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B[e] stars

IV. HD 45677= MWC 142*

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Abstract. On the basis of spectroscopic CCD material obtained at the Haute Provence Observatory, we provide line identifications and equivalent width measurements in the wavelength regions 3750 – 5112 and 7065 – 10212 Å of the spectrum of HD 45677. Over 235 features are identified and a comparison of our results with those of other authors is provided. We also discuss the variability of the lines using equivalent widths and the line spectrum. We conclude that the gaseous shell surrounding the star has a temperature of the order of 7000 K and that its distance to the star is less than ten stellar radii.

We discuss the similarity of this star to other stars previously analyzed.

Key words: stars: emission line, B[e] — stars variables: others — stars: HD 45677

1. Introduction

HD 45677(= MWC 142 = FS CMa) is a much studied object, both because of its observability from the northern hemisphere and its peculiarities. The CDS bibliography of the star lists 144 papers published between 1949 and 1996. The object was discovered almost one century ago by Fleming (1898), but the first descriptions were made by Merrill (1925, 1928). Subsequently the star was studied by Swings & Struve (1940, 1943) and by Merrill (1952) who provided line identifications and descriptions of the spectrum documenting its variability. We shall not attempt to provide a summary of the whole literature, but we shall try to summarize what seems to us to be the essential observational characteristics of this star.

The star exhibits a circumstellar dust shell, responsible for a strong infrared radiation excess, possibly seen edge-on (Swings & Allen 1971). The star is not associated neither a with visible nebulosity (Swings 1973), nor with molecular clouds (Brown et al. 1995). The dust shell (or torus) apparently is the cause for the erratic photometric variations in visual magnitude and in colors (Halbedel 1989 and 1991; Bergner et al. 1995) which occupy the interval $7.55 < V < 8.58$ and $0.0 < B - V < 0.11$. Halbedel (1991) suggests that a quasi-period of 297 days exists, besides a general flickering (Perez et al. 1994). From satellite polarimetric observations in the ultraviolet, Schulte-Ladbeck et al. (1992) conclude that a bipolar reflection nebula is present beside the dust shell. A study of the satellite ultraviolet made Brown et al. (1995) concludes that in the circumstellar disk or torus, predominate the micron-size particles, whereas the sub-micron sized ones are depleted by radiation pressure. The accumulation of micron sized grains might lead eventually to the formation of planetesimals. Sitko et al. (1994) conclude from a comparison of data separated by more than a decade that the variations in photometry and in the spectrum are due to changes in the dust obscuration

The IUE spectra have been studied among others by Grady et al. (1993). They conclude from enhanced redward absorption components that the material shows clear indications of accretions onto the star.

As far as the evolutionary status of HD 45677 goes, the views found in the literature diverge widely. Some authors see the object as a post asymptotic giant branch object on its way to become a planetary nebula. Others insist that it is an object in its contraction phase toward the main sequence, calling it a Herbig Be-Ae object. Some authors go even one step further and state that it is an object in a pre-beta Pictoris phase. It is only fair to say

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* Based on observations obtained at the Haute Provence Observatory (CNRS).

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*** Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html that each of these classifications has its difficulties. For a pre-main sequence object it is too far out of the galactic plane (190 pc) and it has no nebulosity associated with it, a fact which is basic to the classification as a Herbig Be-Ae object. For an evolved object one finds no wind, as usual, but instead accretion.

The aim of the present paper, as well of the others of this series, is to provide an identification list over an extended wavelength interval, together with a list of equivalent widths of the emission lines. This should lead to an improved understanding of B[e] stars and their shells.

2. Material

All the material was obtained on CCD receivers at the 193 cm telescope at the Haute Provence Observatory (OHP). The spectrograph used was CARELEC (Lemaitre et al. 1990) The observational data are collected in Table 1.

