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B[e] stars.
III. MWC 645*,**

M. Jaschek[1], Y. Andrillat[2] and C. Jaschek[1]

[1] Observatoire de Strasbourg, URA 1280, CNRS, 11 rue de l'Université, 67000 Strasbourg, France
[2] Laboratoire d'Astronomie Université de Montpellier 2, URA 1280 and 1981, CNRS, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France

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Abstract. — We analyse spectroscopic CCD material obtained at the Haute Provence Observatory. We provide identifications and equivalent width measurements in the wavelength region 3740-8790. About 350 emissions lines were measured and about 88 of them were identified. A comparison of our results with those of other authors is provided, as well as a table of elements identified in the spectrum of this star. The pattern of elements present is analogous to that of a late B-type star, but some exceptions are noted, such as the absence of Ne and Mg lines and the presence of K, Cu and Zr lines which appear usually in later type stars. We review the little which is known concerning this object and we also present a quantitative account of the variations in equivalent widths. The observations indicate that the spectrum is highly variable, so that in two different years only half of the lines appear on both spectra. Furthermore variations by at least a factor of two in the equivalent widths are present in many lines. The radial velocity derived from the emission lines (−76 km/s) corresponds to that of the shell which probably has a velocity of about 50 km/s with respect to the underlying star.

Key words: stars: emission line, Be — stars variable: others — stars: MWC 346A

1. Introduction

MWC 645 was discovered as a Be star by Merrill & Burwell (1943). The star was studied by Allen & Swings (1976), who classified it into their group 2 which characterizes stars having a rich emission line spectrum in which forbidden lines of low ionization potentials predominate. Their paper provides a line identification based upon a short spectral region (6000 to 7300). Further spectroscopic studies of this star were made by Andrillat & Swings (1976) who studied the infrared region and by Swings & Andrillat (1981) who measured the widths of some lines.

Photometrically, the star was studied by Gottlieb & Liller (1978) who found it to be variable from photographic plate measurements extending over the time interval 1892-1985. In this interval the stars varies around $13^{\mathrm{m}}1$ with an amplitude of 0.3 and a possible period of 23.6 years. At the beginning the star was brigther than it is now.

There exist also two $B-V$ values which differ considerably: 0.86 (Craine & Tapia 1975) and 1.25 (Swings 1981).

The purpose of the present paper as well as that of the other papers of this series is to provide measurements of wavelengths and equivalent widths over an extended wavelength region, in order to carry out a line identification. Since our material was obtained at different epochs, we can also discuss quantitatively line variations, if these exist.

2. Material

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

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

Send offprint requests to: Y. Andrillat
*Based on observations obtained at the Haute Provence Observatory (CNRS)
**Table 2 only available in electronic form at CDS via ftp 130.79.128.5

From 1991 to 1993 the receiver was a CCD Thomson with 576×384 pixels, with 23 micron square pixels, providing a resolving power of about 1 Å. After 1993 the receiver used was a CCD TK 512, with 512×512 pixels, 27 micron square pixels 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 of 300 microns, corresponding to 2″ on the sky.

Table 1. Observational data

Date	Wavelength	Code
22-06-95	3741-4195	i
22-06-95	4138-4592	j
25-10-91	4286-4725	a
25-07-93	4554-5006	b
25-10-91	4697-5137	c
20-06-95	6332-6780	d
18-06-94	7008-7450	e
18-08-91	7590-8014	f
23-07-93	7983-8420	g
17-08-91	8370-8790	h

Date: day-month-year(-1900)

Wavelength region indicated in Angstroem

Code-internal code used in tables 2 and 4.

The data were reduced with the software package IHAP, developed at ESO and installed at the OHP. As remarked above, our 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%.

3. Line identifications

These were made in the classical way, paying attention to both wavelength coincidences and intensities within the multiplets. The complete list of the line identifications is given in Table 2. Our observations extend over an interval of five years, and we hoped that in the absence of variations these regions could be spliced together. It turned out however that the overlapping wavelength regions have different lines. We decided therefore to organize Table 2 not by increasing wavelength, but rather according to the year of observation.

We have measured a total of 348 emission lines and were able to identify 88% of the lines, which is rather similar to the percentage achieved in the two stars analysed before, HD 51585 (Jaschek et al. 1996) and MWC 349 (Andrillat et al. 1996) where these percentages were respectively 85 and 89%.

