Astron. Astrophys. 251, 620–624 (1991)

ASTRONOMY AND ASTROPHYSICS

# The nature of the nebula associated with the luminous blue variable star WRA 751 *

**D. Hutsemékers and E. Van Drom**

Institut d'Astrophysique, Université de Liège, 5 av. de Cointe, B-4000 Liège, Belgium

Received April 3, accepted June 27, 1991

**Abstract.** We present narrow-band filter imagery as well as medium to high resolution spectroscopy of the nebula surrounding the luminous blue variable (LBV) star WRA 751.

The nebula appears as a slowly expanding H II region of low excitation characterized by a significant N/O overabundance which may be due to the presence in the nebula of nuclear processed material ejected by the star.

With the recent discovery of a nebula around HR Car, all but one known galactic LBVs are now shown to be associated with a nebula. These nebulae have rather similar physical characteristics, one of the most important being that all of them apparently contain processed material.

**Key words:** luminous blue variable stars –mass-loss – emission nebulae – WRA 751

## 1. Introduction

WRA 751 is a galactic luminous blue variable star (LBV) recently identified by Hu et al. (1990).

These stars are very luminous evolved supergiants characterized by irregular outbursts or eruptions. Although no more than ten LBVs have been observed in the Galaxy and the Large Magellanic Cloud, they are generally considered as a short but physically important stage in the evolution of massive stars towards the WR stage. They constitute a quite unique group for studying the physics of the stars near the Humphreys-Davidson stability limit (Humphreys 1989).

One of the most interesting characteristics of the LBVs is certainly that some of them are surrounded by a small nebula apparently formed of matter ejected by the star and giving evidence for enrichment by nuclear processed material. The analysis of these nebulae may provide some important clues for understanding the LBV phenomenon and the evolutionary status of these stars.

Since, up to now, very few have been observed, we have started a systematic search and study of the nebulosities associated with luminous emission-line stars in order to better constrain their properties and to know if they constitute a new, quite homogeneous class of nebulae (Hutsemékers & Van Drom 1991 b). Some results have already been presented for the cases of *CD*−42°11721 and HR Car (Hutsemékers & Van Drom 1990, 1991 a). The current paper is devoted to the analysis of new observations of the nebula surrounding the LBV star WRA 751.

WRA 751 (= He3-591) has first been classified as a possible WR star by Henize (Roberts 1962) and later as a Bep type star by Carlson & Henize (1979). These authors have found that the spectrum of WRA 751 is characterized by strong Fe II and [Fe II] emission lines which can be as prominent as the H$\beta$ emission line. On the basis of a photometric and spectroscopic investigation, Hu et al. (1990) suggest WRA 751 as a candidate for a new LBV. They report that this star is variable, very luminous ($M_{\rm bol} = -9\overset{\rm m}{.}6$) and has an equivalent spectral type O9.5. By comparing the spectral energy distributions, and more specifically the IR excesses, they note a definite similarity with AG Car and HR Car, two well known galactic LBVs which also show bright Fe II emission lines in their spectra. In a more detailed study confirming the LBV nature of WRA 751 (de Winter 1990), they also find that this star is most probably embedded in a nebulosity.

In the remainder of this paper, we present narrow-band CCD imagery and medium to high resolution spectroscopy of the nebula associated with WRA 751.

## 2. The observations

The observations of WRA 751 were carried out at the European Southern Observatory (ESO, La Silla). For all the observations, spectroscopy and imagery, the detectors were high resolution CCD chips of type RCA SID 503, 1024 × 640 pixels, each 15 μm$^2$.

The usual calibration frames (bias, darks, flat-fields as well as spectra of HeAr, ThAr and spectrophotometric standard stars) have been obtained. The reduction was performed using the standard IHAP and MIDAS packages available at ESO.

In most cases, we have obtained more than one frame for a given spectroscopic or imaging configuration. All these frames were reduced individually before their eventual comparison and/or addition.