Table 1. Observational data

Date	Wavelength	Code
4 - 04 - 93	3736 – 4197	z
25 - 10 - 91	3896 – 4322	a
25 - 10 - 91	4285 – 4715	b
25 - 10 - 91	4698 – 5120	c
06 - 04 - 93	7000 – 7412	d
24 - 10 - 91	6973 – 7383	e
07 - 01 - 90	7570 – 7980	x
31 - 03 - 93	8358 – 8790	f
21 - 02 - 92	8365 – 8775	g
27 - 12 - 90	8360 – 8770	h
30 - 12 - 90	8305 – 8720	h′
15 - 11- 89	8375 – 8790	i
27 - 12 - 90	9010 – 9420	j
03 - 01 - 90	9840 – 10220	k

Date: day - month - year (-1900).
Wavelength region indicated in Angstroem.
Code- internal code used in Table 2.

For $\lambda < 6500$ Å a grating with 1200 lines/mm, blazed at 4000 Å was used, providing a dispersion of 33 Å/mm in the first order. For $\lambda > 6500$ Å a 1200 lines/mm grating was used, with a blaze at 7500 which provides in the first order a dispersion of 33 Å/mm; filter OG 590 was used to cut out the second order.

From 1990 to 1993 the receiver was a Thomson CCD with 512×384 pixels, (23 square microns), providing a resolving power of about 1 Å. After 1993 the receiver used was a TK 512 CCD, with 512×512 pixels (27 square microns). The resolving power was about 1.2 Å.

For the wavelength calibration we used Ne, Ar and He lamps. Flat field corrections were made with a Tungsten lamp mounted in the spectrograph. The slit width used was 300 microns, corresponding to $2''$ on the sky. The data were reduced with the software package IHAP, developed at ESO and installed at the OHP.

As remarked above, the resolving power is of about one Angstroem, which is not very well suited for radial velocity studies. The smallest equivalent width which can be measured is of the order of 0.15 Å. Since we are working with material obtained under the same conditions as those for HD 51585 (Jaschek et al. 1996 = Paper I) we adopt the errors given in that paper which are of the order of 10%. Furthermore, the resolution prevents us also from resolving structures in the line profiles (double lines for instance) whose separation is less than 75 km/s in the blue and 40 km/s in the red.

3. Line identifications

These were made in the traditional way, paying attention to both wavelengths and line intensities within the multiplets. The identifications were made with the help of the table of Moore (1959); for Fe II we also used Johansson's (1978) compilation and for [NiII] Nussbaumer & Storey (1982) In addition we have used the Meinel et al. (1969) catalogue, for lines which we could not identify (see notes to Table 2).

On our spectra are present 235 features, of which 30 are absorption lines whereas the majority is constituted by emission lines. We were unable to identify 7% of the emission lines, which is about normal in identification work The complete list of identifications is given in Table 2. Parts of the spectrum are reproduced in Fig. 1.

From Table 2 and Fig. 1 it can be seen that up to 4200 Å the spectrum is mostly formed by absorption lines, whereas beyond 4200 the emission lines predominate. Beyond 4200 the only absorption lines belong to the following elements: H (H 4, H 5), He I (4387, 4437, 4471, 4712, 4920, 5014, 7065), C II (4267), and Mg II (4481).

4. Elements present

On the basis of the identifications given in Table 2 we shall discuss the elements present in the spectrum of the star, ordered by atomic number.

Hydrogen.

The Balmer series is present between 3736 and 5120, represented by H 12 – H 4 in absorption. The intensities from H 12 to H 8 follow a regular pattern, decreasing afterwards. In 1991, in H 6 one observes a wide absorption line accompanied by a strong emission redshifted by about 250 km/s from the line center. A similar structure, but much fainter, is also seen in H 7. In H 5 the redshifted emission is much stronger; the shift being of 220 km/s.

On the spectrum from 1993 the redshifted emission component (250 km/s from the line center) is well visible in H 6, wheras in H 7, 8 and 9 only a deformation in the red wing is seen.