The identifications were made with the help of the Moore (1959) table, complemented for Fe II by Johansson (1978). A few lines were taken from other work, for instance from Meinel et al. (1969). We have not observed any stellar absorption features which would have permitted to classify the underlying star. From the emission line spectrum one can conclude that MWC 645 must be a B-type object.

With respect to interstellar features, we observe two diffuse absorption bands, 8621 and 4428. The latter is partially masked by the superimposed emission lines.

Parts of the spectrum are reproduced in Figs. 1 and 2.

4. Elements present

Using the identification made in Table 2, we shall discuss the elements present in the star, ordered by atomic number.

Hydrogen. We have observed on our material Balmer lines in emission from H12 to H4, the lower limit being fixed by the absence of spectra reaching into the ultraviolet beyond 3749 Å. Paschen lines were observed in emission from P23 to P12. The wavelength limit of our material does not permit to detect Paschen lines with $n < 12$. The equivalent widths in both series show a regular progression with n. We notice however that H9 and H10 are weaker than their neighbours, although the spectrum is very noisy. The emissions are narrow and do not present double peaked profiles, with the exceptions discussed below.

In 1991, the H5 line is intense ($W = 45$ Å) and is clearly double, with a peak separation of 170 km/s and $V < R$. H4 is strong ($W = 223$ Å) and has a double structure with $V < R$.

In 1993 the H4 line is very intense (W =199 Å) and has no double structure. At the continuum level, the line is about 2 000 km/s wide, approximately the same value as in 1991. In 1995, H5 is strong (W= 81 Å), doubling almost the equivalent width observed in 1991 and exhibits on the short side an absorption line (P Cyg profile). The distance between the absorption and the emission peaks is of about 800 km/s.

The H3 line is very strong (W = 1910 Å) and has a double structure with $V < R$ and a peak separation of 200 km/s. The width at the continuum level is of about 4 500 km/s.

We can compare our H3 observation with the line profiles observed by Swings & Andrillat (1981) at two dates in 1981. Those authors find a narrow and a wide structure of about 150 and 300 km/s FWHM (with sligth variations between both dates) plus wings extending over about 3 000 km/s. Since in 1995 the wings are about 4 500 km/s wide, but are difficult to measure, we take this to indicate simply that H3 in 1995 is stronger than in 1991.

