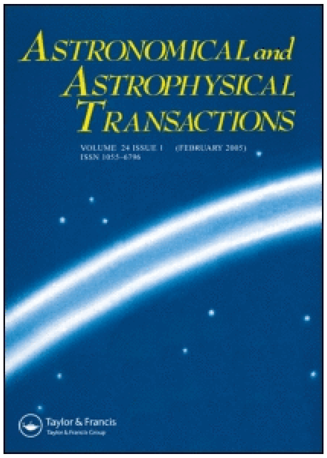

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 January 1995
To cite this Article: Miroshnichenko, A. S. (1995) 'New possible binaries among B[e] stars', Astronomical & Astrophysical Transactions, 6:4, 251 - 263
To link to this article: DOI: 10.1080/10556799508232071
URL: http://dx.doi.org/10.1080/10556799508232071

Astronomical and Astrophysical Transactions, 1995,
Vol. 6, pp. 251–263
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NEW POSSIBLE BINARIES AMONG B[e] STARS

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(Received November 22, 1993)

The majority of B[e] stars are probably Post-Main-Sequence objects with circumstellar dust shells. Their complicated spectral energy distributions (SED) and line spectra make the determination of the object composition very difficult. We present here the results of new photometric and spectral observations of the B[e] star MWC 84 and MWC 930, similar to B[e]-s, and show that they are possible binaries. It is shown that MWC 84 consist of two stars with spectral types approximately KO II and BO V, a strong gas envelope, and a dust shell with the optical depth about 0.1; MWC 930 probably consists of KO I and BO V stars, a gas envelope, and no circumstellar dust. An analysis of Balmer decrements for different emission-line objects is presented.

KEY WORDS Emission-line stars, circumstellar matter, binary systems

1 INTRODUCTION

Having distinguished Be stars by a strong IR excess, Allen and Swings (1976) have noted that objects of different masses and of different evolutionary status may occur among them. They divided 65 selected objects into three groups and suggested that the first one with the smallest IR excesses contains generally Be stars with more extended gas envelopes than that of classical Be-s, the third group objects with high excitation emissions were mainly planetary nebulae (PN). Finally, it was difficult to make suggestions about the nature of the second group objects showing numerous Fe II, [Fe II] and [O I] emissions because they were poorly studied. In connection with this inhomogeneity, B[e] stars have been never investigated as a separate group.

In early 80's, the objects very similar to those of the second group of B[e]-s were discovered in the Magellanic Clouds (Zickgraf *et al.*, 1986). They were recognized as early-type supergiants of high masses with strong stellar winds and dust shells. There are some evidences that several galactic B[e] stars (MWC 300, CPD–52°9243 – Winkler and Wolf, 1989) have the same evolutionary status. Another suggestion about the nature and the current status of B[e]-s was recently considered by Zickgraf and Shulte-Ladbeck (1989). They suppose B[e]-s to be one of early stages of PN evolution or extreme Be stars. Hack (1991) has pointed out during the discussion at the International Colloquium "The Infrared Spectral Region of Stars" that B[e]-s may be Herbig Ae/Be stars or binary systems with circumstellar shells.

Detailed studies of individual stars of this type have shown that some objects belonging to different groups mentioned above were binary systems. These are symbiotic stars RX Pup, BI Cru (Allen, 1984), KM Vel = He2–34 (Whitelock, 1987); Beta Lyr-type systems RY Sct (Cowley and Hutchings, 1976) and GG Car (Chen *et al.*, 1983). Recently some evidences of the binarity were obtained for 3 Pup (Plets, 1994), MWC 623 (Zickgraf and Stahl, 1989), XX Oph (Lockwood *et al.*, 1975), MWC 342 (Miroshnichenko, 1991). Another B[e] star, MWC 17, is a suspected symbiotic system (Martel and Gravina, 1985). In this paper we report the results of observations of the second group B[e] star MWC 84 and of the object MWC 930 which does not belong to the original B[e]-s' list but has many features similar to theirs. An analysis of the data obtained leads us to several evidences of the binarity of these systems.