### 2.1. Imagery

The images of WRA 751 and its nebula were obtained using the 2.2 m telescope equipped with the direct camera and the 3.6 m

*Send offprint requests to:* D. Hutsemékers

* Based on observations collected at the European Southern Observatory (ESO, La Silla)

**Table 1.** Imaging observations of WRA 751 and its nebula

| Date | Instrument | Filter | $\lambda_c$/FWHM (Å) | Exposure time (min) | Seeing |
|---|---|---|---|---|---|
| 27/04/90 | 2.2 m | [N II] | 6580/20 | 5+10+15+30 | 1″.6 |
| 27/04/90 | 2.2 m | [O III] | 5007/27 | 15 | 1″.8 |
| 29/04/90 | 2.2 m | Hα+[N II] | 6572/40 | 15 | 1″.2 |
| 29/04/90 | 2.2 m | [N II] | 6580/20 | 20 | 1″.0 |
| 29/04/90 | 2.2 m | [O III] | 5007/27 | 60 | 1″.3 |
| 30/04/90 | 2.2 m | continuum | 6450/61 | 10 | 1″.2 |
| 28/06/90 | 3.6 m+EFOSC | Hα+[N II] | 6548/63 | 2+3 | 1″.4 |

**Table 2.** Spectroscopic observations of the nebula surrounding WRA 751

| Date | Instrument | Spectral range (Å) | Resolution (Å) | Exposure time (min) |
|---|---|---|---|---|
| 10/05/90 | CAT+CES | 6535–6592 | 0.12 | 2×30+60 |
| 15/05/90 | 1.5 m+B&C | 4820–6800 | 4.7 | 15+30 |
| 16/05/90 | 1.5 m+B&C | 4820–6800 | 4.7 | 60 |
| 17/05/90 | 1.5 m+B&C | 3570–5510 | 4.9 | 2×60 |
| 18/05/90 | 1.5 m+B&C | 3570–5510 | 4.9 | 60 |
| 19/05/90 | 1.5 m+B&C | 4820–6800 | 4.7 | 60 |
| 28/06/90 | 3.6 m+EFOSC | 3600–7000 | 6.4 | 10 |
| 01/12/90 | 1.5 m+B&C | 4550–7450 | 5.3 | 50 |

telescope equipped with the EFOSC camera (Melnick et al. 1989). At the 2.2 m and 3.6 m telescopes, the RCA CCD pixel size of 15 μm corresponds to 0″.175 and 0″.337 on the sky, respectively. We essentially used narrow-band interference filters centered on the spectral lines of Hα, [N II], [O III] and a red continuum.

A summary of these imaging observations is given in Table 1, together with the filter characteristics.

We should notice that in nearly all frames, the image of WRA 751 does not reach the saturation level.

### 2.2. Spectroscopy

Low dispersion spectrograms of the nebula surrounding WRA 751 were obtained at the 1.52 m telescope equipped with a Boller and Chivens spectrograph (Heydari-Malayeri et al. 1989). They cover the 3570–7450 Å spectral range. In May 90, the 2″.0 wide slit was oriented E–W and positioned in order to cross the northern part of the nebula, i.e. at ∼9″ from the star. In December 90, the spectrum was recorded using a 1″.1 wide slit oriented E–W and positioned ∼8″ south of the star. An additional spectrogram was obtained with the EFOSC spectrograph attached to the 3.6 m telescope (Melnick et al. 1989), the 0″.75 wide slit being positioned north of the star and oriented E–W as in the May 90 B&C observations.

Because the slit has to be positioned quite near the star which is comparatively bright, the spectrum of the nebula is often contaminated by the stellar one. Fortunately, most of this contamination is spatially well defined on the two-dimensional spectrum and can therefore be eliminated during the reduction procedure. For the spectrograms obtained under bad seeing conditions, a small contamination is still present, its most unpleasant effect on the nebular spectrum being an increase of the Hα emission line intensity relative to other nebular emission lines like [N II] or [S II], Hα being very prominent in the spectrum of the star itself. We should therefore keep in mind that even for the good spectrogram discussed in the next section and for which the contamination is certainly small, the Hα emission line intensity might be slightly overestimated. Excepting this effect, the spectra recorded at different epochs essentially show the same features.

