MWC 930 – a new luminous blue variable candidate

A. S. Miroshnichenko, 1,2,3* K. S. Bjorkman, 1 M. Grosso, 4 H. Levato, 4 K. N. Grankin, 5 R. J. Rudy, 6 D. K. Lynch, 6 S. Mazuk 6 and R. C. Puetter 7

1Ritter Observatory, Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606-3390, USA
2Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
3Central Astronomical Observatory of the Russian Academy of Sciences at Pulkovo, 196140, Saint-Petersburg, Russia
4Complejo Astronómico El Leoncito (CASLEO), Casilla de Correo 467, 5400 San Juan, Argentina
5Ulugh Beg Astronomical Institute, Astronomicheskaya St. 33, Tashkent 700052, Uzbekistan
6The Aerospace Corporation, M2/266, PO Box 92957, Los Angeles, CA 90099, USA
7Center for Astrophysics and Space Science, University of California, San Diego, C-0111, La Jolla, CA 92093, USA

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ABSTRACT

We present the results of optical high-resolution and near-infrared low-resolution spectroscopy and multicolour optical and near-infrared photometry of the emission-line star MWC 930. The spectrum is rich with Fe II emissions, most of which have P Cyg-type profiles. The emission lines are strong and narrow, indicating a powerful stellar wind (M > 1.5 × 10^-6 M☉ yr^-1) with a low terminal velocity (vₖ ∼ 140 km s^-1). The photospheric absorption lines are broad and show splitting, which might be due to the object’s binarity. MWC 930 is most probably located in the Norma spiral arm at a distance of D = 3–4 kpc. This strong and slow wind as well as the star’s luminosity (log L/L☉ ∼ 5.5) and the infrared excess shape suggest that MWC 930 is an unusual B-type supergiant, most likely undergoing the luminous blue variable evolutionary phase.

Key words: techniques: photometric – techniques: spectroscopic – circumstellar matter – stars: emission-line, Be – stars: individual: MWC 930.

1 INTRODUCTION

Massive stars spend most of their lifetime as mass-losing objects of OB spectral types. During rapid evolution at the main sequence and beyond, they [e.g. of stars, B[e] stars and luminous blu variables (LBV; also known as S Dor variables)] display variable mass loss and undergo a number of short-term spectroscopically distinct stages (Conti 1997). Since massive stars are relatively rare, each new object caught at such a stage is very important for a better understanding of stellar evolution.

When mass loss is strong, stars exhibit bright emission-line spectra, which are easily detected even with an objective prism. Galactic surveys, such as the Mount Wilson survey (Merrill & Burwell 1933, 1949), the Bosscha surveys (Thé 1966; Maehara 1982) and the Hamburg survey (Kohoutek & Wehmeyer 1999), became valuable sources for finding objects with significant mass loss. However, many early-type emission-line stars discovered in the course of these surveys have not been sufficiently studied yet to derive reliable physical parameters and their evolutionary state. Numerous papers about hot emission-line stars published during the past decade showed the importance of high-resolution spectroscopy for classification of these complicated objects.

*E-mail: a.mirosh@uncg.edu

Our previous studies of B-type emission-line stars with infrared (IR) excesses resulted in the finding of very interesting and rare objects. These include two LBV candidates (MWC 314 and AS 314, Miroshnichenko et al. 1998; Miroshnichenko, Cheintsov & Klochkova 2000a, respectively) and nearly a dozen newly found B[e] stars (e.g. AS 78 and MWC 657, Miroshnichenko et al. 2000b). In this paper we present our results on the relatively unstudied object, MWC 930.

MWC 930 was discovered by Merrill & Burwell (1949) as an emission-line star in Scutum. Maehara (1982) confirmed its identification. Allen (1975) suggested that MWC 930 might be either a very reddened Be star or a VV Cep-type binary containing a cool supergiant primary and a hot secondary. Dong & Hu (1991) included it in the list of early-type objects with extremely strong IR excesses (V − [25] ≥ 8 mag, where V and [25] are the magnitudes in the V band and in the IRAS 25-μm band). This was the basis for inclusion of MWC 930 in the latest catalogue of the Herbig Ae/Be group by Thé, de Winter & Pérez (1994) as a pre-main-sequence star candidate. In a search for binaries among Herbig Ae/Be stars, Corporeon & Lagrange (1999) took three high-resolution spectra of MWC 930. They did not report any radial velocity (RV) variations, but estimated the projectional rotational velocity v sin i = 100 km s^-1.