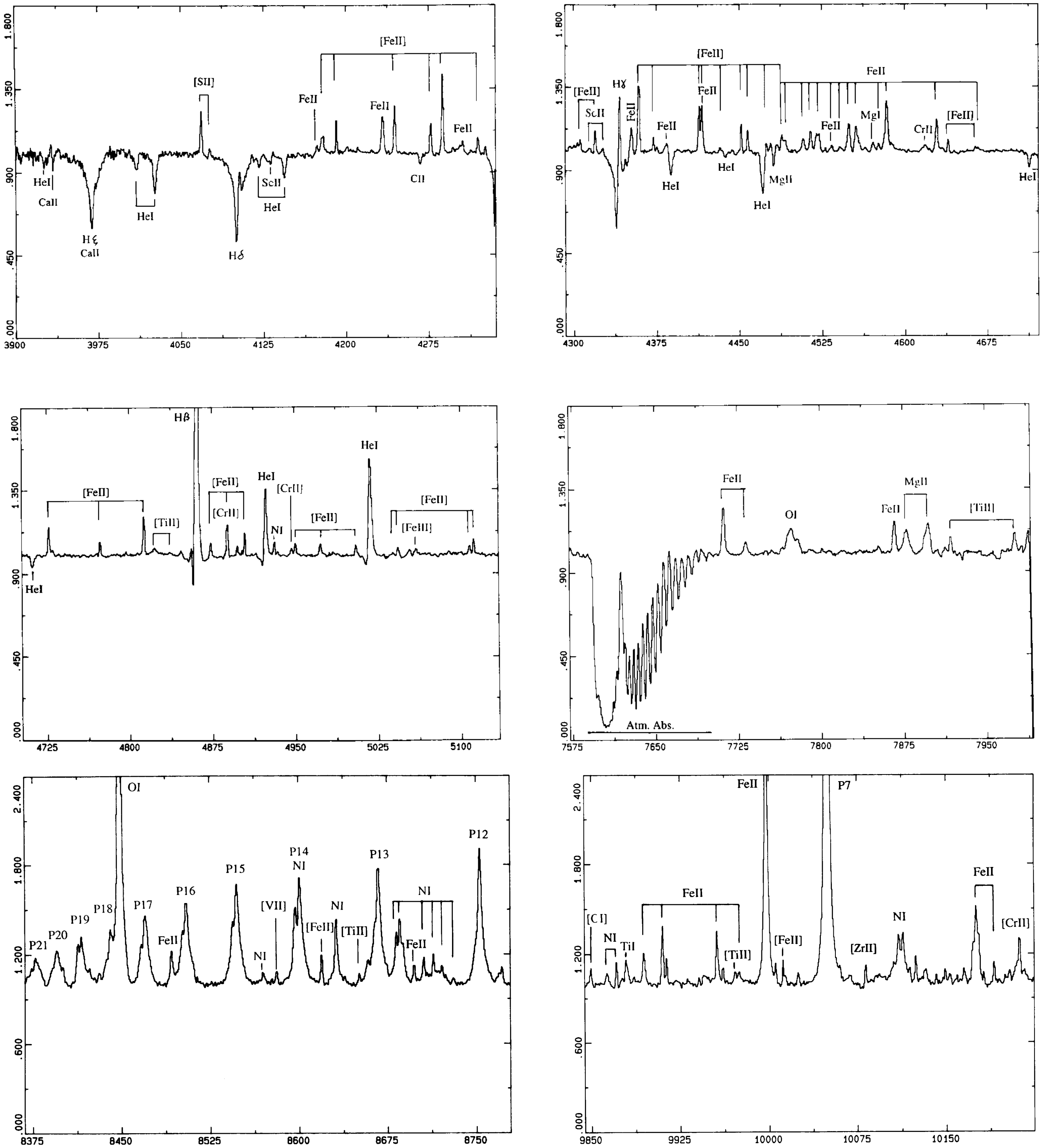

Fig. 1. Reproduction of CCD spectra of HD 45677. Abscissae: wavelengths in A. Ordnates: Intensities. The continuum level is set to unity. Important lines are identified. The spectra reproduced correspond to the following dates: 3900 − 4336, 23-10-1991 4292 − 4721, 25-10-91 4702 − 5135, 25-10-1991 7573 − 7991, 07-01-1990 8369 − 8779, 21-2-1992 9838 − 10225. 03-01-1990

In H 4 (observed only in 1991) there exists a wide (3900 km/s) and shallow absorption line upon which a strong emission ($W = 5.96$ Å) is placed. A blue and fainter emission component is also visible at -300 km/s from the emission line center. A sharp and intense blue shifted absorption at -197 km/s from the emission line center is also present. We are thus in presence of a rather complicated structure.