Higher dispersion spectrograms centered on the Hα emission line were obtained with the CES spectrograph attached to the CAT telescope (Lindgren & Gilliotte 1989), the full-length 2″.0 wide slit (decker removed) being positioned on the star.

The spectra of the nebula have been sky-subtracted, this subtraction taking also into account the eventual contamination due to the very faint diffuse nebulosity in which WRA 751 looks embedded. This ambient nebulosity, which does not seem related to WRA 751, is detectable on the ESO/SRC sky survey plates and most probably belongs to the Carina nebula located in front of the star.

Table 2 gives a summary of the spectroscopic observations.

## 3. The characteristics of the nebula

### 3.1. The optical morphology

Figure 1 illustrates an image of WRA 751 and its surroundings obtained in the Hα + [N II] light. The image clearly shows the presence of a nebula around WRA 751, whose morphology,

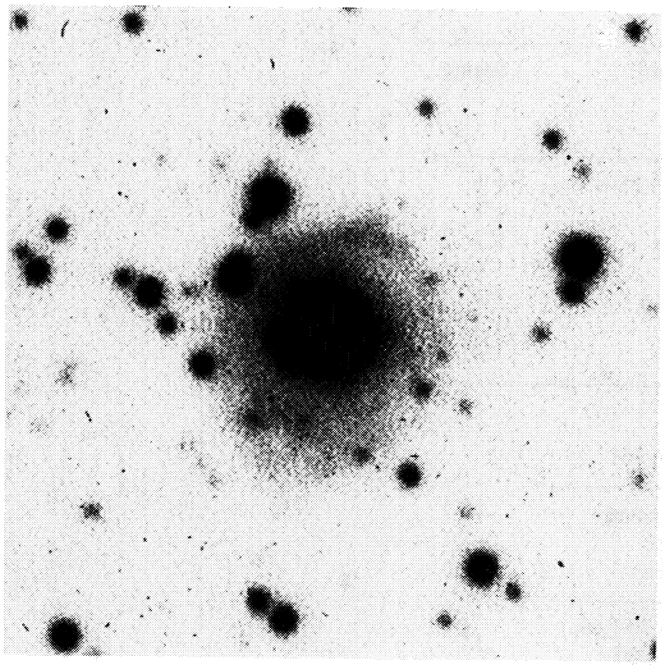

**Fig. 1.** An image of WRA 751 and its nebula in the Hα + [N II] light. This image is the weighted sum of the frames obtained at the 2.2 m telescope with the Hα + [N II] and [N II] filters. On all these frames the stellar image was not saturated. The resultant seeing is 1".3 FWHM. The field is 1' × 1'. North is up, east to the left

mainly symmetric relative to the star, gives evidence for a physical association. The nebula is roughly circular, 22" in diameter, and slightly elongated in the NW–SE direction. It is apparently not detached from the star. The surface brightness is not uniform: the easter part of the nebula is brighter than the western part while an arc-shaped condensation is well seen at the NW edge. On our best seeing image, a similar feature is suspected at the opposite SE edge, as well as some filamentary condensations to the west.

On the frames obtained with the [O III] and continuum filters the nebula is not detected indicating that it is not of reflective nature but mainly of emission type.

We should also notice that WRA 751 is located in a rather crowded field of stars, two of them being quite near: one is located at 3".2 E, 0".8 S from WRA 751 and the other at 2".9 N, 0".7 E. The first of these stars, easter of WRA 751, is only $2^{m}.5$ fainter in the [O III] filter and should therefore be taken into account in doing precise photometry.

