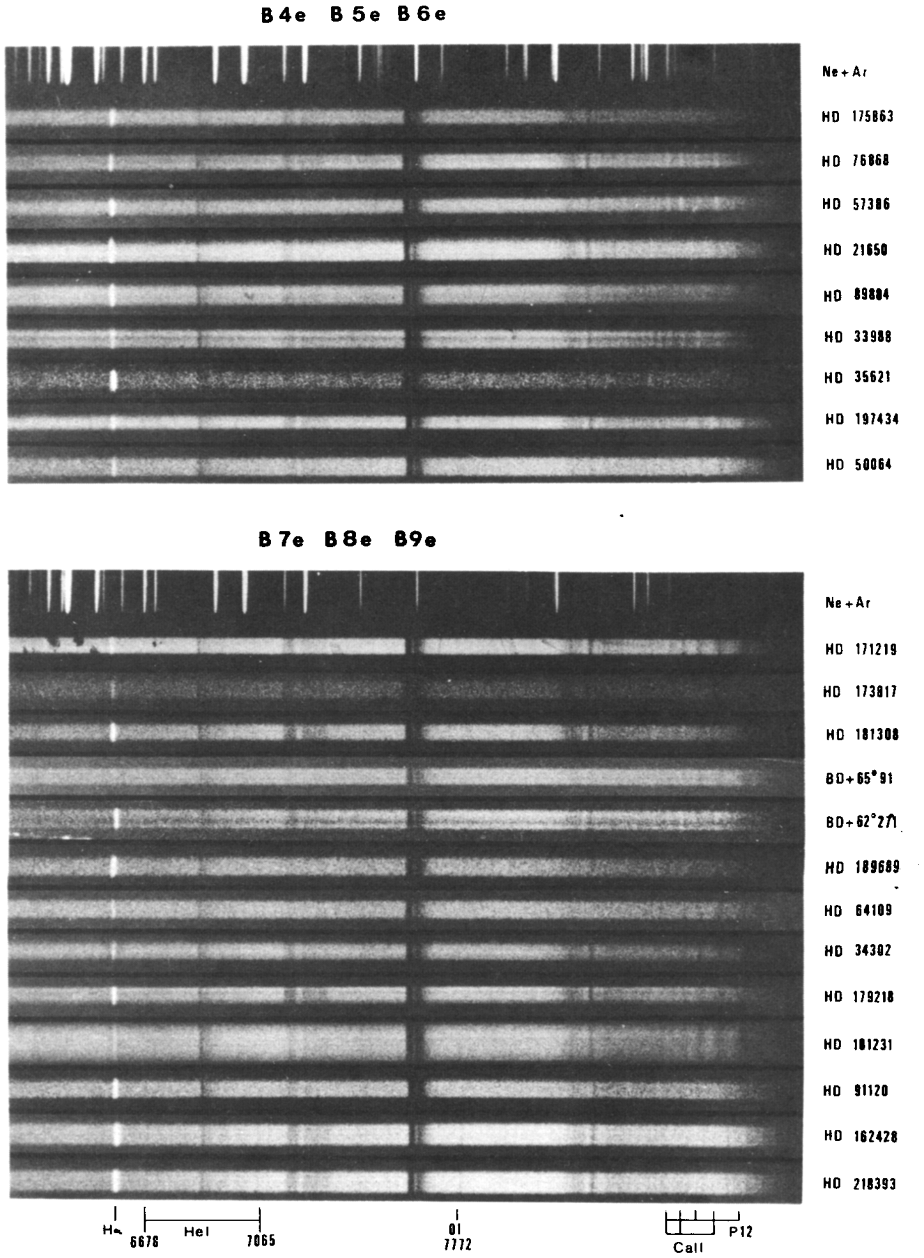
7772
OI
8446
CaII
P12

Plate 2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Ne+Ar
HD 171219
HD 173817
HD 181308
BD+65°91
BD+62°271
HD 189689
HD 64109
HD 34302
HD 179218
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Hα
6678
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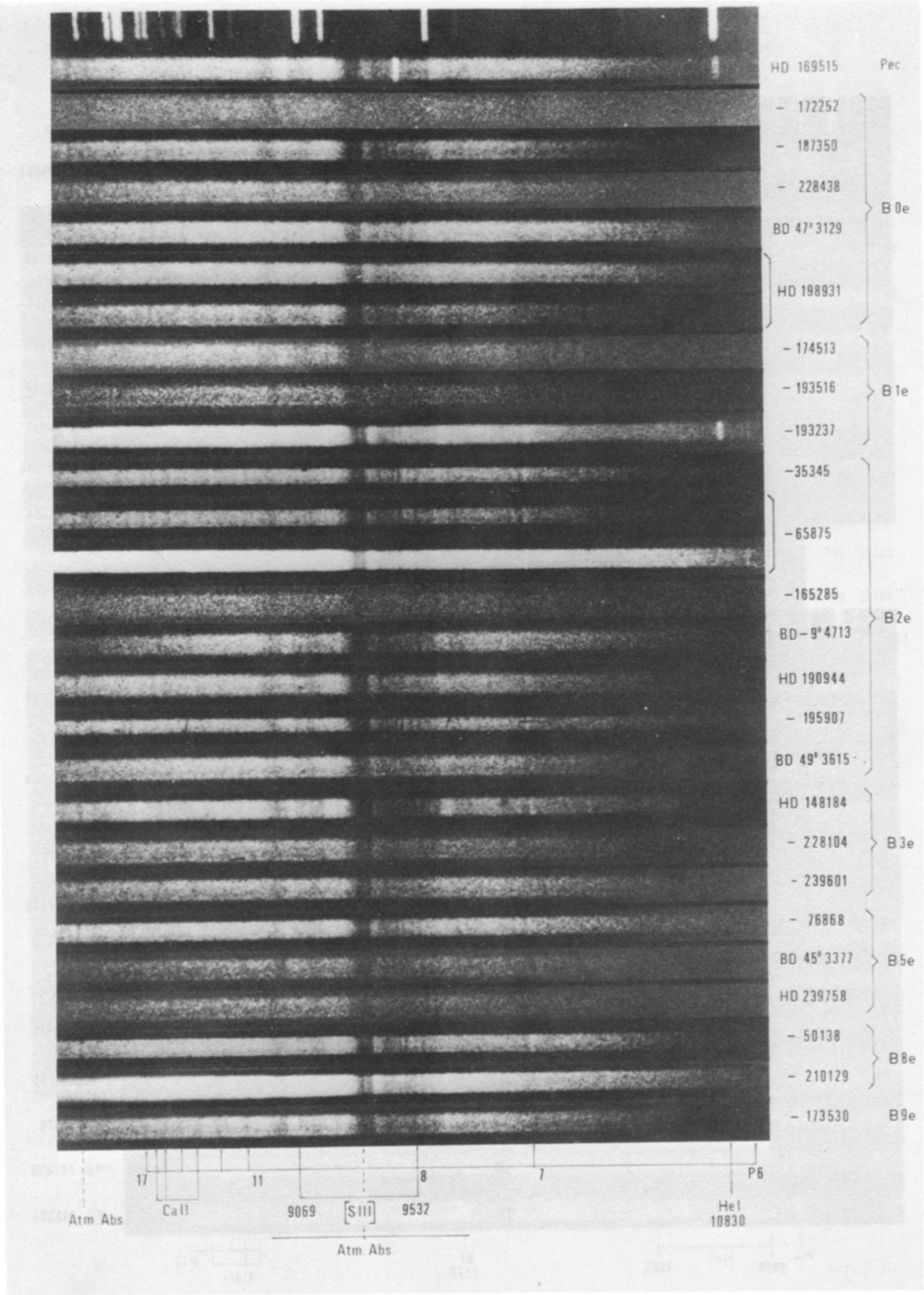
Plate 3


HD 169515
Pec
- 172252
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- 228438
BD 47° 3129
HD 198931
B 0e
- 174513
- 193516
-193237
B 1e
-35345
-65875
-165285
BD-9° 4713
HD 190944
- 195907
BD 49° 3615
B2e
HD 148184
- 228104
- 239601
B3e
- 76868
BD 45° 3377
HD 239758
B5e
- 50138
- 210129
B8e
- 173530
B9e
17
11
8
7
P6
Atm Abs
Ca II
9069
[S III]
9532
He I
10830
Atm Abs

Plate 4

have measured JHKL (1.2 to 3.5 μm) magnitudes of southern early-type stars. Intrinsic visual-infrared indices have been determined and R is found to be 3.12 ± 0.05, thus close close to the classical value for field stars.