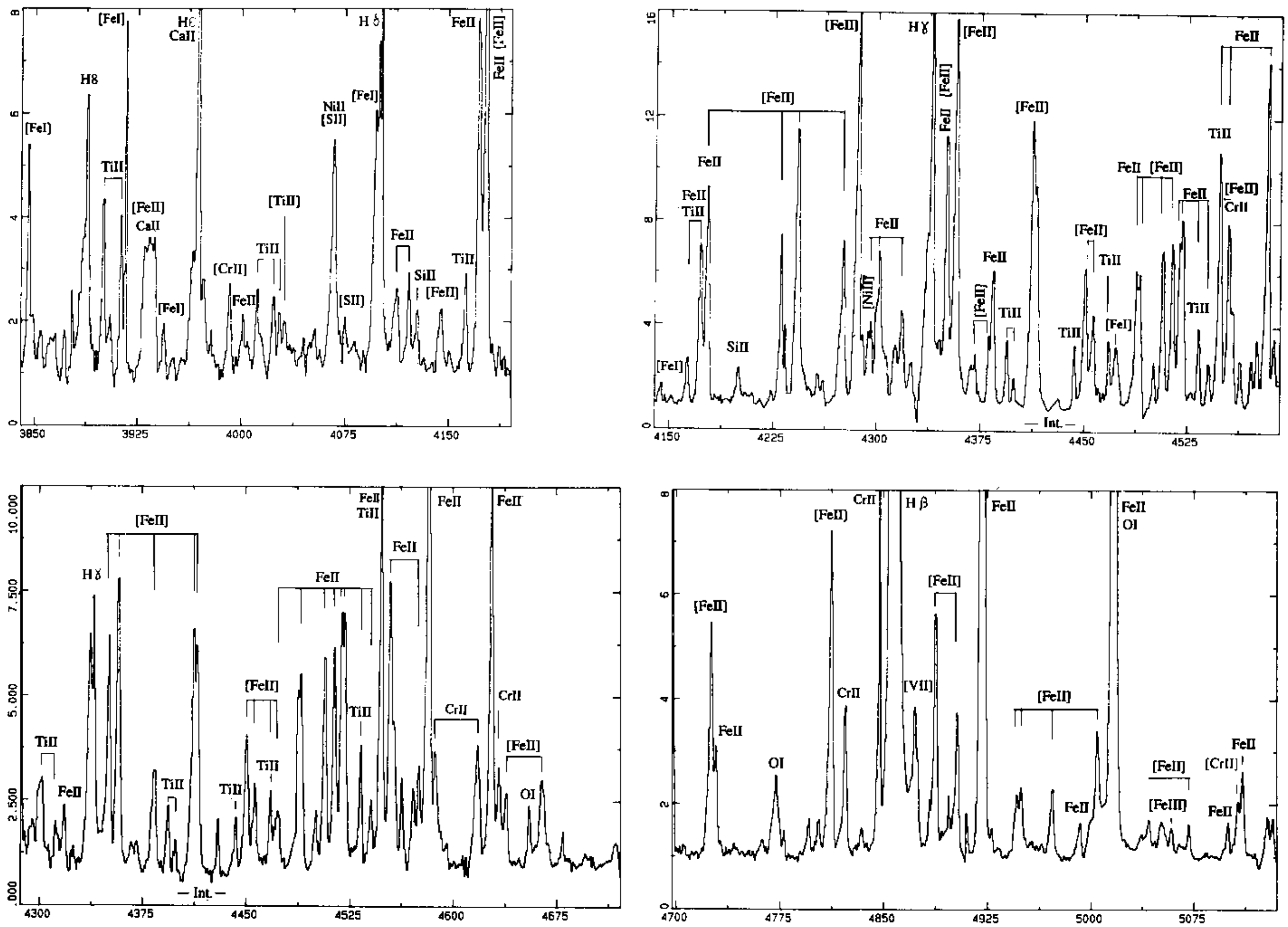

Fig. 1. Comparison between spectra from 1991 and 1995. On top, on the left spectrum $i(1995)$, on the rigth side spectrum $j(1995)$. At bottom, on the left spectrum $a(1991)$, on the rigth side spectrum $c(1991)$. Compare the profiles of H5 in 1991 and 1995

The two spectra of Swings and Andrillat, taken at five months interval suggest changes in the profile of H3. As mentioned above, on our material, H5 in 1991 had an equivalent width (W) of 45 Å, whereas in 1995 the value was 81 Å. On the other hand H4 had about the same W in both 1991 and 1993. The Paschen line 19 (Table 4, part 1) confirms this. The Paschen line 20 differs by a factor of about two, but the continuum is difficult to determine since the line is at the end of spectrum. We disregard therefore this measurement.

Hydrogen seems thus to be rather strongly variable, but we ignore if the changes occur from nigth to nigth or over a longer time scale.

Helium. The evidence for neutral He is weak and rests on the presence in 1995 of the $\lambda6678$ (^{1}D) line, with W= 0.93 Å. We notice that the line was not visible on the spectra taken by Swings & Andrillat (1981). In 1994 $\lambda7065$ (^{3}S), W=0.54, is perhaps present. No evidence exists for ionized He. The absence of ionized helium and the weakness of the neutral helium lines suggest that the spectrum corresponds to a late B-type object.

Carbon. This element is present only once, in 1995, represented by one weak line from ionized carbon, M.2. ($\lambda6582$).

Nitrogen. Neutral nitrogen is present at all epochs, except 1994, but the region covered that year does not include strong nitrogen lines. In 1991 lines from M.1 and 8 were present; in 1993, from M.2 and in 1995, from M.23.

Oxygen. Neutral oxygen is present in 1991 (M.1, 4, 13, 16, 18 and 19), in 1993 (M.14, 16 and 18) and in 1994 (M.20). In 1995 we do not observe O I but the region covered does not include strong lines of O I. Instead we observe the strong 6363 line of [O I].

Silicon. Ionized silicon is seen in 1995, represented by lines from M.1 and 13, as well as the high excitation line 4200.