2 INITIAL DATA FOR THE STARS STUDIED

MWC 84. This is a $11^{m}_{.}5$ star situated in Camelopardalis at R.A. = $4^{h}15^{m}39^{s}$ and Dec. = $+55°52'45''$ (1950). It shows strong emissions of HI, He I, and numerous Fe II lines. The first quantitative study of its spectrum was fulfilled by Chkhikvadze (1970). He obtained 10 spectrograms with the dispersion of 166 Å/mm near H_γ and estimated its spectral class as 06–BO from the Balmer line characteristics. The value of $A_v = 1^{m}_{.}5$ was determined from the spectral energy distribution (SED) in the continuum. The distance $D = 1$ kpc was estimated from the relationship between A_v and D around the object. Using these data, the value of $M_v = 0^{m}_{.}5$ was obtained. The latter does not agree with modern calibrations. Strajzhys and Kurilene (1981) give $M_v = -3^{m}_{.}1$ even for a BO ZAMS star. Downes (1984) obtained the 4000–7000 Å spectrum of MWC 84. He compared it with that of XX Oph and MWC 314 = BD+14°3887 noting the difference in the intensities of He I emissions in their spectra. MWC 84 has the strongest He I lines among them. Arguing with Allen (1973) who suggested that we see the continuum of a late-type star in the near IR of XX Oph and MWC 314, but MWC 84 demonstrates a circumstellar dust radiation, Downes considered this difference as a consequence of the stellar temperature difference in these objects, and hence, while the secondaries in MWC 314 and MWC 84 have not been detected, their evolutionary status remained unknown. Miroshnichenko and Gubochkin (1992) have shown that MWC 314 is a single BO-supergiant with a strong gas envelope very similar to that of P Cyg-type stars or LBVs.

MWC 930. The star of V $\sim 12^{m}_{.}5$ is situated in Scutum at R.A. = $18^{h}23^{m}43^{s}$ and Dec. = $-7°15'07''$ (1950). It has an emission-line spectrum of low excitation with dominant hydrogen and Fe II lines. The photometry has been obtained only in the IR-region (Allen and Glass, 1975; Gezari *et al.*, 1987). The objective prism spectrum was classified as B8e (Sanduleak and Stephenson, 1973) or OB (Maehara, 1982). Allen (1975) analyzing the information about the star has pointed out that MWC 930 can be a composite system or a reddened Be star. IRAS observations have shown a strong excess at 60 μm. Optical photometry and spectra in the 10–20 μm range have not been published for both stars.

The author (Miroshnichenko, 1992) has published preliminary results of the study of this object without any detailed analysis of his observations. The conclusion was that MWC 930 is a hot high-luminous star with a strong stellar wind and cool dust in its environments. We show here the importance of a careful investigation of such a complex system.

3 OBSERVATIONS

The photometric UBVRIJHK observations were carried out at the 1-m telescope of the Astrophysical Institute of the Kazakhstan Academy of Sciences (Assy Observatory) with a two-channel photometer-polarimeter (Bergner *et al.*, 1988) in 1989–1992 (diaphragm 26″). BS 1313 was used as a comparison star for MWC 84 and BS 6892, for MWC 930. We have obtained 25 UBVRIJHK and 25 UBVRI observations for MWC 84, and 12 BVRIJHK observations for MWC 930. Ninety UBVR observations of MWC 930 were obtained at the Astronomical Institute of the Uzbekistan Academy of Sciences using the 60-cm telescope at the Mt. Maidanak (diaphragm 13″) in 1990 (the photometry in the U-band was not obtained every time). The original photometric data will be published separately.

The spectral observations of MWC 84 were fulfilled by V. A. Lipovetsky in September and October 1986 and in April and December 1987 at the 6-m telescope of the Special Astrophysical Observatory in the Northern Caucasus with a photoelectric scanner in the range of 4000–7400 Å and dispersions of 25 and 50 Å/mm. The observations of MWC 930 were obtained by the author in July 1989 and July 1991 with the same equipment and dispersions of 50 and 100 Å/mm. Eight spectra of MWC 84 and three spectra of MWC 930 were obtained.