At this occasion, colour indices revealed infrared excess in some of the shell stars. E(V-K) may be unusually large with respect to E(B-V), which is itself larger than in normal stars. Their study shows also that high rotation Be stars and nebular shell stars exhibit an infrared excess, (with two stars showing extreme values), because normal or dark clouds reddening corrections cannot place the star in the domain of unreddened stars.

In the H-K, K-L diagram the slope and normal reddening points almost in the direction of a black-body so that the dereddening is not as unambiguous than in the previous case.

Infrared observations of 27 CMa have led Danks and Houziaux (1978) to propose an extension of 17 stellar radii and an electron density of 6.10^{11} cm^{-3} for the shell surrounding this object.

In 1967, we published infrared spectra of bright Be stars. The work has been continued in order to increase the number of objects, on hypersensitised IN plates using the 120-cm telescope at Haute-Provence and with the Roucas image tube spectrograph at the Cassegrain focus of the 193-cm telescope. In both cases the reciprocal dispersion is 230 A mm^{-1} and a projected slit width reaches 7 A.

The spectra are shown on plates 1 to 3. The classification has been made according to Mount Wilson Catalogue, all these stars belonging to the Merrill-Burwell Catalogue.

As one can see, the H_α emission has in some stars seriously weakened or disappeared. The minimum detectable equivalent width is about 0.5 A. In about half of the stars O I at 8446 A is present and the proportion is somewhat less for high Paschen lines. The highest proportion for O I and H lines emissions is the Mount Wilson class B2. This is also true for the Ca II triplet.

When looking further into the infrared (plate 4) the quality of the spectrum is somewhat degraded. In some of the stars one sees P7 and P6 in emission and He I λ 10830 but the spectrum is often underexposed above 1 μm.

Although these objects have been identified as bright H_α stars for several decades, one can find only very little about them in the literature. In looking in the files of the S2/68 ultraviolet spectrometer units, we found a fair proportion of the stars observed during the sky survey and typical results between 1350 and 2740 A are shown on fig. 3. There is nothing spectacular about these spectra where the resolution is only 35 A. The noise is fairly high since the V magnitudes of the objects are in the 7-9 range and no emission appears under such conditions. The "line" spectrum resembles that of ordinary B stars with noticeable λ 2200 interstellar absorption in fainter objects (as HD 43703 (B 1 IV p) V = 8.62 and 206773 (B 0 V p) V = 6.92). The noise has been computed for flux averages over 100 A and then the monochromatic magnitudes

$$m_\lambda = -2.5 \log F_\lambda - 21.17$$

have been computed from 1400 A to 2500 A and at 2740 A. In order to obtain spectral characteristics in the visual, spectra have been obtained with the CNRS-Liège objective prism Schmidt telescope on IIaJ and 098-02 plates.

Certain stars show clearly variations but very few have been observed for a sufficient period of time to state anything on periodicity.

In dereddening these stars in the B-V, U-B diagramme, the representative points reach the unreddened sequence at places corresponding to an earlier spectral type than the MK type determined chiefly from inspection of He I lines, supposed to be of photospheric origin. Hence there appears differences in colour excesses ΔE(B-V) and ΔE(U-B), which are most likely due to shell reemission in the Paschen and Balmer continua. In all but few cases, the colour excess E(B-V) derived by the Q method from U, B, V magnitudes is larger than the E(B-V) deduced from ultraviolet colours (Thompson et al., 1978). Starting from model atmospheres by Kurucz, Peytremann and Avrett (1977), Delcroix (1979) has computed ultraviolet colours $(m_\lambda - V)_0$ averaged over 50 A wavebands in the range λ 1400 to λ 2500. These colours have been reddened for values of E(B-V) from 0.1 (0.1) to 0.4. Furthermore, in summing up all the fluxes in the range λ 1400 to λ 2500, Delcroix has defined an index

$$TD1 - V = -2.5 \log (F_{1565} + F_{1965} + F_{2365}) - V + C$$

where the fluxes F_{1565}, F_{1965} and F_{2365} are taken from Thompson et al. (1978). The constant C is such that TD1 - V