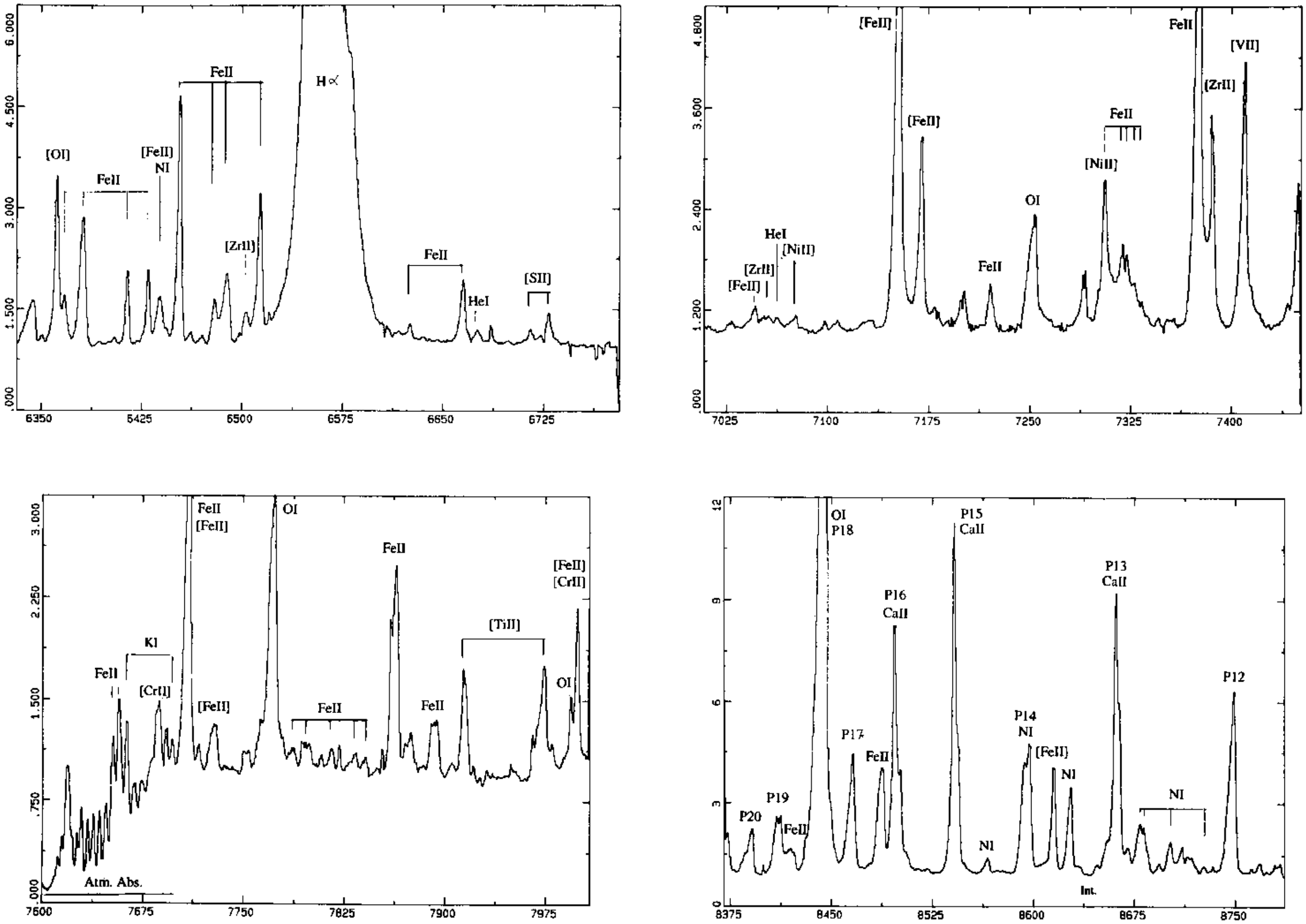

Fig. 2. On top, on the left side spectrum $d(1995)$, on the right side spectrum $e(1994)$. At bottom, on the left side spectrum $f(1995)$, on the right side spectrum $h(1991)$

Sulphur. Ionized sulphur is present in 1991 (M.12) and 1993 (M.68). In 1995 we observe lines from M.44 and also two lines from M.1 and 2 of [S II].