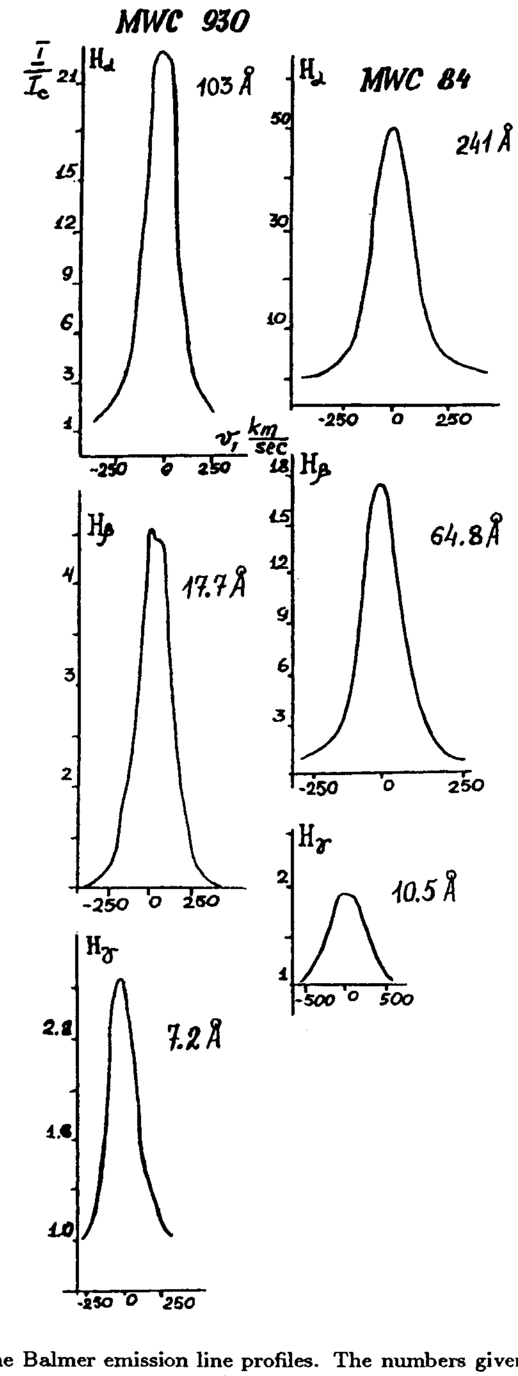
4 OBSERVATIONAL FEATURES

a) Spectra

The main features of the optical spectra of both objects are Balmer emission lines. They show symmetrical profiles with equivalent widths indicated in Figure 1.

Strong He I emissions and weak but numerous Fe II lines are seen in the spectrum of MWC 84 (Figure 2). Besides, we have detected C II emissions at 4267 and 7234 Å. MWC 930, on the contrary, has strong Fe II lines and weak He I emissions. The Balmer decrements ($H_\alpha : H_\beta : H_\gamma$) are 1 : 0.17 : 0.033 for MWC 84 and 1 : 0.05 : 0.0047 for MWC 930. He II lines were not detected in the spectra of both objects.

Since the emission parts of the objects' spectra are strong, it is difficult to detect absorption lines. However, we have found them for both stars. Their identifications



gure 1 The Balmer emission line profiles. The numbers given near the profiles are the line uivalent widths.