The IRAS discovery of a strong IR excess with flux rising towards longer wavelengths led to the suggestion that MWC 930
might be a Population I Be star or LBV (Parthasarathy, Vijapurkar & Drilling 2000). At the same time, Gauza et al. (2003) suggested that MWC 930 could be a post-asymptotic giant branch (AGB) star based on the strong Hα emission and the presence of weak forbidden lines. These studies used low-resolution spectra.

Summarizing the previous studies of MWC 930, one can say that none of them were sufficiently comprehensive to derive physical parameters. No convincing justification for any suggestion about the object’s nature has been offered. We have been observing the object photometrically and spectroscopically for over a decade. The collected information enabled us to suggest a consistent explanation for the behaviour of MWC 930.

Our observations are described in Section 2, our spectroscopic results and analysis of the existing photometric data are presented in Section 3, analysis of the observed properties and derived physical parameters are given in Section 4, and conclusions are summarized in Section 5.

2 OBSERVATIONS

The photometric Johnson \textit{UBVR} observations of MWC 930 were obtained during the period 1990–2000 at Mt. Maidanak (Uzbekistan) with two 48-cm reflectors AZT-14 and a standard pulse-counting photometer (Shevchenko 1980). The Johnson \textit{BVRJHK} observations were obtained in 1989–1992 at the Assy Observatory (Kazakhstan) with the tw-channel photometer–polarimeter FP3U of the Pulkovo Observatory (Bergner et al. 1988). These data were published by Bergner et al. (1995). Also, one \textit{BVRJHK} observation was obtained in 1998 at the Tien Shan Observatory (Kazakhstan) with the same photometer by one of us (ASM). In total, 426 observations have been obtained. Typical photometric errors were as follows: \( \sigma U \sim 0.2 \text{ mag}, \sigma BV \sim 0.05 \text{ mag} \) and \( \sigma R \sim 0.02 \text{ mag} \) for the Maidanak data, and \( \sigma B \sim 0.07 \text{ mag}, \sigma V \sim 0.05 \text{ mag}, \sigma R1 \sim 0.03 \text{ mag}, \sigma J \sim 0.07 \text{ mag}, \sigma H \sim 0.05 \text{ mag} \) and \( \sigma K \sim 0.02 \text{ mag} \) for the Kazakhstan data.

MWC 930 has also been observed in the course of the All Sky Automated Survey (ASAS, Pojmanski 2002), and its \textit{V}-band data were retrieved from the ASAS-3 catalogue. The \textit{V}-band and \textit{K}-band light curves are shown in Fig. 1.

The IR imaging was performed on 2001 October 22 at Mauna Kea with the 3-m NASA Infrared Telescope Facility (IRTF) and the camera MIRLIN. The observations were obtained in the \textit{N} band (effective wavelength \( \lambda_{\text{eff}} = 10.79 \mu \text{m} \), passband \( \Delta \lambda = 5.66 \mu \text{m} \)). MWC 930 was observed along with a number of other emission-line stars as well as close standard stars (HR 6869 and 7525). Details of the observing procedure and data reduction can be found in Miroshnichenko et al. (2004).

Most of our spectroscopic observations were obtained at the 2.1-m telescope of the Complejo Astronómico El Leoncito (Argentina) with the echelle spectrograph REOSC, mounted at the Cassegrain focus and equipped with a 2000 \times 2000 pixel charge-coupled device (CCD) chip. This setup allowed us to achieve \( R \sim 15000 \). One spectrum was obtained at the 2.1-m Otto Struve telescope of the McDonald Observatory (Mt. Locke, Texas) with the Sandiford echelle spectrograph (McCarthy et al. 1993) with \( R \sim 60000 \) and a 1200 \times 400 pixel CCD. Data reduction was performed in IRAF. The log of these high-resolution spectroscopic observations is presented in Table 1. Portions of the optical spectrum of MWC 930 along with that of the LBV candidate MWC 314 are shown in Fig. 2.

The low-resolution IR spectroscopic observations were acquired on 2000 July 19 with the 3-m Shane reflector of the Lick Observatory and the Aerospace Corporation’s Near-Infrared Imaging Spectrograph. The spectrograph, which is described by Rudy, Puettner & Mazuk (1999), uses two channels to provide wavelength coverage from 0.8 to 2.5 \( \mu \text{m} \). The blue (0.8–1.4 \( \mu \text{m} \), resolution 14 \( \AA \)) and red (1.4–2.5 \( \mu \text{m} \), resolution 36 \( \AA \)) spectra were acquired simultaneously. A more detailed technical description of this type of observation is given in Miroshnichenko et al. (2000b). A 2.7 arcsec slit was used.