Potassium. Two lines from M.1 of K I are observed in 1991. This region is not covered in the other years.

Calcium. Ionized calcium is present in 1991 (M.2) and 1995 (M.1). No strong Ca II lines exist in the regions covered in the other two years.

Titanium. We observe many Ti II lines in the three epochs. In 1991 we see lines from M.19, 31, 41, 50, 51, 59, 82, 86 and 92; in 1993, from M.50 and 82 and in 1995 from M.11, 13, 19, 31, 34, 41, 50, 51, 82, 87 and 105. One observes also lines from [Ti II]: in 1991 from M.6, in 1993 from M.7 and 23 an d in 1995 from M.11.

Vanadium. One line from ionized vanadium is present in 1995 (M.10), whereas one observes several lines of [V II] at different dates. In 1991 one line from M.8, in 1993 from M.7 and 8, and in 1994 one line from M.4.

Chromium. Lines from ionized chromium are present at three epochs. We find in 1991 and 1993 lines from M.30, 44 and 130, and in 1995 from M.44 and 130. Lines of [Cr II] are also present in the three epochs. In 1991 from M.1, 11 and 14; in 1993 from M.1 and 20 and in 1995 from M.4.

Iron. Iron lines make up for about 53% of all identified lines and are found in all four years.

Neutral iron is present only in 1995. It is represented by several lines from M.20, 42 and 43. That year we observe also lines from [Fe I], M. 6, 7 , 8 and 9. It should be noed that the [Fe I] lines are considerably stronger than those of Fe I.

Ionized iron is present with many lines from many multiplets in all four years. In 1991, from M.36, 37, 38, 42,43, 73 and 220. In 1993 from M.17, 36, 37, 38, 42, 43 and 54; in 1994 from M.73 and 209 and in 1995 from M.14, 27, 28, 29, 37, 38, 40, 74, 153, 154, 199, 210 and 220. Besides this there exist many lines listed by Johansson, but which are not identified by multiplet numbers.

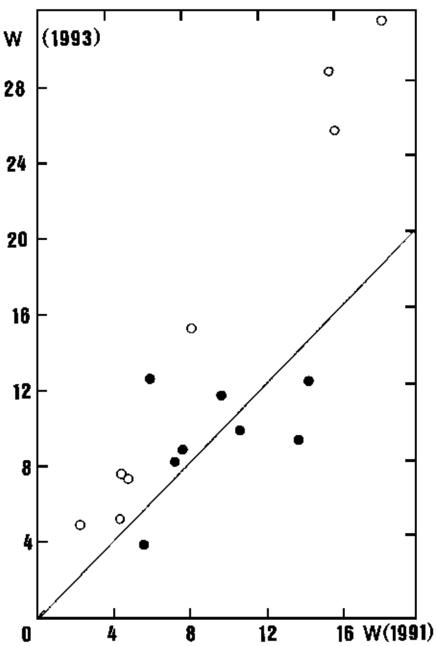

Fig. 3. Equivalent widths in 1991 versus 1993. Points for permitted lines, circles for forbidden lines

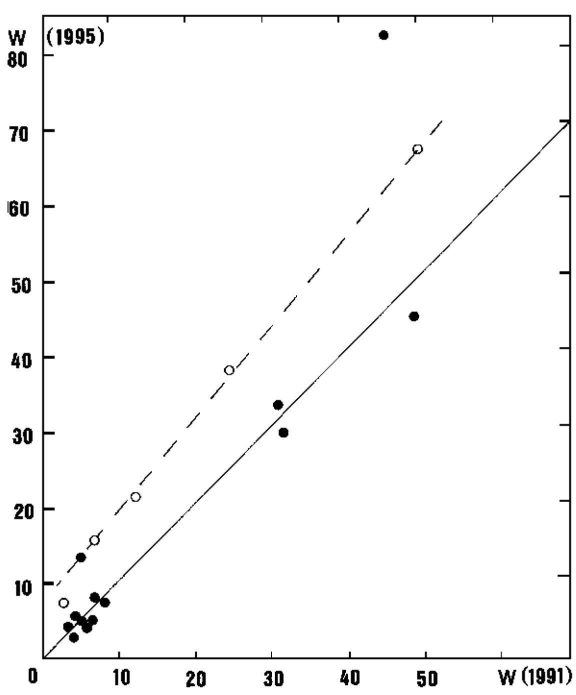

Fig. 4. Equivalent widths in 1991 versus 1995. Points for permitted lines, circles for forbidden lines. The full and the dashed line represent the average relation for permitted and forbidden lines. Notice that the H line falls outside the mean relation. for the permitted lines