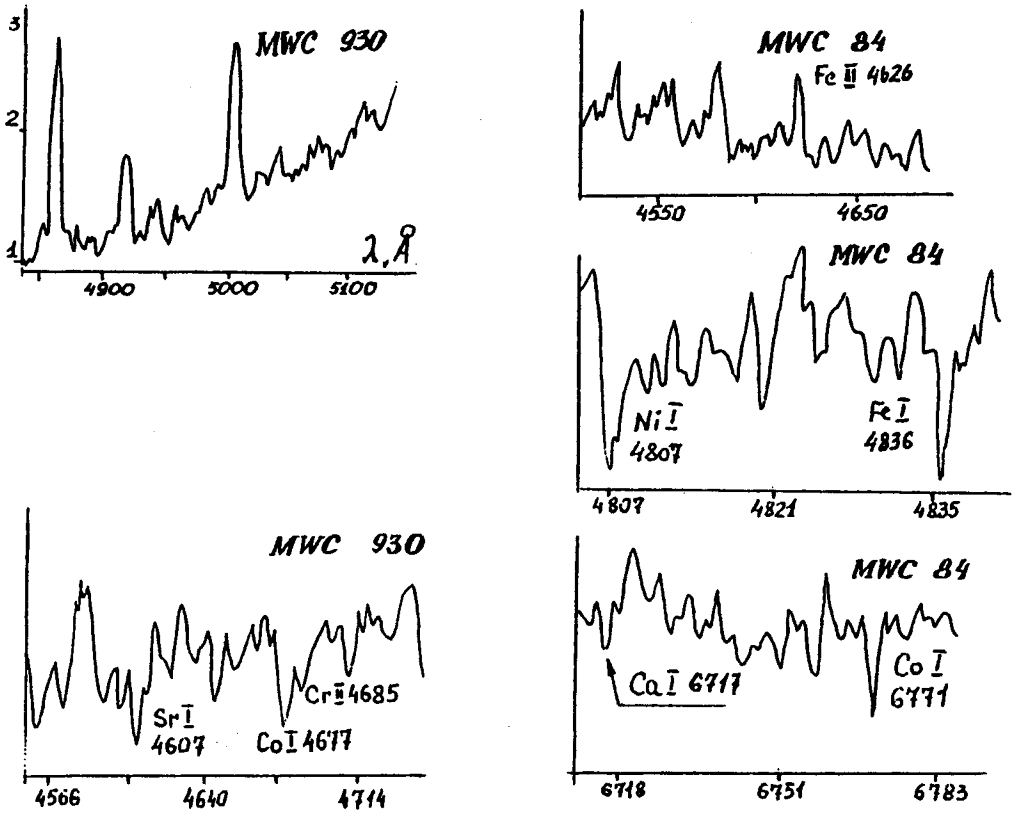


Figure 2 Portions of the objects' spectra containing Fe II emission lines and absorptions.

are presented in Table 1 and in Figure 2. All of these absorptions are usually observed in the spectra of late-type stars. In both cases, they are narrower than emissions arising in the circumstellar envelope. Hence, one can suppose that they belong to stellar photospheres.

b) Photometry

Our observations have shown that both objects have photometric variations (Table 2), but the mean brightness level for them remained the same over all the period of observations.

An analysis of the Maidanak observations, obtained during a not so long period (115^d) but for almost every night, have demonstrated a regular character of the MWC 930 variability. We have investigated its light curves using Deeming's (1975) technique and have determined the following values of the periods: $58^d.4, 29^d.2$ and

Table 1. The absorption lines in the spectra of MWC 84 and MWC 930

MWC	λ, Å	*Ident.*	λ, Å	*Ident.*
84	4807.0	Ni I 4807.0	4835.2	Fe I 4835.9
	4946.4	Fe I 4946.4	4951.3	Fe I 4950.1
	6716.8	Ca I 6717.7	6771.0	Co I 6771.0
930	4608.9	Sr I 4607.3	5583.0	Ca I 5582.0
	4677.4	Co I 4677.5	4684.9	Cr II 4684.8

Table 2. The characteristics of the variability of MWC 84 and MWC 930

Object	*U*	*B*	*V*	*R*	*I*	*J*	*H*	*K*
MWC 84	12.05	12.49	11.62	10.59	9.73	7.64	6.25	4.99
	0.68	0.35	0.32	0.22	0.41	0.64	0.34	0.27
MWC 930	16.54	15.25	12.51	9.99	8.31	6.75	5.85	5.33
	2.54	0.92	0.20	0.45	0.29	0.46	0.58	0.31

Note. The mean magnitudes in Johnson bands are listed in the first lines for each object. The amplitudes of the variability are presented in the second lines.

$26^{\mathrm{d}}.3$ in the R, V and B bands, respectively. The difference in the period for the B and V bands is probably due to the effect of an irregular part of the variability and observational errors ($0^{\mathrm{m}}.02 - 0^{\mathrm{m}}.03$), and is not significant. The amplitude of the regular variations does not exceed $0^{\mathrm{m}}.1$ in the V and R bands, and $0^{\mathrm{m}}.4$ in the B band (Figure 3). It is seen that deep and shallow minima follow one after another. The comparison of the variations in the B and R bands has shown that the minima of different types are anticorrelated in them. We note that the star is weak in the U band, and the errors there are about $0^{\mathrm{m}}.1 - 0^{\mathrm{m}}.2$. The variability pattern was not studied in this band due to a small number of the available observations. The strongest amplitude in this band may be due, in part, to weather conditions.