\[ \text{Figure 1. The optical and near-IR light curves of MWC 930. The Kazakhstan \textit{V}- and \textit{K}-band data are shown by filled circles, the Uzbekistan \textit{V}-band data by open circles, the ASAS-3 \textit{V}-band data for two adjacent fields by crosses and pluses, the observation reported by Gauza et al. (2003) by an upward triangle, the Lick data by a downward triangle, and the 2MASS data (Cutri et al. 2003) by an open square. The time-scale is represented by Julian dates.} \]

\[ \text{Table 1. Log of high-resolution spectroscopic observations of MWC 930.} \]

<table>
<thead>
<tr>
<th>Date</th>
<th>MJD</th>
<th>Exp. (s)</th>
<th>Sp. region (( \AA ))</th>
<th>S/N</th>
<th>Observatory</th>
</tr>
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<tbody>
<tr>
<td>2000/07/23</td>
<td>1748.698</td>
<td>2700</td>
<td>5580–8410</td>
<td>80</td>
<td>Leoncito</td>
</tr>
<tr>
<td>2001/10/10</td>
<td>2192.569</td>
<td>2400</td>
<td>5540–6950</td>
<td>70</td>
<td>McDonald</td>
</tr>
<tr>
<td>2002/05/23</td>
<td>2417.759</td>
<td>1800</td>
<td>5640–8750</td>
<td>50</td>
<td>Leoncito</td>
</tr>
<tr>
<td>2002/06/24</td>
<td>2449.770</td>
<td>1500</td>
<td>5810–9020</td>
<td>50</td>
<td>Leoncito</td>
</tr>
<tr>
<td>2002/06/25</td>
<td>2450.790</td>
<td>1800</td>
<td>5810–9020</td>
<td>60</td>
<td>Leoncito</td>
</tr>
<tr>
<td>2004/06/01</td>
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<td>2700</td>
<td>4320–6830</td>
<td>50</td>
<td>Leoncito</td>
</tr>
<tr>
<td>2004/07/05</td>
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<td>8100</td>
<td>4320–6830</td>
<td>80</td>
<td>Leoncito</td>
</tr>
<tr>
<td>2004/07/06</td>
<td>3193.674</td>
<td>5400</td>
<td>4320–6830</td>
<td>60</td>
<td>Leoncito</td>
</tr>
</tbody>
</table>

\[ ^a \text{Listed are the date (YYYY/MM/DD), exposure starting time (in MJD = JD − 2450000), exposure time, spectral region covered, signal-to-noise ratio at \( \lambda = 6000 \text{ Å} \) and the observatory.} \]

\[ ^1 \text{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.} \]
Figure 2. Portions of the high-resolution optical spectrum of MWC 930 obtained at the McDonald Observatory on 2001 October 10. A spectrum of MWC 314, shown for comparison, was obtained with the same equipment an hour later. The intensities are in continuum units, and the wavelengths are in angstroms.

Figure 3. Portions of a near-IR spectrum of MWC 930. A spectrum of MWC 300, shown for comparison, was obtained with the same equipment in 2002 July. The intensities are in continuum units, and the wavelengths are in micrometres.

employed for the observations of MWC 930 and its calibrator star HR 7034, an F7 dwarf (V = 6.31 mag, K = 5.21 mag). The instrumental response and most of the effects of atmospheric absorption were removed by dividing the spectra of the stars by that of the calibrator. To remove the intrinsic spectrum of the calibrator from this ratio, we used a model from Kurucz (1994) appropriate for an F7V star. Conversion of the spectrum with the JHK bandpasses gives the following brightness of MWC 930: J = 6.81 mag, H = 5.94 mag and K = 5.46 mag. Portions of the IR spectrum of MWC 930 along with that of the B[e] supergiant MWC 300 are shown in Fig. 3.
Table 2. Parameters of some spectral lines in the spectrum of MWC 930.\(^a\)