Forbidden ionized iron is also present at all times. In 1991 we find lines from M.1, 3, 4, 5, 6, 7, 13, 19, 20, 21, 30, 36, and 42 In 1993 from M.1, 3, 4, 20, 29 and 30; in 1994 from M.14 and 31 and in 1995 from M.6, 7, 8, 9, 15, 21, 23 and 36. Doubly ionized iron is observed only once, namely in 1991 by the line 5060 from M.1.

Nickel. Ionized nickel is present in 1995 with lines from M.11. [Ni II] is present each year with one or two lines. In l991, from M.7; in 1993, from M.2, 7; in 1994, from M.7 and 8 and in 1995 by lines from M.3 and 4.

Copper. Ionized copper is represented by an emisson line at 3806 A, M.2 of [Cu II] is present in 1995. Since only one line is observed we regard the evidence as marginal.

Zirconium. This is so far the heaviest element detected. It is represented by two lines from M.3 and 5 of [Zr II] in 1994 and by one line from M.17 in 1995

5. Comparison with other work

We have collected in Table 3 the elements found in this star by other authors. The region covered by Allen & Swings (1976) is part of the regions covered by our observations, whereas we have only a partial overlap with the region covered by Andrillat & Swings (1976). Whereas we coincide in the majority of the elements, there are some noticeable differences, in the sense that in 1976 apparently more forbidden lines of higher ionization potential were present, such as [N II], [S III] and [Ar III]. We could find no [Ar III] despite a careful search. From the other two elements we have no lines in our wavelength regions.

When we compare the elements present in this star with the elements present in HD 51585 (Jaschek et al. 1996) and MWC 349 (Andrillat et al. 1996) we find some remarkable differences. For instance we detect very weak helium in MWC 645, whereas in the other stars helium is rather strong. We do not find C (except one line on one occasion), Ne and Mg, and to the contrary we find K I and very probably Cu II (usually seen in stars later than F-type stars) and Zr II (usually seen in stars later than A0-type). The spectral types where these elements appear normally were taken from Jaschek & Jaschek (1995).

In summary it seems that at least at present the emission spectrum of MWC 645 corresponds to a late B-type object- in any case later than that of the other two stars previously studied in this series with the same type of material (HD 51585 and MWC 349 A). This agrees with the absence of elements with lines with higher ionization stages than the singly ionized one, if one excepts a single line of [Fe III] seen once.

6. Variability

We analyse next the line variability on the basis of the lines present in the zones common to spectra taken at different epochs.

If one compares the common stretches in 1991 and 1993 (see Fig. 3 and Table 4, part 1) one observes that in general the permitted lines of the elements remain about equal or that they weakened in 1993 with respect to 1991. On the contrary the forbidden lines have strengthened in 1993. One exception is O I 4773 which has also strengthened and another, the 4947 line of [Fe II] which has weakened.

A comparison of the 1991 and the 1995 data (see Fig. 4 and Table 4, part 2) shows the same effect. The forbidden elements also here have changed by factors up to two. A detailed examination of both zones confirms this. A further fact which speaks in favor of the variability is that in the overlapping region one finds 34 lines in 1991 and 39 in 1995, but only 18 lines have the same identifications. Thus about half of the lines have different identifications.

The same is found from a comparison between the Allen & Swings (1976) identifications with ours in the region 6364-6678 which shows that out of 20 lines they measured, only nine lines with the same identifications appear on our spectra.

If we combine this with what we said concerning the hydrogen lines, the conclusion is that this object is strongly variable over the years, like the two other stars examined in this series of papers (Papers I and II). We found in all three stars equivalent width variations of factors up to two. Due to a lack of data we can not ascertain the time scale of the variations, which migth well be daily, weekly or monthly.