### 3.2. *The spectrum and physical characteristics*

The optical spectrum of the nebula surrounding WRA 751 essentially consists of the Balmer emission lines Hα and Hβ in addition to the [NII] λλ 6548–6583 and [S II] λλ 6716–6731 forbidden lines (Fig. 2). It is quite remarkable by the low excitation, the strong Hα/Hβ ratio as well as the absence of oxygen lines like [O I] λ 6300, [O II] λλ 3726–3729 or [O III] λλ 4959–5007. Since the blue [O II] lines, if present, may be difficult to see due to the strong extinction indicated by the Hα/Hβ ratio, we have searched for the [O II] λλ 7320–7330 lines which are not observed in the spectrum recorded in December 90. Compared to the presence of bright [N II] lines in the spectrum, the absence or weakness of oxygen lines for three stages of ionization suggests a significant N/O overabundance in the nebula.

Assuming case B recombination with $T_e = 10^4$ K, we use the Hα/Hβ ratio to determine the logarithmic extinction coefficient $c(H\beta) \simeq 3.1$ which corresponds to $A_V \simeq 6.5$. This high value confirms, in the limit of the uncertainties, the large extinction towards WRA 751 already found by Hu et al. (1990) from photometric observations. The corrected emission line ratios $I(\lambda)/I(H\alpha)$ are given in Table 3, together with the measured ratios $F(\lambda)/F(H\alpha)$.

Since the [N II] λ 5755 emission line is not observed in our spectra, only an upper limit to the electron temperature $T_e$ may be estimated. Adopting $I([N\,II]\lambda 5755)/I([N\,II]\lambda 6548 + \lambda 6583) \leqq 0.03$, we find $T_e \leqq 15000$ K. The electron density is derived from the [S II] line ratio: $n_e \simeq 400\ cm^{-3}$ (Aller, 1984). These values are typical of normal H II regions. Considering the [N II]/Hα, [S II]/Hα and [O III]/Hβ line ratios in the framework of classification diagrams like those constructed by Veilleux & Osterbrock (1987), we can see that the spectrum of the nebula associated with WRA 751 is compatible with the spectrum of a photoionized H II region in which N is overabundant relative to H while S/H is

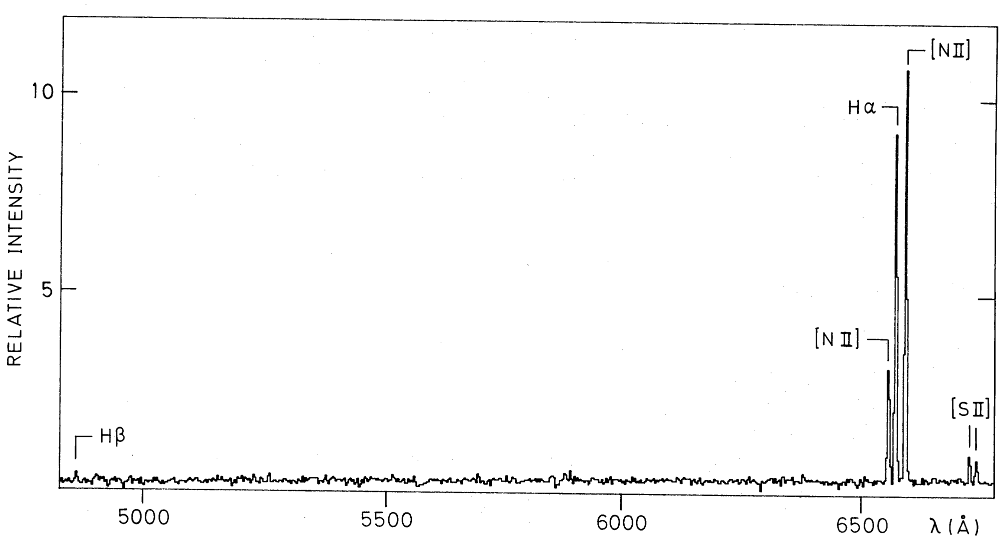


**Fig. 2.** A good red spectrum of the northern part of the nebula surrounding WRA 751. It was obtained on May 19, 1990 with the B&C spectrograph attached to the 1.52 m telescope