<table>
<thead>
<tr>
<th>Date</th>
<th>Fe ii emis.</th>
<th>N</th>
<th>Fe ii abs.</th>
<th>N</th>
<th>DIB</th>
<th>N</th>
<th>Ne i 6402 Å</th>
<th>blue</th>
<th>Hz</th>
<th>cent.</th>
<th>red</th>
<th>EW</th>
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<td>7</td>
<td>47</td>
<td>-120</td>
<td>-33</td>
<td>117</td>
<td>43</td>
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<td>18</td>
<td>-14±2</td>
<td>3</td>
<td>4±5</td>
<td>7</td>
<td>35/120</td>
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<td>-38</td>
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<td>27</td>
<td></td>
</tr>
<tr>
<td>2002/05/23</td>
<td>99±7</td>
<td>5</td>
<td></td>
<td>4±2</td>
<td>2</td>
<td>57</td>
<td>-114</td>
<td>-32</td>
<td>113</td>
<td>63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002/06/24</td>
<td>96±9</td>
<td>12</td>
<td>-26±2</td>
<td>2</td>
<td>9±4</td>
<td>2</td>
<td>-116</td>
<td>-31</td>
<td>114</td>
<td>46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002/06/25</td>
<td>99±7</td>
<td>9</td>
<td>-30±6</td>
<td>3</td>
<td>2±2</td>
<td>2</td>
<td>47</td>
<td>-110</td>
<td>32</td>
<td>114</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>2004/06/01</td>
<td>95±8</td>
<td>20</td>
<td>-27±4</td>
<td>8</td>
<td>4±2</td>
<td>4</td>
<td>59</td>
<td>-96</td>
<td>-28</td>
<td>115</td>
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<tr>
<td>2004/07/05</td>
<td>93±8</td>
<td>20</td>
<td>-23±7</td>
<td>12</td>
<td>3±6</td>
<td>5</td>
<td>29/103</td>
<td>-103</td>
<td>-28</td>
<td>114</td>
<td>54</td>
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<tr>
<td>2004/07/06</td>
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<td>11</td>
<td>-21±8</td>
<td>5</td>
<td>7±5</td>
<td>3</td>
<td>-94</td>
<td>-29</td>
<td>116</td>
<td>54</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)The mean RV of the emission and absorption components of Fe ii lines are listed in columns 2 and 4, and the number of measured lines in columns 3 and 5, respectively. The mean RV and the number of measured DIBs are listed in columns 6 and 7. The RV of the absorption component(s) of the photospheric Ne i 6402 Å line is listed in column 8. The RVs of the blue emission peak, the central depression and the red emission peak of the Hz line are listed in columns 9–11, respectively. The RVs listed in columns 8–11 are derived by fits to a Gaussian. The equivalent width of the Hz line red peak (in Å) is listed in column 12.

3 RESULTS

3.1 The brightness variations

MWC 930 has been extensively observed by our team in 1989–2000 (with a gap between 1995 and 2000) and within the ASAS-3 programme since 2001. Although the ASAS-3 data lack colour information, its 2001 results are in good agreement with our 2000 observations. Therefore, we assume that there is only a little systematic shift of no more than 0.1 mag between the two data sets (see Fig. 1).

The V-band brightness was slowly variable with an overall amplitude of ~0.8–0.9 mag. The colour indices during the lowest state (V = 12.4–12.8 mag) were stable within ±0.05 mag. The K-band variations seem to correlate with those in the V band. Such behaviour can be explained by a variable mass-loss rate, which may also cause the linestrength variations (see Table 2). Another reason for the optical and near-IR brightness correlation can be stellar pulsations of the S Dor type. We are not able to distinguish between the variability mechanisms due to the absence of multicolour data during the highest state (2003–2005). If the dominant mechanism is pulsations, the star should now display bluer colour indices. Also, both mentioned mechanisms may act simultaneously.

3.2 The spectrum

To date, the optical spectrum of MWC 930 has been described only qualitatively. A low-resolution spectrum obtained by Parthasarathy et al. (2000) shows Balmer lines as well as several permitted and forbidden Fe ii lines in emission.

Our spectra show a strong and variable Hz line with a relatively narrow double-peaked profile. Its blueshifted peak is usually at a level of 1.1–2 densities of the underlying continuum (L\(_c\)), while the red one is much stronger (10–25 L\(_c\)). The RVs of the blue peak and the central depression show a small drift with time towards positive velocities, while the red peak does not change its position (see Table 2).

The H\(_\beta\) line has a P Cyg-type profile. The same profile type includes the He i 5876-Å line and almost all Fe ii lines. The absorption component was not detected either in the weakest lines or in blends. We reliably detected only a few forbidden lines in the spectral region between H\(_\beta\) and ~9000 Å. These are the [N ii] 5755 Å, a very weak [N ii] line at 6584 Å, and [Fe ii] lines at 6507 and 8617 Å. Neither the [O i] lines at 6300 and 6363 Å nor the [O iii] lines at 4959 and 5007 Å were present.

We also detected photospheric lines. The Ne i 6402 Å line is seen in all our spectra, while N ii, Si iii and Al iii lines between 5660 and 5740 Å are detected in those with the highest signal-to-noise ratios. Some of them are good luminosity indicators. According to a calibration of the Si iii 5739 Å line equivalent width by Miroshnichenko et al. (2004), the luminosity of MWC 930 exceeds log L/L\(_\odot\) = 5, taking into account a possible circumstellar (CS) veiling due to free–bound and free–free continuum that reduces the linestrength (see Section 3.3.1 for the modelling results).