The Paschen lines observable in the wavelength range covered by us run from 25 to 7 (except 8), but the lines 25-22 were only observed in 1990. From P 21 to P 12, the lines follow a regular pattern. Whereas in 1990 and 1993 the equivalent widths were rather similar (differences less than 10%), in 1992 the W's are systematically weaker by about 20%. The lines appear symmetric on all spectra, except in 1992 when double structures can be appreciated in P13 − P19. The average separation between peaks is of the order of 110 km/s. It should be noticed that P 14 is double even in the years when all other Paschen lines are simple, and this is due to NI 8595.51.

Helium.

Neutral helium is well represented by absorption lines from the ^{3}D, ^{3}S, ^{1}D series and perhaps by two lines from ^{1}S. However in the latter series 5047 is only doubtfully present, so that we regard the presence of this series as dubious.

In general the helium lines are simple pure absorption profiles, but on one spectrum from 1991 we find two lines with abnormal profiles. In this year, both 4920 and 5017 have a P Cyg profile, with a displacement of 190 km/s between the absorption and the emission peaks. There exists further a violet absorption component, displaced 250 km/s from the central absorption.

Carbon.

C I is represented by lines from M.3, as well as by one line (9849) of [CI], all in emission. C II is represented by two weak features from M.4 and 6, both in absorption.

Nitrogen.

Neutral nitrogen is represented by many lines from M.1, 7, 8, 9, 15, 18, 19 and 174, all in emission. We do not observe N II, but in our wavelength regions no strong lines are expected.

Oxygen.

Neutral oxygen is represented by emission lines from M.1, 4, 8 and 54. The strength of M.4 is surely due to fluorescence effects from Lyman alpha. Its intensity has a minimum in 1992 (1.8 Å), as compared to 24 (1990) and 27.3 (1993) Ionized oxygen is represented by emission lines from M.50 and 97.

Magnesium.

Neutral magnesium is represented by a weak line of M.1, in emission. Ionized magnesium is represented by emission lines of M.1 and 8, whereas the strong M.4 (4481) is seen in absorption. The latter line is however flanked by two symmetrical emission peaks.

Silicon.

Ionized silicon is represented by M.3 (4128 − 30) in absorption and by the high excitation lines at 4200.6 and 4200.8, in emission.

Sulphur.

Forbidden ionized sulphur is represented by two weak emission lines of M.1.

Calcium.

Ionized calcium is present with a weak absorption line 3933 from M.1. The other line, 3968 is lost in the structure of H 7. Because of the lack of an enhancement of P 13, 15 and 16 with regard to other lines of the Paschen series, we infer that no infrared triplet Ca II lines are present.

Scandium.

Ionized scandium is represented by two weak emissions from M.15 and by one forbidden line from M.1, 8650. The element seems thus to be present.

Titanium.

Neutral titanium is represented by two lines from M.149 and by two weak lines from M.13 of [Ti 1]. Ionized titanium is present under the form of [Ti II] from M.5, 6, 10, 23 and 25.

Vanadium.

Ionized vanadium is present with the two strongest lines from M.56. [V II] is represented by lines from M.4 and 11.

Chromium.

Ionized chromium is represented by the strongest lines from M.44 and [Cr II] by lines from M.4, 10 and 15.

Manganese.

Ionized manganese is represented by only one line from an infrared multiplet. (Thackeray & Velasco 1976) The other lines of the multiplet are blended.

Iron.