**Table 3.** Relative intensities of the emission lines observed in the spectrum of the nebula surrounding WRA 751

| Line | $F(\lambda)/F(\mathrm{H}\alpha)$ | $I(\lambda)/I(\mathrm{H}\alpha)$ |
|---|---|---|
| Hβ | 2.8: | 35: |
| Hα | 100 | 100 |
| [N II] λ6548 | 37 | 37 |
| [N II] λ6583 | 113 | 113 |
| [S II] λ6716 | 6.7 | 5.8 |
| [S II] λ6731 | 6.3 | 5.4 |

normal. It is very interesting to notice that these emission line ratios are nearly identical to those measured in the spectrum of M1–67, the ring nebula surrounding the WN 8 star 209 BAC, in which Esteban et al. (1991) have recently found a remarkable abundance pattern i.e. a strong N/O overabundance due to both N/H enhancement and O/H deficiency.

Bright nebular [N II] lines are also well seen on the CES spectra, superimposed on the stellar spectrum and significantly narrower than the stellar Hα emission line. These lines are resolved in two peaks of nearly equal brightness suggesting that the nebula is expanding. From the separation of the peaks, we measure an expansion velocity of $\sim 26\,\mathrm{km\,s^{-1}}$, while the FWHM/2 gives $\sim 39\,\mathrm{km\,s^{-1}}$. In fact, the [N II] and Hα lines are spatially resolved on the two-dimensional CES spectra, clearly extending out of the stellar spectrum (see Fig. 3). The [N II]/Hα intensity ratio measured on this spatially extended nebular spectrum is in agreement with the values reported in Table 3. Despite the low signal-to-noise ratio (the observations were not initially intended for this purpose), we can see that the overall velocity distribution of these lines roughly corresponds to the symmetric expansion of a sphere of non uniform brightness, more material being redshifted than blueshifted at least for this position of the slit (Fig. 3). Very interesting is the fact that the part of the [N II] lines which is superimposed on the stellar spectrum has a much greater intensity. These lines may be partially formed near the star but not in the stellar wind whose terminal velocity, measured from the Hα P Cygni type profile, amounts to $190\,\mathrm{km\,s^{-1}}$. On low dispersion spectra of the star recorded at the same time as those of the nebula (in May 90), faint [S II] lines are clearly observed in addition to the [N II] ones but with an intensity ratio $I(\lambda 6716)/I(\lambda 6731) \simeq 0.6$ indicating that a much higher electron density, $n_e \simeq 2500\,\mathrm{cm^{-3}}$, prevails closer to the star. On the other hand, the intensity of these [S II] lines relative to the [N II] lines is the same as in Table 3, giving no indication for a different excitation mechanism. These observations suggest that the nebula is extending up to close to the star, its density increasing towards the center with apparently no change of the expansion velocity. They also indicate that the distribution of matter in the nebula significantly departs from the spherical symmetry, as suspected from the imagery.

Finally, adopting a kinematic distance of 7 kpc determined from the heliocentric radial velocity of the [N II] lines, +24 $\mathrm{km\,s^{-1}}$, and in good agreement with the distance suggested by the large extinction (Hu et al. 1990), the nebula has a radius of 0.38 pc. Assuming a constant expansion velocity of $26\,\mathrm{km\,s^{-1}}$, this radius corresponds to a kinematic age of $1.5\;10^4$ years. With the approximation that the nebula is spherical and homogeneous, we may also give a rough estimate for the mass of the ionized gas: $\sim 3.2\,M_\odot$.