In spite of a rather small number of the MWC 84 observations, the Deeming analysis of them shows the presence of a regular variability with the period of $11^{\mathrm{d}}.7$ and the amplitude of $\sim 0^{\mathrm{m}}.3$ in the B and V bands, and $\sim 0^{\mathrm{m}}.2$ in the K band (Figure 4). The anticorrelation between the changes in the visual and the IR is observed. (V–R) increases and (R–I) decreases with the decrease in the V band. Phase pictures in the U, J and H bands are less clear. In the IR, it is probably due to a small signal-to-noise ratio (~ 10) and the change between the correlation and the anticorrelation. In the UV, it is due to a strong influence of the gas envelope. The irregular part of the variability has the amplitude of 1.5 times less than of the regular one.

On the whole, the changes in the color-indices are rather small for both objects, and the near IR brightness is very close to that observed almost 20 years ago.

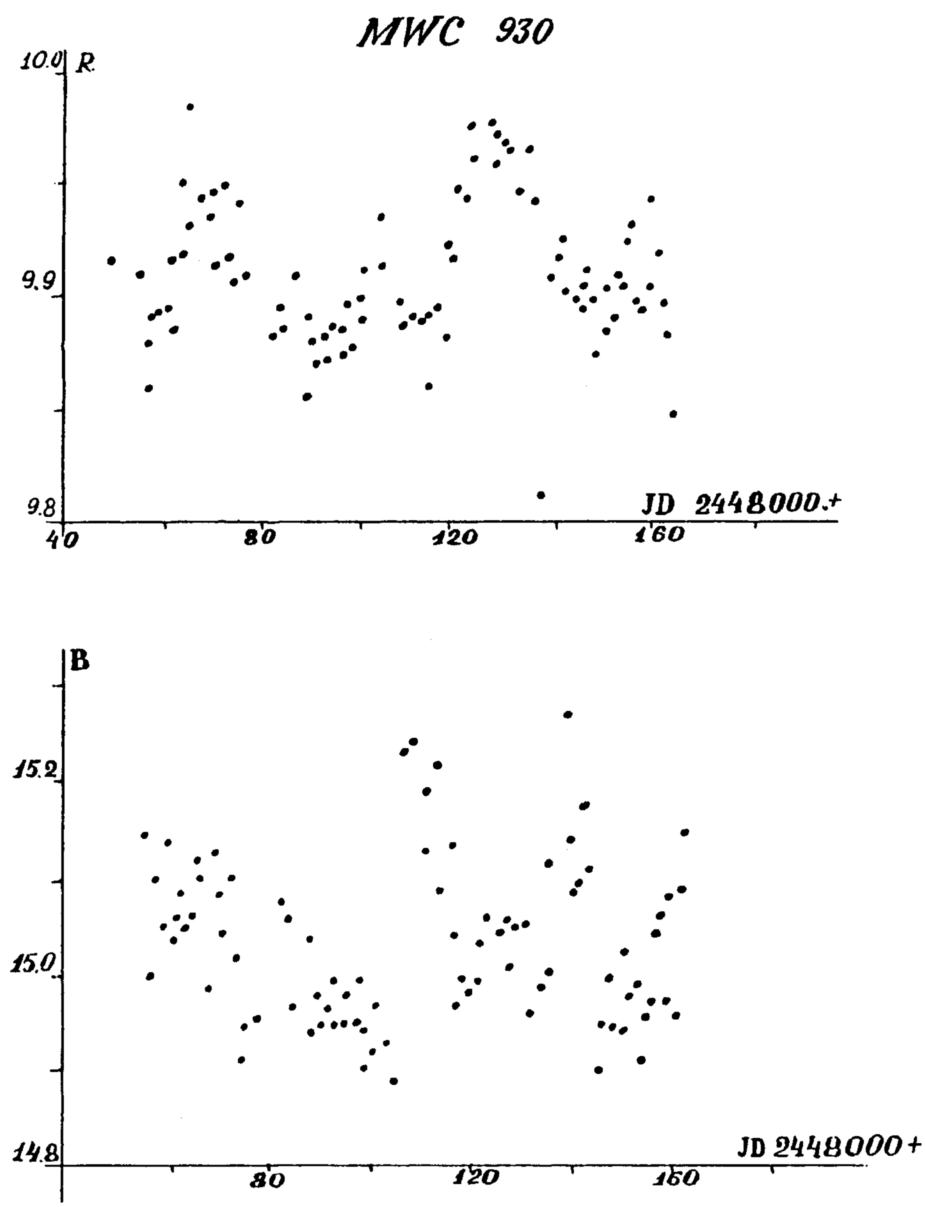


Figure 3 The light curves of MWC 930 in the B and R bands.