This is the element which has the largest number of lines both in absolute as well as in relative number (36%). Ionized iron is represented by lines from M.27, 28, 37, 38 and 43. [Fe II] is represented by lines from M.3, 4, 5, 6, 7, 8, 13, 14, 19, 20, 21, 23, 30, 35, 37 and 41. [Fe III] is represented by one weak line 5059, from M.1.

Nickel.

Ionized nickel is present in the form of [Ni II], with two weak lines from M.2 and 3.

Copper.

Ionized copper is present in the form of [Cu II], with one weak line from M.1. (4375).

Zirconium.

Ionized zirconium is represented by the strongest line from M.88 and, under the form of [Zr II] by 10083 from M.13.

Comparison with the identifications of other authors.

The most extended line identification work on this star was carried out by Swings (1973), based upon material covering the region 3200 − 8700 Å with a variety of dispersions, obtained in the years 1962-72. He lists about 200 features, number to which iron contributes with about 45% of the lines.

In our work we list about 235 lines in a shorter interval (3300 Å), and 35% of these correspond to iron. The percentage of unidentified features is about the same in both cases.

The results of a comparison of the elements identified by different authors is given in Table 3.

Some comments upon the differences between the two most extended identifications - the present work and Swings (1973) - seem to be relevant. The main differences are due to our lack of coverage of the 5100 − 7000 region which prevents us from observing the presence of Na I, [N II] and [O I]. Our non observation of Mn II and Ni II is mostly due to our lack of coverage of the region below 3750, where Swings found most of the lines. The elements which we found and he did not, are most likely due to genuine variability of the shell. For instance he did not observe C II 4267 although this line was present in other epochs. A similar case can be made for O II and Si II. This implies that the lines of some elements appear and disappear over the years. We should recall that this has also been found

Table 3. Elements identified by different authors

	PW	Swings	Sw+Str	Gr	Isr
		1973	1943	1993	1996
H	x	x	x		
He I	x	x	x		
C I	x				
[I]	x				
II	x		x	x	x
IV				x	
N I	x	x			
II			x		x
[II]		x			
O I	x	x			
[I]		x	x		
II	x		x		
Na I					x
Mg I	x				
II	x	x	x		
Al III				x	
Si II	x			x	
IV				x	
S II					x
[II]	x	x			
Ca II	x	x	x		
Sc II	x				
[II]	x				
Ti I	x				
[I]	x				
II	x	x			
V II	x				
Cr II	x	x			
[II]	x	x			
Mn II	x	x			
Fe II	x	x	x	x	
[II]	x	x	x		
III				x	
[III]	x				
Co II		?			
Ni II		x			
[II]	x	x			
Zn II		x			
Cu [II]	x	x			
Zr II	x				
[II]	x				

Notes:
PW = Present work.
Sw-Str = Swings & Struve (1943) based upon photographic plates.
Gr = Grady et al. (1993) based only upon IUE spectra.
Isr = Israelian et al. (1996) These authors state that they find essentially the same as Swings (1973) with the exception of the elements marked.

in other B[e] stars investigated in this series, so that the phenomenon seems to be a general characteristics of B[e] stars and similar objects.

5. Line variability

After the first paper of Swings & Struve (1943), many authors have shown that the lines vary in strength and in structure. We shall not recapitulate all facts discovered, except to summarize saying that up to now no period or cycle has been discovered. This is true for the total light, as well as for line structures and line strengths (intensities or equivalent widths). For more details, see for instance Swings et al. (1980) and Israelian et al. (1996).

In what follows we shall report on the variations of the equivalent widths of the lines in our material. We stress the point that despite the large amount of descriptions available, our measures represent the first attempt to collect objective measures of line strengths.

The lines observed on different occasions are listed in Table 4 and displayed in Figs. 2 and 3. Table 4a and Fig. 2 show that between 1991 and 1993 no large changes have occurred, although He I is slightly weaker in 1993. The same is true for Si II, whereas Ca II is stronger in 1993. Let us observe that both Si II and Ca II have shown large variations in the past. Si II 4130 was not seen by Swings (1973) and Ca II has undergone changes from very strong and neat in 1943 to the weak line we see in 1991.