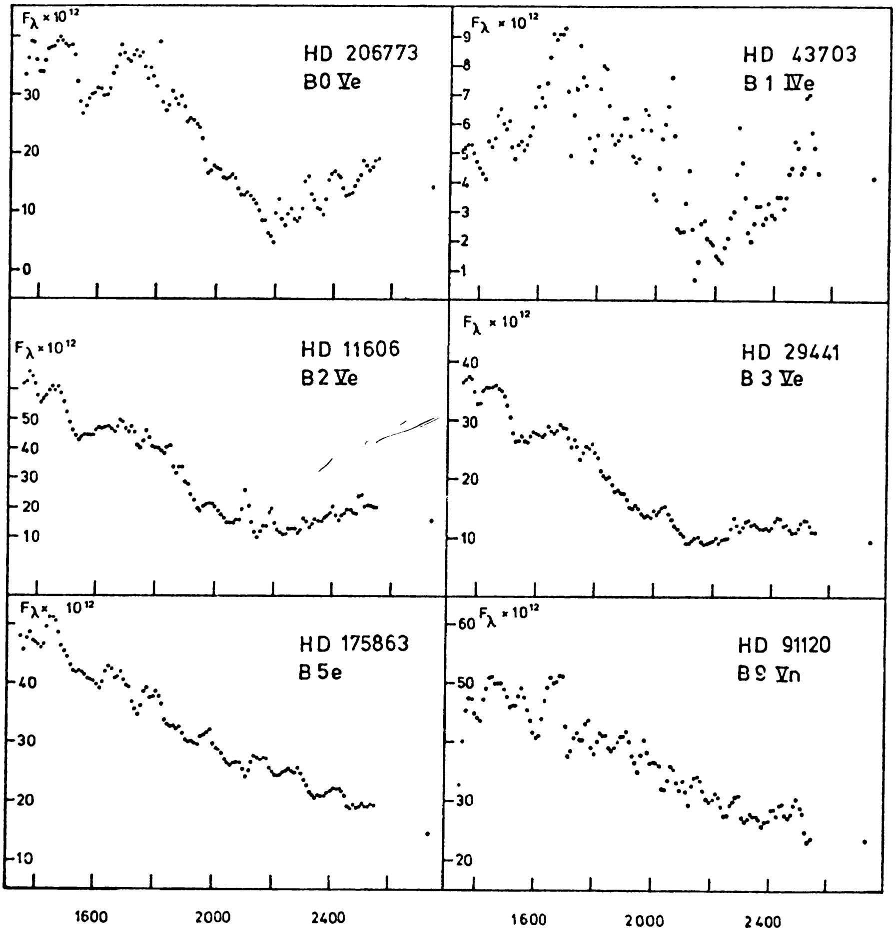

Figure 3. Sample of spectra of Be stars obtained with the S2/68 ultraviolet scanning spectrometer. Abscissa is wavelength in Angstroms. Ordinates give fluxes in 10^{-12} ergs cm^{-2}s^{-1} Å^{-1}. The resolution of 35 A permits to distinguish a few spectral features, notably at λ 1400-1420 (Si IV in early B and Si II in late B stars), λ 1475 (Si II, late B), λ 1550 (C IV), λλ 1850, 1960, 2110 (Fe Fe III, early B stars), λλ 2240, 2350, 2450 (Fe II and ionised metals). The interstellar band at λ 2200 is quite conspicuous in the intrinsically bright objects (B0, B1). Noise varies according to the V magnitude (V = 7.03 for HD 11606 and V = 8.62 for HD 43703).