Some photospheric lines (e.g. Si iii 5739 Å and Ne i 6402 Å) are split into two components in our highest signal-to-noise ratio and highest-resolution spectra (see Fig. 2d). Such an effect is observed in the atmospheres of some high-luminosity stars and might be due to an emission component at a RV close to that of the other emission lines (e.g. Chentsov et al. 2003). However, this might also be a sign of the object’s binarity. For example, the Ne i 6402 Å line shows noticeable width variations and is wider in our highest-resolution McDonald spectrum than in any of the Leoncito spectra (Fig. 4). The uncertainties in the photospheric linestrength nature and in the CS continuum buildup (see Section 3.3.1) make the luminosity estimate based on photospheric lines unreliable. On the other hand, it should be noted that, even considering that the Ne i 6402 Å line consists of two roughly equal components (see Fig. 2d), this suggests a luminosity type Ia for the object (see table 5 in Miroshnichenko et al. 1998).

As seen in Fig. 2(a), the photospheric lines of MWC 930 (even non-split) are wider than those in the spectrum of MWC 314. The same situation holds when comparing the spectrum of MWC 930 with those of other peculiar high-luminosity objects (e.g. MWC 300, HD 168625, P Cyg). This might be either another sign of binarity or an indication of a high rotation rate (\(\geq 100\) km s\(^{-1}\)). The latter seems to be less likely, since rotation would make the emission-line profiles more complicated than just P Cyg type, whose formation is mainly due to radial expansion (e.g. Sobolev 1960). In any case, the linewidth is definitely not due to a high gravity, because low-luminosity and similar temperature stars show weaker (a factor of 2 in equivalent width) and narrower absorption lines even at an almost zero projected rotational velocity. This conclusion is derived from comparison of high-resolution spectra from various archives, including our data from different telescopes.
In Fig. 3 we compare the IR spectra of MWC 930 and MWC 300 obtained with the same equipment. The IR continuum of these objects behaves differently due to the thermal emission of CS dust in MWC 300. This effect reduces the equivalent widths of spectral lines of MWC 300 around 2 μm. At the same time, dust in MWC 930 is cold as in other LBV candidates (see Section 4), and the line strengths are only diluted by the stellar and free-free continuum.

3.3 Modelling

3.3.1 Hydrogen lines

The fact that most of the emission lines in the spectrum of MWC 930 show P Cyg profiles suggests that the CS gas is distributed essentially spherically symmetrically around the star. The blue emission peak and broad wings of the Hα line may be attributed to electron scattering. The RVs of the blue and red edges of the Hα and Hβ lines indicate that the terminal velocity of the stellar wind is ~140 km s⁻¹. Furthermore, the P Cyg absorption minimum intensity is not very close to 0 (~0.5 for both Hα and Hβ in the Leontocto spectra and 0.15 for Hα in the McDonald spectra), indicating that the hydrogen opacity is not extremely strong and that, in turn, the CS gas temperature is relatively high (since the hydrogen opacity increases as the temperature decreases).

Using these estimates, we calculated a grid of models in order to fit the observed profiles of Hα and Hβ as well as the strength of the Brγ line, which was not resolved in our low-resolution spectrum. We used a 1D radiation transfer code described by Pogodin (1986). It calculates departure coefficients from local thermodynamic equilibrium (LTE) level populations for a hydrogen atom with 12 levels in non-LTE and eight more levels in LTE as well as the envelope ionization structure. Then the code integrates radiation from hydrogen lines over the entire envelope using the ray tracing method. The code was modified by one of us (ASM) to treat the line optical depth effects more accurately (a more careful integration procedure to calculate CS optical depth near the hydrogen series limit) and to include calculations of the contribution of free–bound and free–free radiation to the emergent continuum radiation. The latter is converted into synthetic photometry using the optical and near-IR passbands from Bessell & Brett (1988) and Bessell (1990), respectively, and IRAS passbands from the IRAS Explanatory Supplement (Beichman et al. 1985).

The input parameters included Kurucz (1994) model atmospheres for a range of stellar effective temperatures (Teff) with the smallest gravity available in the grid (log g = 2.5 or 3.0), mass-loss rates (M) and stellar wind terminal velocities (v∞). The wind kinematics was determined by a β velocity law (Castor & Lamers 1979). Electron scattering was not taken into account, and thus we tried to fit only the profile parts without the wings. The stellar wind was considered isothermal with an electron temperature of 0.8Teff.