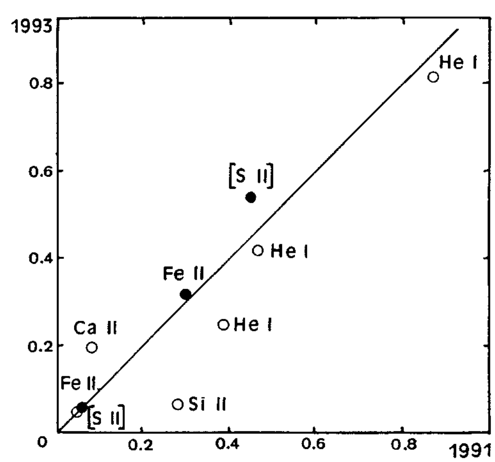

Fig. 2. Equivalent widths of different lines in 1991 and 1993, in the region 3896 − 4189. Empty circles stand for absorption lines, full circles for emission lines

If we examine the results of Table 4b and Fig. 3 we see immediately that the Paschen lines had a minimum in 1992 and came back to previous strength in 1993. O I 8446 also had a minimum in 1992, a fact which is in line with the weakening of the hydrogen lines. For the lines of N I, [Fe II] and [V II] there might be a minimum, but it is rather uncertain. What is remarkable is that the Paschen lines seem to be much less sensitive to the profile changes which are observed in the Balmer lines. In fact we cannot compare the equivalent widths of H7 and H 6 from 1991 and 1993 because of the changes in profile, whereas we see no obvious structure in the Paschen lines. We add that the two spectra of 1990 were taken at a three days interval, so that they can be used to obtain an impression of the precision of the equivalent width measures.

6. Towards a spectral classification of HD 45677

One curious fact, already mentioned, is that the photospheric absorption spectrum is visible in the region up to 4200 Å. After this limit, the spectrum is dominated by emission lines. The lines which are visible correspond mostly to hydrogen and neutral helium, which can be used to classify the star as B2. Such a classification was already proposed by Swings & Struve (1940). Although this type corresponds to the presence of the lines observed, the object is definitely not a well behaved B2 object. In the first place the equivalent widths of the He I lines are too weak by a factor up to two, which according to the interpretation of Israelian et al. (1996) is due to emissions filling in the absorption lines. Now if filling-in exists, one would expect it to be present also at other lines, like those of Si II, C II and H. However the equivalent widths of these lines correspond to B2. In second place we do not see the CIII-O II lines in the interval 4070 − 86. And in last place we see the Ca II line 3933 which is characteristic of later stars (around B 5). If veiling is present, we should have an even stronger Ca II line, which would make the disagreement even worse.

As far as luminosity is concerned, the star has been classified as luminosity class IV by Burnichon et al. (1967) This is however not a spectrocopic classification, since the classical criteria involving He I lines (4121, 4144, 4009) and N II (3995) cannot be applied because the helium are affected by fill-in and the N II line is absent. Observe also that there is an emission line at 3993, which would affect anyway the N II line.

The classification by Burnichon et al. (1967) is based upon the Chalonge - Barbier spectrophotometric system, which uses the Balmer discontinuity. In that paper the authors find that the three indices of the system are sligthly variable, a fact which they attribute to the influence of the emission envelope.

In view of all this, it seems best to state cautiously that the object is probably an object lying on or near to the main sequence. From a purely spectroscopic viewpoint it can also be added that the star is certainly not a supergiant.