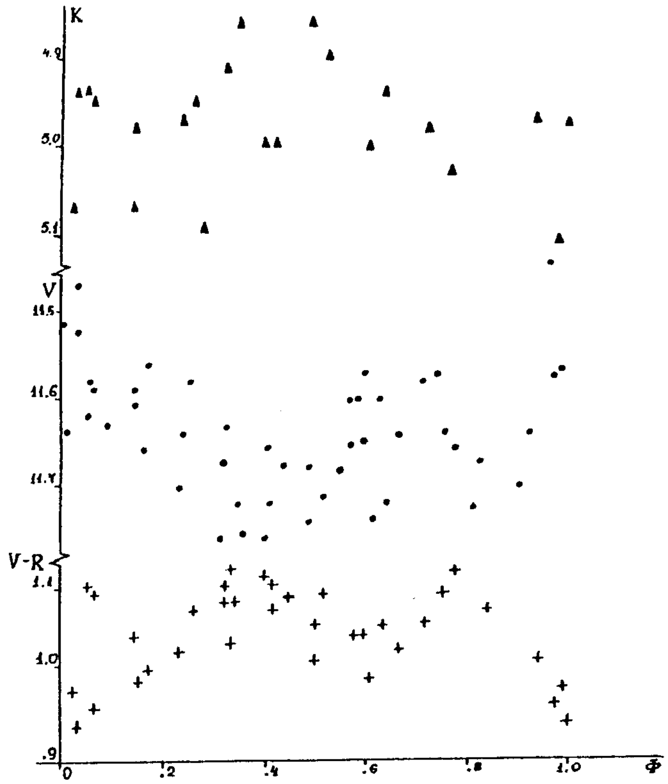


Figure 4 The phase curves for MWC 84 in V and K bands, and the (V–R) color-index. The period of the variability is $11^{d}.7$.

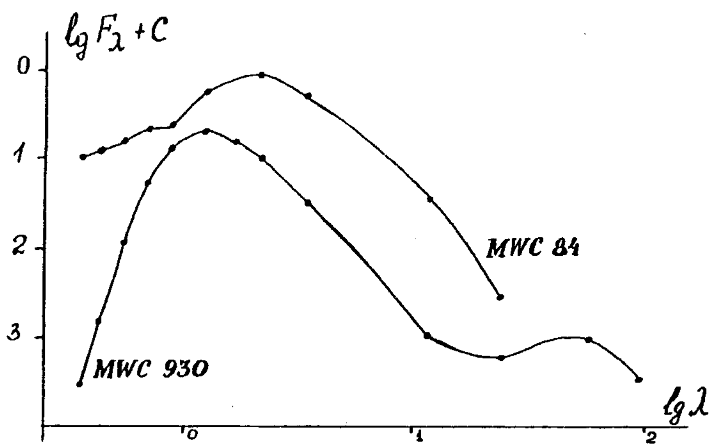


Figure 5 The mean SEDs for MWC 84 and MWC 930 in arbitrary units; λ, μm.

Using our results and previously published data, we have constructed the mean SEDs (Figure 5). We discuss them in the next section.

5 DISCUSSION

Let us summarize the data obtained for the objects. A strong emission spectrum of both objects tells us about the presence of hot underlying stars with strong stellar winds. The presence of He I emissions suggests that their spectral types are not later than B2, the absence of He II emissions indicates that they are not earlier than 08. All the absorptions detected in the spectra are typical of late-type stars. The absence of molecular absorption bands shows that the spectral types of possible secondaries are not later than MO. The influence of a hot star and gas emission in both continuum and lines does not allow us to estimate the temperatures of the cool companions more precisely.

The periodic changes detected may also be the evidences of the binarity of these objects. But rather a small number of the observed cycles (two in each case) makes ambiguous this explanation of such a variability. The influence and the changes of a gas envelope make the observational picture even more complicated.

The SEDs in the IR indicate that the objects are surrounded by circumstellar dust. The dust near MWC 84 is hot. This object is located in a region of cool stars with optically thin dust shells on the diagram of the IRAS color-indices. We note that many single hot stars with dust shells (Herbig Ae/Be, majority of B[e]-s, PN) have the fluxes at 12 μm not larger than those at 25 μm. $F_\nu(12)/F_\nu(25) > 1$ are observed in cool stars, symbiotic stars, and B[e] binaries like 3 Pup, MWC 17, KM Vel, RY Sct and MWC 623. In MWC 84, this ratio is too large (~ 3) for a B[e] star. The IR excess of MWC 930 in the 1–3.5 μm range may be explained by the influence of the interstellar extinction together with a circumstellar gas radiation or that of the cool companion. But at the IRAS wavelengths it demonstrates the presence of a cool dust. It is similar to SEDs of some LBVs or proto-PN.