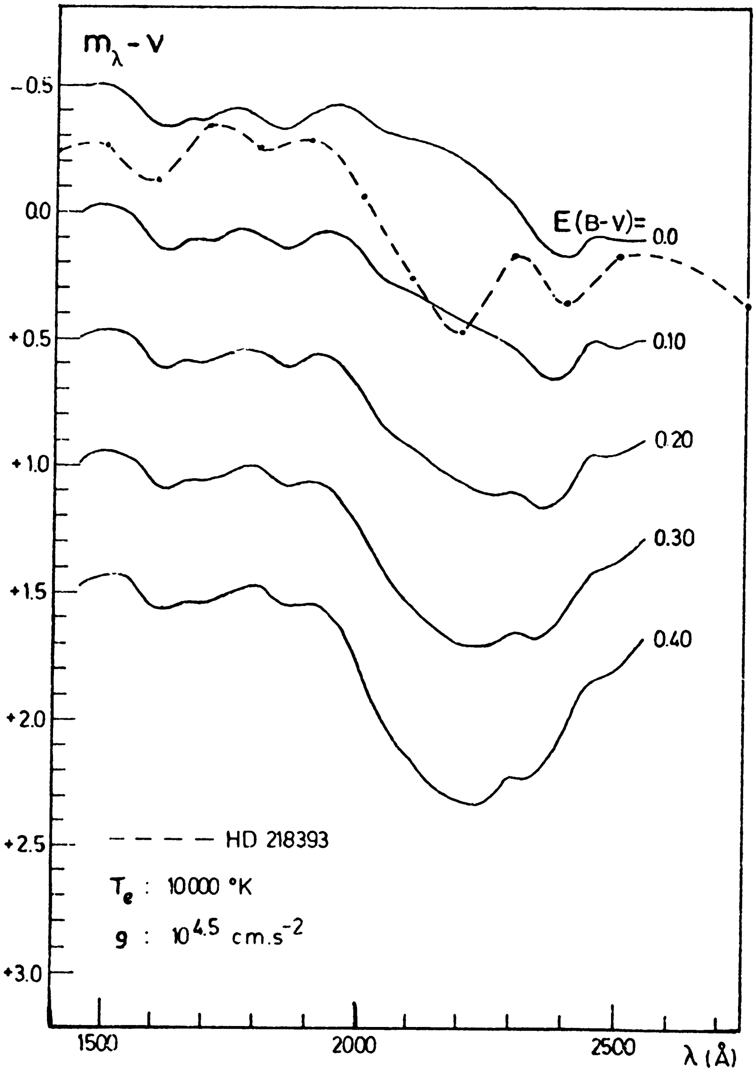

Figure 4. Colour indices computed from a model atmosphere including a great number of lines and averaged over 50 A intervals. The four lower lines show how the colour indices are modified by interstellar absorption for four values of E(B-V). Points represent the colour indices of the star HD 218393, derived from S2/68 data averaged over 100 A wavebands. Note that the shape of the observations does not fit the model, although the range in colour index is appropriate to a slightly reddened 10,000°K model atmosphere.

equals zero for an average AOV star. The index TD1 - V has also been computed in the same way at the (m_λ - V) colours mentioned above, and reddened for several values of E(B-V). When E(B-V) is determined from the observed colours m(1565) - m(2740) and m(1565) - m(2365), as well as its mean error, it is possible to assign from the observed TD1-V index, values of T_e and log g to a given star. This procedure minimises the errors on the ultraviolet fluxes due to noise. It is also possible to compare the observed (m_λ - V) indices to (m_λ - V) for model atmospheres appropriately reddened. Such a comparison leads generally to a very satisfactory fit, except in a few particular cases. We mention as an example on fig. 4 the (m_λ - V) indices of the star HD 218393. As seen in plate 3, this star shows a bright Hα line but no other emission in the near-infrared. It has been erroneously classified as Ave in the Mount Wilson Catalogue. The total ultraviolet flux leads, via the TD1 - V procedure to an effective temperature of 10,100°K. However, as seen on fig. 4, the colours indicate that this star cannot have such a low temperature. It is rather a hot object with an appreciable amount of reddening and/or abnormally strong absorption features in the ultraviolet.

Near infrared spectra of these stars led us to extend the observations to other spectral regions. Furthermore, infrared lines carry important information, especially the Paschen and Brackett lines of hydrogen. Emission lines of chemically abundant atoms are more frequently seen at infrared wavelengths than in visible or ultraviolet regions, since the radiation emitted from the shell has to compete with relatively weak photospheric emission.

We have to hope that observatories will develop and provide new facilities for visiting astronomers, so that both photometry and spectrometry in the infrared will retain the attention of many Be stars observers.

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DISCUSSION

Coyne: Does the curvature in the reddening curve shown by models in the far UV imply any curvature, at least theoretically, in the B-V, U-B reddening law?

Houziaux: The curvature in the reddening line in the UV does not imply a curvature in the B-V, U-B diagram, since the shape of the absorption curve is not the same in the ultraviolet and in the visible. However, because of the width of the U,B,V filters such a curvature may well appear in the visible, especially if one considers large values of E(B-V).

Thomas: I caution against diagnosing these very essential IR data only in terms of uniform shells, as you have done. In particular, in stressing agreement between data and computations based on shells of $T_e \sim 20000$ K you ignore the contributions of those chromospheric-wind regions which we know exist. For example the computations by Casinelli should be mentioned. Also, we know now the great uncertainty in deriving mass flux velocities from H_α profiles alone (cf. Doazan et al this colloquium).

Houziaux: I quite agree that the compatibility between mass flux derivations from infrared data and from computations based on shells of T_e 20000 K is not a proof of the consistency of the model, especially when velocities used in calculations based on infrared observations are derived from H_α profiles, the width of which may not be due to motion effects.