7. The emission line spectrum of the star

We shall now try to obtain an idea about the temperature of the shell using the presence of the elements observed in

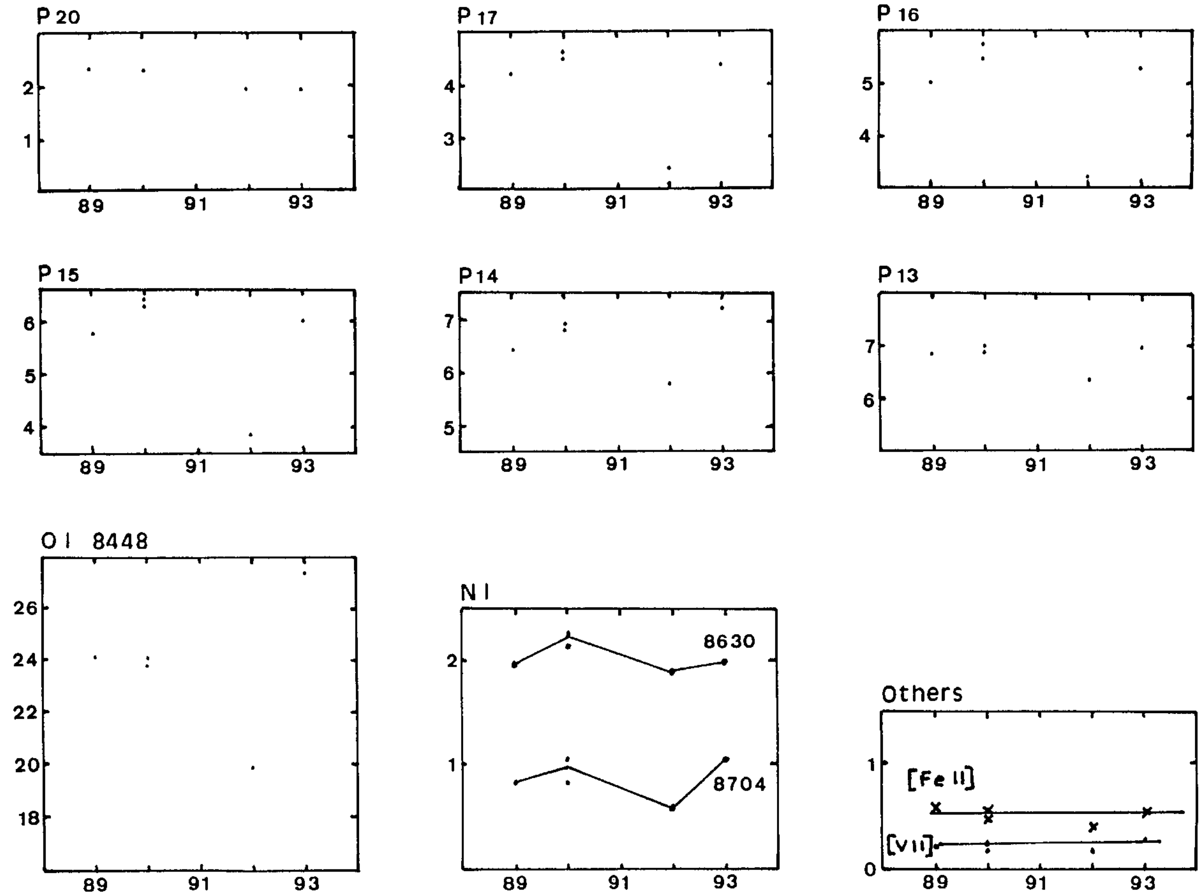

Fig. 3. Equivalent widths of different lines over the years. Abscissa: time in years Ordinate: Equivalent width in A. Please observe the scales, which differ according to the line

emission. We have already applied this procedure in the other papers of this series, because in the other stars we did not see any part of the underlying spectrum. Judging from the the ionization stage of the elements present, we can say that the spectum corresponds to a late A or early F type object, a fact which would place the temperature of the shell at about 7000 K. Assuming the photospheric temperature to be 22 000 K (Israelian et al. 1996), and a black-body model for the two entities one can calculate the radius of a star which would dominate at wavelengths beyond 4200 Å, which is what one observes. One comes out with a radius of about ten times the radius of a 22 000 degree K star, which would be the distance of the shell. This seems to be a reasonable order of magnitude. Observe however that we have supposed implicitely that the shell is spherical. Since probably the shell is restricted to the equatorial region, the distance of the shell should be less, in order to cover a sizable fraction of the stellar disc. Otherwise we should see the absorption line spectrum over all wavelengths.