7. Radial velocity

Despite the fact that our material is not well suited for a radial velocity determination, we have derived the velocities from the different spectra. Since large variations exist between spectra oberved on the same night, we prefer not to provide the results from the individual spectra, but rather the grand average, which is -76 ± 5 km/s. This is the velocity of the emission lines, which is probably rather different from the stars velocity, which we would expect to lie in the range -10 to -15 km/s if one assumes very roughly a heliocentric distance of 2$-$3 Kpc. What one is measuring is thus the velocity of the expanding shell which could be therefore of the order of 50 km/s, similar to what is known in MWC 349A.

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Table 3. Elements detected by different authors

Element	This paper 1991	1993	1995		Other papers AS	AIS
H	I	I	I		I	-
He			(I)&		I	
C			II			
N	I	I	I		I?	
						[N II]*
O	I	I	&		I	
			[I]			[I]?
Si			II			II
S	II	II	II			
			[II]		[II]	
					[III]	
Ar						[III]
K	I					
Ca	II		II	II	II	
Ti	II	II	II			
	[II]	[II]	[II]&			
V			II			
	[II]	[II]	&			
Cr	II	II	II			
	[II]	[II]	[II]			
Fe			I			
			[I]			
	II	II	II&		II	II
	[II]	[II]	[II]&			[II]
	[III]				[III]	
Ni			II			
	[II]	[II]	[II]&			[II]?
Cu						
	[II]					
Zr						
			[II]&			

AS = Andrillat and Swings(1976) range 8000 -11200 A, dispersion 230 A/mm

AIS = Allen and Swings (1976) range 6000 - 7300 A, dispersion 30 A/mm

& also observed in 1994

Table 4. Zones in common of different spectra

Part 1. Regions in common in 1991 and 1993

Spectra a and b.

	W(1991)	W(1993)	Identification
4563.76	5.64	3.86	Ti II 50
76.33	7.87	8.46	Fe II 38
4618.83	14.33	12.26	Cr II 44
34.11	9.78	11.53	Cr II 44

Spectra c and b

	W(1991)	W(1993)	Identification
4728.07	15.30	32.57	[Fe II] 4
73.76	5.98	12.46	O I 16 at 2.54+2.89+3.76
98.28	2.13	4.80	[Fe II] 4 at 8.28+9.31
4814.55	18.38	35.15	[Fe II] 20
24.13	7.20	8.12	Cr II 30
48.24	13.93	9.24	Cr II 30
61.32	222.72	199.10	H 4
89.68	15.71	25.23	[Fe II] 4 at 9.63+[Fe II] 3 at 9.70
4905.35	8.29	15.08	[Fe II] 20
47.38	4.07	5.00	[Fe II] 20
50.74	4.57	7.48	[Fe II] 20
73.39	4.86	7.15	[Fe II] 20

Spectra h and g

	W(1991)	W(1993)	Identifications
8392.40	5.38	2.32:	P 20
8413.32	10.74	9.81	P 19

Part 2. The regions common in 1991 and 1995.

Spectra a and j

	W(1991)	W(1995)	Identification
4318 96	5.38	13.88	Fe II 220
40 47	45.31+p	81.37+p	H I
51.42(a)	25.17		[Fe II] 36 at 1.05+[Fe II]1.80
51.64(j)		38.0	[Fe II] 36 at 1.05 +[Fe II] at 1.80+Fe II 27 at 1.76
72.43	3.25	7.29	[Fe II] 21
99.77	4.01	3.11	Ti II 51
4413.78(j)		67.29+f	[Fe II] 7
14.45(a)	45.97+f		[Fe II] 6
43.80	4.48	5.95	Ti II 19
52.11	12.30	20.71	[Fe II] 7
57.95	7.10	15.99	[Fe II] 6
4501.27	3.83	4.03	Ti II 31
20.22	31.43	33.43	Fe II 37
34.07	8.59	7.61	Fe II 37 at 4.17+ Ti II 50 at 3.97
41.52	5.54	4.86	Fe II 38
49.54	32.03	29.70	Fe II 38 at 9.47+Ti II 82 at 9.62
63.76	5.64	4.20	Ti II 50
71.97(a)	6.80		Ti II 82
72.60		4.80	Ti II 82 +[Fe I] 6 at 3.23
76.33	7.87	8.00	Fe II 38
83.33	49.37	44.7	Fe II 37 at 2.83+ Fe II 38 at 3.83