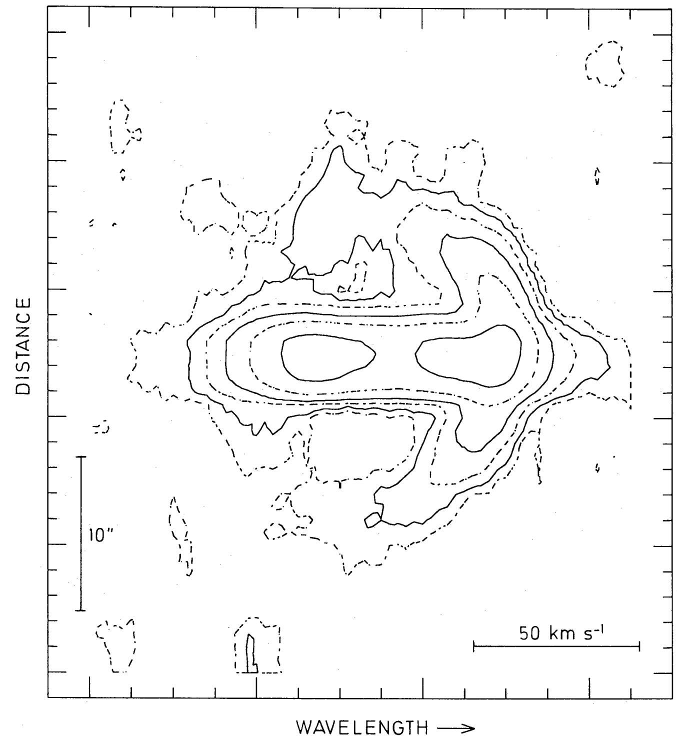


**Fig. 3.** Smoothed contour plots of the [NII] λ 6583 emission line observed in the CAT + CES spectrum of WRA 751. The adjacent stellar continuum has been subtracted. Between the contours, the intensity increases by a factor 2. The slit was roughly oriented NE–SW, NE at the top (because the field is rotating at the CAT, the orientation of the slit is not precisely known)

## 4. Discussion and conclusions

From the present observations, the nebula associated with WRA 751 appears as an expanding H II region of low excitation and non uniform brightness. It shows a significant N/O overabundance which suggests that it is constituted, at least in part, of processed material most probably ejected by the star whose mass-loss, as for other LBVs, should be quite strong. The data are in agreement with the interpretation that WRA 751 is a very luminous evolved star.

The presence of a nebula around WRA 751 strengthens the perspective that the formation of a nebula is an important characteristic of the LBV evolutionary stage: if we except P Cygni, all the other galactic LBVs – η Car, AG Car, HR Car as well as the possibly related star He3-519 – are embedded in nebulosities while many LBVs of the LMC have spectroscopically detected circumstellar shells (Walborn 1982; Wolf & Stahl 1986), some of them being resolved by direct imagery (Stahl 1987). Despite definite differences, the physical and chemical characteristics prevailing in the nebula associated with WRA 751 are in first approximation remarkably similar to those reported for the nebulae surrounding AG Car and HR Car (Mitra & Dufour 1990; Hutsemékers & Van Drom 1991a). Also the nebulae resolved around two LMC Ofpe/WN9 stars and the one around He3-519 have comparable masses and densities (Stahl 1987). The majority of these nebulae seem to constitute a class of objects whose characteristics, significantly different from those of classical planetary nebulae, appear rather homogeneous, suggesting that their formation may be due to a common physical mechanism. We should nevertheless remark that, unlike the case of AG Car, the nebula surrounding

WRA 751 does not appear detached from the star, suggesting that it is due more to a continuous mass-loss rather than to a sudden outburst.