8. Is HD 45677 a typical B[e] star?

We would like to add a last comment upon the group into which HD 45677 has been classified. It has usually been put either in the group of B[e] stars or in the group of Herbig Be-Ae stars. From the definitions of the groups (see Jaschek & Jaschek 1987), it is difficult to conclude that the object belongs clearly to either one of them. It has certainly many forbidden lines in emission, as required by B[e] stars, but contrary to other stars of the group, one perceives the photospheric spectrum of the underlying star. With regard to the membership in the group of Herbig Be-Ae stars, one of the original criteria was the existence of an associated nebulosity, which in HD 45677 is absent. It is thus not a Herbig Be-Ae star.

The fact that the three stars analysed in this series (MWC 51585, MWC 349A and MWC 645) do not show any absorption lines, whereas HD 45677 (as well as HD 50138) do show absorption lines, provides a clear indication of (at least) two subgroups of B [e] stars. Until many more stars of the group are analysed, it seems premature to call HD 45677 (or MWC 645) the typical B[e] star. Caution is thus be recommended and one should not

Table 4. Variations in equivalent width at different epochs

Part a

Lambda	Id	a/e	1991	1993
3933.7	Ca II 1	a	0.08	0.20
4009.3	He I 7^1D	a	0.39	0.26
26.2	He I 5^3D	a	0.87	0.81
68.6	[S II] 1	e	0.45	0.54
76.2	[S II] 1	e	0.06	0.06
4130.9	Si II 3	a	0.29	0.07
43.8	He I 6^1D	a	0.47	0.42
73.4	Fe II 27	e	0.06	0.06
78.9	Fe II*	e	0.30	0.31

Note * blend of [Fe II] 23 at 8.95+Fe II 28 at 8.86 a = absorption e = emission

Part b

Lambda	Id	1989	1990	1990	1992	1993
8374.5	P 21	p	2.03	p	1.52	1.40
92.4	P 20	2.29	2.27	2.31	1.92	1.91
8412.0	P 19	2.93	3.60	3.43	p	2.83
38.0	P 18	p	2.90	3.23	p	2.87
46.5	O I 4	24.22	23.82	24.10	17.87	27.34
67.3	P 17	4.15	4.60	4.50	2.30	4.35
90.4	Fe II J A	0.88	0.96	0.83	0.88	0.99
8502.5	P 16	5.01	5.74	5.47	3.07	5.26
45.4	P 15	5.74	6.44	6.30	3.82	6.00
67.7	N I 8	0.27	0.25	0.30	0.24	0.35
79.2	[V II] 11	0.23	0.16	0.23	0.18	0.27
98.4	P 14	6.45	6.80	6.92	5.78	7.24
8617.0	[Fe II] 13	0.57	0.50	0.53	0.41	0.53
29.2	N I 8	1.95	2.13	2.24	1.89	1.97
49.1	[Sc II] 1	p	0.14	0.21	0.19	0.26
55.9	N I 8	p	0.63	0.75	p	0.76
65.0	P 13	6.85	6.88	6.92	6.33	6.91
80.2	N I 1	4.06	3.53	4.36	3.46	4.33
83.4	N I 1	p	2.89	2.81	2.21	p
95.1	Fe II B	n	0.37	0.43	0.35	0.51
8703.2	N I 1	0.82	1.04	0.82	0.60	1.01
11.7	N I 1	0.86	0.87	0.67	0.73	0.97
18.8	N I 1	0.51	0.67	*	0.64	0.89
28.9	N I 1	p	0.18		0.10	0.30
50.5	P 12	6.63	7.05		5.23	7.67

Notes: All lines are emission lines.
p = present but difficulties with measurement because of blend
n = line absent
A = blend of two lines of Fe II
B = in eta Carinae
* plate ended here
All measured equivalent widths are given to two digits,for the sake of uniformity. Observe however that the precision is of the order of 10%.

apply whatever is known on this particular star to other B[e] stars.

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