Since both systems have a complex structure, i.e., several components contribute to the energy emission and absorption processes in them, a conclusion on their real composition is difficult to obtain from the SED analysis alone. Let us analyze the objects' SEDs in the framework of the model of a single star and a binary system with gas and dust shells. To model them, we have used the method described by Bergner *et al.* (1990) for the calculation of the individual component contributions to the total emission. The SEDs of central stars were taken from Strajzhys (1977) and Koorneeff (1983) in the form of normal color-indices, and the wavelengths dependence of interstellar extinction was taken from Savage and Mathis (1979). We adopt equal optical characteristics for the circumstellar and interstellar dust. For the optically thin dust shell around MWC 84 this assumption is not so bad. The parameters derived from the SEDs best fitting in the wavelength range between 0.3 and 3.5 μm are given in Table 3. For MWC 84, the mean difference between the calculated SEDs and the observed ones for the model of a binary system is 1.5 time less than that for the single star model. Besides, we can estimate from the modeling

Table 3. **Objects' parameters from the model fitting**

Model	*Binary*		*Single star*	
MWC	*84*	*930*	*84*	*930*
Sp_1	BO V	BO V	BO V	BO I
Sp_2	KO II	KO I	–	–
Lv^2/Lv^1	3.0	12.0	–	–
U_0	11.8	9.4	7.9	3.7
Av	1.1	6.0	3.7	8.9
τ_v	0.2	–	0.5	–
Td, K	1050	–	1150	–
$\lg\varepsilon$, cm^{-3}	–	–	–	60.5
D, kpc	6.0	4.8	2.4	1.5

Sp_1, Sp_2 – MK types for a hot and a cool stars, respectively,
Lv^2/Lv^1 – the ratio of their luminosities,
V_0 – the dereddened visual magnitude of a hot star,
Av – the interstellar part of the common extinction,
τ_v, Td – the optical depth of a dust shell and its internal temperature,
ε – the emission measure of a gas shell,
D – the distance toward the object calculated using calibrations of absolute magnitudes for hot stars from Strajzhys and Kurilene (1981).

the product of the dilution coefficient for the inner boundary of the dust shell (W) and the intensity of the stellar radiation. Since W depends mainly on the amount of the stellar UV radiation and changes a little for different optical properties of the circumstellar dust, we can derive theoretically the relationship between W and the stellar temperature using the energy equilibrium equation for a dust particle. For the single star model of MWC 84, we have obtained that W calculated for a BO star and T (dust) = 1150 K exceed, by more than one order of magnitude, the theoretical value, while for the binary model there is a reasonable agreement.

It is more difficult to make a choice between the two models of MWC 930 SED. The deviations mentioned above are close to each other, and the resulting parameters look plausible for them. It is curious that, despite the large values of A_v obtained from the modeling, we have detected no interstellar absorption lines in the spectrum of MWC 930. Hence, another object's observational features will be of crucial importance to determine their composition.

Consider the Balmer decrements for hot stars surrounded by gas and dust shells and having strong H emissions (Figure 6). In spite of a rather poor statistics, the majority of the decrements are situated along the mean reddening line passing through the position of the theoretical decrement in the case B for gaseous nebulae. MWC 84 and MWC 930 have the decrements strongly deviating from this relationship. This may be a consequence of the real intensity distortion by the contribution of a late-type companion.