Our calculations suggest that Teff is unlikely to be lower than ~20000 K, since the P Cyg absorption component becomes very strong at lower temperatures. On the other hand, Teff should be lower than ~28000 K, as no HeI lines are seen in the spectrum of MWC 930. We obtained reasonably good fits to the observed Hα and Hβ lines in this range of Teff with the mass-loss rates M of (1.0–1.5) × 10⁻⁶ M⊙ yr⁻¹ and β = 3–3.5. The calculated equivalent width of the Brγ line was found to be within 10–15 Å, not far from the observed value (20 Å). Since the near-IR spectrum was not taken simultaneously with the optical one (dashed lines in Fig. 5), we consider this result satisfactory. In fact, the Leoncito spectrum of 2000 July 23, which was obtained a few days later than the Lick
near-IR spectrum, shows a weaker Hα line (Table 2). This might imply a weaker mass loss and a weaker CS continuum in the IR region. Therefore the Brγ line might have been stronger at that time.

We also found that the contribution from free–bound and free–
free radiation to the emergent continuum is significant in both the optical and IR wavelength regions. In particular, the envelope contrib-
utes 0.5 mag to the V band, 1.6 mag to the K band and 4.2 mag to
the IRAS 60-μm band for the model with the Balmer line profile
shown in Fig. 5 and the continuum emission shown in Fig. 6). This
contribution needs to be taken into account in the dereddening
procedure, which we discuss in Section 3.3.2.

We have to note that, since the contribution of helium to the wind
and electron scattering were not considered in our calculations, the
result for the mass-loss rate is only a lower limit. On the other hand,
the use of a simplified code here is justified by difficulties of more
advanced existing codes to reproduce accurately line profiles in such
complicated objects (e.g. Hillier et al. 1998).

3.3.2 Spectral energy distribution

The observed spectral energy distribution (SED) was composed
from our photometric data as well as from the IR satellite (IRAS
and MSX) and our IRTF measurements. The optical and near-IR
data were averaged seasonally, and then the seasonal averages were
used to derive the mean brightness in each photometric band. The
average optical and near-IR colour indices are as follows: B − V =
2.65 mag, (V − R)J = 2.55 mag, (R − I)J = 1.72 mag, J − H =
0.80 mag and H − K = 0.50 mag. Their mean uncertainty is
0.05 mag (see Section 3.1).

The satellite data obtained 13 yr apart are consistent after taking
into account colour correction of the IRAS fluxes (Beichman et al.
1985). In our IRTF data, the star appears as a point source (the im-
age full width at half-maximum is 1.1 arcsec, the same as that of
MWC 300 and HR 7525 observed within an hour from MWC 930)
with brightness $N = +3.54 \pm 0.12$ mag. The latter is in good agree-
ment with both the MSX and IRAS data in the 8–12 μm region. As
noted by Parthasarathy et al. (2000), the IRAS 25–100 μm fluxes are
indicative of a detached dusty envelope, which might be a result of
an LBV eruption.

The spectrum, typical for a hot star, the strong DIBs and the
absence of late-type star features along with the mean colour indices
imply a very strong reddening, which may contain both IS and
CS contributions. An upper reddening limit for the colour excess
$E(B − V) = 2.83 \pm 0.05$ mag can be estimated from the mean
observed $B − V = 2.64 \pm 0.02$ mag and an intrinsic colour index for
an early B-type supergiant $(B − V)_0 = −0.19 \pm 0.04$ mag (Wegner
1994). On the other hand, a relationship between the strength of the
DIB at 5780 Å (Herbig 1993), which has EW = 0.82 ± 0.02 Å in
the spectrum of MWC 930, gives $E(B − V) = 1.6 \pm 0.1$ mag.

The difference between the two estimates is very large. A simi-
lar situation was found for an ex/dormant LBV HD 316285 (van
Gendener 2001). The discrepancy may be attributed to the CS
reddening due to free–bound and free–free emission, to the pres-
ence of dark IS clouds in the line of sight and to an additional
extinction in the dust, responsible for the IR excess (Hillier et al. 1998).

The CS envelope parameters found from our line profile modelling suggest that the CS reddening is significant. Taking it into account reduces the amount of IS reddening to $E(B - V) = 2.5$ mag (see fig. 6), which is still larger than that following from the DIB strength. On the other hand, dereddening with $E(B - V) = 1.6$ mag leaves a colour index $(B - V) = 1.0$ mag, which cannot be explained by CS gaseous emission. Also, neither our optical spectra show signs of a cool stellar companion nor our near-IR spectrum shows signs of CS dust. Thus, one can assume that part of the IS extinction arises in the material not producing DIBs. Unfortunately, no satellite ultraviolet data exist for MWC 930 to verify this suggestion.

4 DISCUSSION

The results of our spectroscopic and photometric observations strongly suggest that MWC 930 is a distant high-luminosity star. In this section we consider its properties and constrain its evolutionary state.