In this view, it is striking that P Cygni, whose luminosity is intermediate between that of AG Car and HR Car (Humphreys 1989), is not surrounded by a comparable nebulosity (the radio arc detected in the vicinity of P Cygni is not really comparable (Baars & Wendker 1987; Lamers 1989; see also Stahl 1989). But, if the stellar spectra of both AG Car and HR Car are, at some epochs, nearly identical to that of P Cygni, they nevertheless reveal a much stronger N/O overabundance: the oxygen lines are practically absent from the spectra of AG Car and HR Car (Caputo & Viotti 1970; Hutsemékers & Kohoutek 1988; Hutsemékers & Van Drom 1991a) while they are well seen in that of P Cygni (Luud 1967). Since a significant N/O overabundance is also observed in the nebulae surrounding AG Car and HR Car (Mitra & Dufour 1990; Hutsemékers & Van Drom 1991a), it is tempting to say that the ejection of a nebula arises at a peculiar moment of the LBV stage, when a sufficient amount of nuclear processed matter is present at the stellar surface. In this view, P Cygni could be in a younger evolutionary stage than AG Car and HR Car. It would be worthwile to obtain a high resolution spectrum of WRA 751 near the minimum phase in order to see if this star also shows such a strong N/O overabundance as AG Car and HR Car.

Finally, it is particularly interesting that the physical conditions prevailing in the nebula associated with WRA 751 are apparently similar to those prevailing in some WR ring nebulae like M1–67, especially if we consider the N/O ratio (Vilchez & Esteban 1991; Esteban et al. 1991). This gives further support to the idea that there exists a close relationship between these two classes of stars.

It is definitely clear that before one draws definite conclusions more nebulae of this kind should be known and studied. In a future work, we will analyse other objects which could be related to those discussed in this paper.

*Acknowledgements.* Part of this work was done when the authors were at the European Southern Observatory, La Silla. This research is also supported in part by contract ARC 90/94-140 "Action de recherche concertée de la Communauté Française" (Belgium).

**References**

Aller L. H., 1984, Physics of Gaseous Nebulae. Reidel, Dordrecht
Baars J. W. M., Wendker H. J., 1987, A&A 181, 210
Caputo F., Viotti R., 1970, A&A 7, 266
Carlson E.D., Henize K.G., 1979, Vistas Astron. 23, 213
de Winter D., 1990 (private communication)
Esteban C., Vilchez J. M., Smith L. J., Manchado A., 1991, A&A 244, 205
Heydari-Malayeri M., Jarvis B., Gilliotte A., 1989, ESO Operating Manual No. 9
Hu J. Y., de Winter D., Thé P. S., Pérez M. R., 1990, A&A 227, L17
Humphreys R.M., 1989, Physics of Luminous Blue Variables. IAU Coll. 113, Kluwer, Dordrecht, p. 3
Hutsemékers D., Kohoutek L., 1988, A&AS 73, 217
Hutsemékers D., Van Drom E., 1990, A&A 238, 134
Hutsemékers D., Van Drom E., 1991a, A&A 248, 141
Hutsemékers D., Van Drom E., 1991b (in preparation)
Lamers H.J.G.L.M., 1989, Physics of Luminous Blue Variables. IAU Coll. 113, Kluwer, Dordrecht, p. 135
Lindgren H., Gilliote A., 1989, ESO Operating Manual No 8
Luud L. S., 1967, SvA 11, 211
Melnick J., Dekker H., D'Odorico S., 1989, ESO Operating Manual No 4
Mitra P. M., Dufour R. J., 1990, MNRAS 242, 98
Roberts M. S., 1962, AJ 67, 79
Stahl O., 1987, A&A 182, 229
Stahl O., 1989, Physics of Luminous Blue Variables, IAU Coll. 113, Kluwer, Dordrecht, p. 149
Stahl O., Wolf B., 1986, A&A 158, 371
Veilleux S., Osterbrock D. E., 1987, ApJS 63, 295
Vilchez J. M., Esteban C., 1991, Wolf-Rayet stars and Interrelations with Other Massive Stars in Galaxies. IAU Symp. 143, Reidel, Dordrecht, p. 379
Walborn N.R., 1982, ApJ 256, 452