After summarizing all indications of the binarity, let us consider the luminosities of the companions. Since MWC 84 is located in the Galactic anticenter direction, the

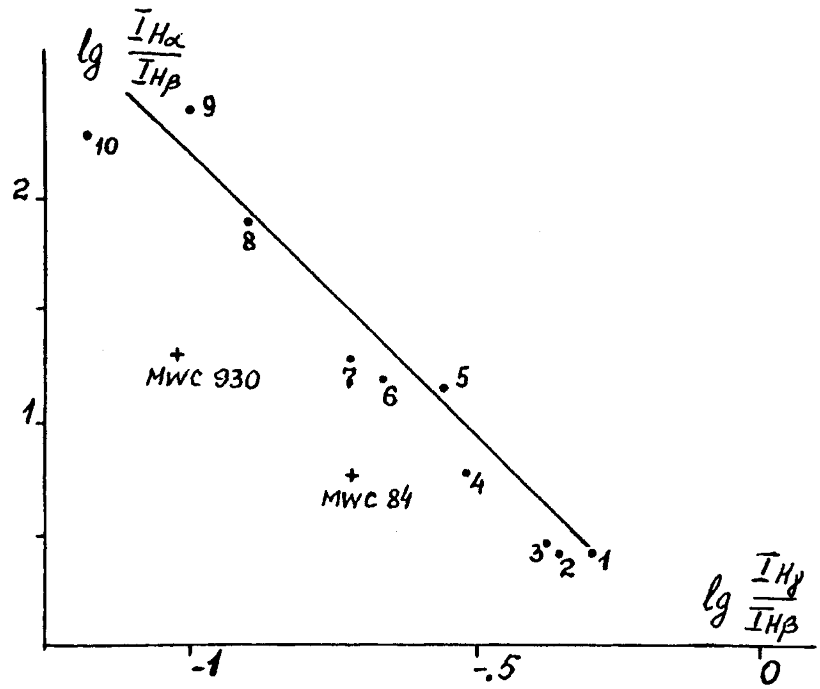


Figure 6 The Balmer decrements for some Herbig Ae/Be stars, B[e] supergiants and B[e] stars.

hot star appears to be a dwarf. In the opposite case, the object would occur beyond the Galactic boundaries. From the visual brightness ratio for the components of MWC 930, we can conclude that the hot star appears to be a dwarf. This implies that the cool star must be a Iab-Ib supergiant. A higher luminosity of the hot star is hardly plausible because the luminosities of hot and cool supergiants are close to each other. The cool dust in this system may have been formed during the evolution of the cool companion.

The presence of C II emission lines in the spectrum of MWC 84 may indicate that this may be an evolved star. The existence of cool companions without T Tau star features also implies that the objects must be evolved. This conclusion follows from that both stars are not surrounded by strong nebulosities and are located relatively far from star formation regions.

6 CONCLUSIONS

1. The optical photometry of MWC 84 and MWC 930 was obtained for the first time. The brightness variability of both objects with periods $11\overset{\mathrm{d}}{.}7$ and $58\overset{\mathrm{d}}{.}4$ for MWC 84 and MWC 930, respectively, has been detected.

2. The objects' spectra in the range of 4000–7400 Å have been obtained. Several absorption lines typical of late-type stars have been detected. It is shown that their Balmer decrements are essentially different from those of hot stars with gas and dust shells.

3. The model fitting of the objects' SEDs in the range of 0.3–3.5μm has been performed using the models of a single star and a binary system with a circumstellar shell. Estimations of the spectral classes for the stellar components, interstellar extinction, and some shell characteristics are presented.

4. The following observational features of the objects may be considered as the evidences of their binarity:

   a) an extremely large ratio between the IRAS fluxes of MWC 84 at 12 and 25 μm, close to those of late-type stars and binary systems consisting of a hot and a cool star,

   b) the features mentioned in the points 1 and 2 in this section.

Certainly, the binarity of these objects is only a suggestion, the evidences presented here must be checked and extended, but we have detected some new and interesting phenomena. New spectral observations are needed to detect possible line intensity variabilities for both objects. Also, it will be useful to obtain a more precise U-light curve for MWC 930. The number of such systems may be increased during a study of the objects from Dong and Hu's (1991) catalogue containing more than 100 poorly investigated early-type objects having emission lines and a very strong infrared excess. Both objects discussed in the present paper are listed there.

ACKNOWLEDGEMENTS

The author is very grateful to R. V. Yudin, K. S. Kuratov, D. B. Mukanov and T. A. Sheikina for their help in obtaining the photometry data, to N. V. Borisov for his help in obtaining the spectroscopy data, to V. A. Lipovetsky for providing the results of his spectral observations, to V. S. Shevchenko, M. A. Ibragimov, S. D. Yacubov and K. N. Grankin for obtaining the photometry of MWC 930 at Maidanak. The author is also grateful T. R. Miroshnichenko for drawing the figures.

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