4.1 Stellar parameters, reddening, distance

MWC 930 is located near the Galactic plane ($b = 2.2$ degrees), where IS extinction is high. Using optical photometry of a few stars, Neckel & Klare (1980) showed that the IS extinction in this direction rapidly increases with distance and reaches $A_V \sim 3$ mag at $D \sim 1$ kpc. Observations of other peculiar stars, close to MWC 930 in the sky, support this result. In particular, MWC 300 (at an angular distance of 1.5 degrees) and Ry Sct (at 5.5 degrees) have similar $E(B - V) \sim 1.2$ mag. They are both located at $D \sim 2$ kpc (Smith et al. 2002; Miroshnichenko et al. 2004), a kinematic distance from the Galactic rotation curve by Duhath et al. (1988). MWC 930 with its higher reddening and a more positive photophere line RV is most probably located further away from the Sun.

Kalchева et al. (2003) showed that the Norma spiral arm of the Milky Way can be traced at $D = 3 - 4$ kpc at the Galactic latitudes $l = 250 - 350\degree$. MWC 930 is probably located within this arm (the Scutum–Crux arm in the Galaxy model by Russell 2003) rather than within the closer Sagittarius arm at $D = 1 - 2$ kpc. The excess IS extinction, which is not traced by DIBs, might arise in the Norma arm. Furthermore, the IRAS data show that only cold, and therefore distant and optically thin, dust exists in the vicinity of the object. Thus, we suggest that statements that the CS dust can be responsible for the large colour excess of MWC 930 and that its $D \sim 0.2$ kpc by Gauba et al. (2003) are not supported by the object’s observed properties.

This consideration shows that $D$ towards MWC 930 is most probably more than 3 kpc, which is in rough agreement with that derived from the Galactic rotation curve. With the observed mean brightness $V = 12.5$ mag, IS reddening $E(B - V) = 2.5$ mag ($A_V = 7.8$ mag) and a CS continuum contribution of $\Delta V = 0.5$ mag, the object would have an absolute visual magnitude of $M_V = -7.2$ mag at $D = 3$ kpc. If then its $T_{\text{eff}} \sim 22,000$ K ($BC \sim -2.2$ mag, Miroshnichenko 1998), it would have a luminosity of $L/L_\odot \sim 5.6$, which is comparable with those of LBVs and the brightest B[e] supergiants. However, the uncertainties in $D$, the CS contribution to the optical continuum, and the stellar content of the system (single or binary) make this estimate quite rough.

If MWC 930 is a single object at the Humphreys–Davidson limit (Humphreys & Davidson 1979) and the CS continuum contributes no more than $\Delta V = 1$ mag (which would lower the IS extinction a little, since the CS reddening is rather small), then an upper limit for $D$ is $\sim 6.5$ kpc, which corresponds to a Galactocentric distance of 3.6 kpc. If it is a binary with a similar luminosity companion, then the object would be even further away from the Sun. This is not a realistic situation, since recently discovered LBV candidates near the Galactic Centre (e.g. G79.29+0.46, Voors et al. 2000) are obscured much more heavily. Therefore, the most probable range of $D$ towards MWC 930 is $3 - 4$ kpc.

We estimated the object’s $T_{\text{eff}}$ using spectroscopic criteria, such as the presence of He i emission lines and the absence of He ii lines. The He i lines in the spectrum of MWC 930 are significantly weaker than those in the spectrum of HD 316285, which shows an evolutionary overabundance of He ($T_{\text{eff}} = 15,000$ K, Hillier et al. 1998). This is more consistent with a smaller He abundance in MWC 930 than with its lower $T_{\text{eff}}$, since the photospheric lines seen in the spectrum of MWC 930 are much weaker in late B-type supergiants (e.g. Miroshnichenko et al. 1998; Chentsov et al. 2003). Also, lowering the $T_{\text{eff}}$ of MWC 930 to $\sim 15,000$ K would introduce only small changes to its reddening and luminosity estimates. Nevertheless, a more thorough line profile modelling, including treatment of the He lines, is needed to derive a more accurate value of $T_{\text{eff}}$.

Taking into account all the uncertainties discussed above, one can find a luminosity estimate of $\log L/L_\odot = 5.5 \pm 0.2$ for $D = 3.5 \pm 0.5$ kpc and $T_{\text{eff}} = 22,000 \pm 5000$ K. These parameters correspond to an initial mass of $35 \pm 5 M_\odot$ (Schaller et al. 1992) and a surface gravity of $\log g = 2.7 \pm 0.5$. With such a luminosity and the stellar wind properties derived in Section 3.3.1, the performance number $\eta = cM_{\text{w,s}}/L$, which describes how efficiently momentum from the radiation field is deposited into the wind, is only $\sim 0.05$. This is much lower than $\eta$ for P Cyg (0.5) or HD 316285 (18, Hillier et al. 1998) and might be a result of an underestimated mass-loss rate due to the neglect of the helium opacity and electron scattering in the line profile calculations. An order-of-magnitude increase in $M$ would bring the $\eta$ of MWC 930 close to that of P Cyg. However, this needs to be investigated with more comprehensive modelling.

4.2 Evolutionary state

We have shown that MWC 930 is an emission-line supergiant of an early B spectral type. Thus, it cannot be a post-AGB star as suggested by Gauba et al. (2003). Post-AGB objects with cold IS dust, also known as proto-planetary nebulae, have luminosities not exceeding $10^4 L_\odot$ (e.g. Blöcker 1995).

MWC 930 has a very strong mass loss, indicating that it is undergoing one of the short-term evolutionary phases mentioned in Section 1. It is not an Of-type star, as its $T_{\text{eff}}$ is too low. It is not a B[e] supergiant either, as it does not show evidence for a significant amount of hot dust and a disc-like CS envelope (e.g. Zickgraf et al. 1986).

The low terminal velocity of the stellar wind in connection with the high luminosity and far-IR excess make MWC 930 a very good candidate for the class of LBVs. Despite the fact that no giant eruption or large-amplitude brightness variations accompanied by dramatic temperature changes, seen in the behaviour of other LBVs and candidates (e.g. Stahl et al. 2003), have been detected in the existing data for the object, it definitely shows photometric activity. The far-IR excess, which is very similar to those of some LBVs and candidates (e.g. AG Car, HR Car and AS 314, see Miroshnichenko et al. 2000a), might be due to dust formed during a giant eruption. Binarity is also not unusual for LBVs, as $\eta$ Car is suspected to be a binary system with an orbital period of 5.5 yr (Damiani et al. 1996).
5 CONCLUSIONS

We presented spectroscopic and long-term photometric observations of an almost unstudied emission-line object, MWC 930. Our analysis of the brightness variations revealed a possible correlation in the changes of the optical and near-IR brightness, while the optical colour indices are stable within ~0.05 mag. However, more recent ASAS-3 V-band monitoring data show that the star has been brightening since about 2003. The observed variations may be due to S Dor-type pulsations.

Our most recent BVR photometric data obtained at Mt. Maidanak in 2005 July–August confirm the object's brightening (the average brightness and colour indices are as follows: $V = 12.14 \pm 0.02$, $B - V = 2.52 \pm 0.03$, $V - R = 2.58 \pm 0.02$ mag). The current average $B - V$ is ~0.1 mag bluer than that in our earlier data before the brightening (see Section 3.3.2), supporting the S Dor classification for MWC 930.

We found strong and broad photospheric lines, indicative of a high luminosity and possibly binarity of the object. The low velocity, strong stellar wind and the far-IR excess due to cold CS dust suggest that the object is most likely to belong to the LBV (S Dor) type.

A simplified 1D radiation transfer code was used to model the Balmer line profiles. The modelling results suggest that the mass-loss rate is large, $M \geq 1.5 \times 10^{-5}$ M$_\odot$ yr$^{-1}$ and that there is a noticeable contribution to the observed continuum due to free–bound and free–free radiation of the CS gas. The IS reddening, estimated from the DIB strength [$E(B - V) = 1.6$ mag], is significantly lower than the total observed colour excess [$E(B - V) = 2.8$ mag]. However, a distant location of MWC 930 ($D = 3-4$ kpc) allows us to suggest that part of the IS extinction, probably local to the Norma (Scutum–Crux) spiral arm, does not contribute to the DIBs.

In order to constrain the properties of this remarkable object and to verify our findings, we suggest the following programme of observations and modelling:

(i) spectroscopic monitoring of the object for a few years on timescales from weeks to months with $R \geq 2000$ and signal-to-noise ratio of ~100 to search for cyclic variations of the photospheric line RVs and emission-line strengths as well to study the photospheric line splitting;

(ii) multicolour photometric (optical and near-IR) monitoring of the object to study correlations between the optical and IR brightness and to search for stronger brightness variations, similar to those found in LBVs;

(iii) spectroscopic and photometric observations of nearby stars to trace the behaviour of the DIB strengths and colour excesses with distance from the Sun; and

(iv) application of a more sophisticated radiation transfer code to model the observed profile of hydrogen and helium and to refine the physical parameters of the star and its wind found in this study.

Such a programme is not difficult to conduct, since the object's brightness requires a 2-m class telescope for spectroscopy and a 0.5-m class telescope for photometry. Also, several codes capable of doing better line profile modelling have recently been introduced in the literature (e.g. Carciofi & Bjorkman 2004).

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