CIRCUMSTELLAR EJECTA AROUND LBV'S

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ABSTRACT. The properties of circumstellar shells around LBV's are reviewed. Some LBV's are surrounded by very extended nebulosities, similar to classical planetary nebulae, with AG Car as the prototype. The masses of these nebulae are of the order of a solar mass and their kinematic ages are about 10^4 years. The origin of these nebula is still controversial, but they probably have been ejected in some major outburst in the past. It is then remarkable that the historical outburst of P Cyg has left no bright remnant. There is evidence for CNO processed matter in the ejecta. LBV's with no detectable extended emission also commonly have nebular emission lines. Some of these nebulae are probably related to the resolved nebulae, but some certainly are very much smaller and have much higher densities.

1 Introduction

The observations of circumstellar shells around LBV's are important for a number of reasons.

- The analysis of the spectra of the circumstellar ejecta is much easier than the analysis of the complicated stellar spectra, which is now just becoming feasible. Especially, the chemical abundances of the ejecta can be studied with standard techniques from the nebular lines.
- The circumstellar ejecta allow us to study the mass-loss history of the central stars and also the integrated mass-loss rates, in particular the importance of major eruptions, which are rarely directly observable.

Nevertheless, so far only limited information is available for the circumstellar ejecta around LBV's. This information will be reviewed here.

K. Davidson et al. (eds.), Physics of Luminous Blue Variables, 149–157.

https://doi.org/10.1017/S0252921100004401 Published online by Cambridge University Press

2 Galactic objects

The analysis of spatially resolved objects allows to extract more information than is possible with unresolved objects. Obviously, the galactic objects are most easily resolved. Unfortunately, few LBV's are known in the Galaxy. Most people agree that η Car, AG Car and P Cyg are galactic LBV's. Probably HR Car should be added to this list, but it is a very little studied star. A number of direct images in narrow band filters (Stahl, unpublished) did not reveal any nebulosity around HR Car.

2.1 η Car

The nebula around η Car is of course very well known. Both η Car and its nebula are unique objects and thus it is dangerous to draw general conclusions from η Car. It should suffice here to say that the η Car nebula has a mass of a few solar masses and is expanding with a velocity of about 700 $\mathrm{km\,s^{-1}}$. (For more details see the paper by Davidson in this volume.)

2.2 AG Car and He3-519

The ring nebula around AG Car has been discovered by Thackeray (1950). It is roughly elliptical with a size of about $40 \times 30''$. Milne and Aller (1975) detected the nebula in the radio continuum. Johnson (1976) observed the nebula spectroscopically with a Fabry-Perot instrument. He derived a density and a mass for the nebula. Long-slit spectra of the nebula have been discussed by Thackeray (1977). He found a complicated velocity field which we do not want to discuss here in detail. The typical expansion velocity is ≈ 50 $\mathrm{km\,s^{-1}}$. Viotti et al. (1988) found from IUE observations of the star and the nebula that the nebula reflects starlight and thus contains dust. Dust emission from the nebula in the far-IR was detected and discussed by McGregor et al. (1988). (See also the review of Mc Gregor in this volume). Spectacular high resolution images of the AG Car nebula have been obtained by Paresce (this volume).

AG Car has always been assumed to be at the distance of the Car OB association. New distance determinations based on the radial velocity of the star and the nebula (Humphreys, this volume) and the extinction to the star (Hoekzma and Lamers, this volume) favor a larger distance of up to 7 kpc. This has of course implications for the inferred properties of the nebula, in particular its age and mass. The properties of the nebula (based on a distance of 2.5 kpc) have been reviewed by Stahl (1987). With a revised distance of 7 kpc, the nebula becomes older and more massive.

The object He3-519 has also been discussed by Stahl (1987). The star is not known to be an LBV, but its spectrum is similar to AG Car in minimum, suggesting a relation with the LBV's. It is surrounded by a ring nebula with a diameter of about $1'$. The distance of the object is uncertain, but likely larger than the distance to AG Car, since its reddening is larger and the distance on the sky to AG Car is only $20'$. A detailed study of the object has not yet been done but is certainly worthwhile.

2.3 P Cygni

Since it is well known that P Cygni had an outburst in the 17th century, several people have tried to find a remnant similar to the shells around η Car and AG Car. Indeed Wendker (1982) and Baars and Wendker (1987) found extended radio-emission ($\approx 30''$ radius) around P Cygni which may be due to the outburst. Although initially thought to be of non-thermal origin, the emission is now considered to be thermal. No optical counterpart of the radio emission is known, but there is no report of a serious attempt to find it.

Recently Leitherer and Zickgraf (1987) (hereafter called LZ) reported the detection of a small ($\leq 8''$) circumstellar shell around P Cygni by direct imaging with narrow-band filters around Hα and [NII]λ6583 and a CCD detector. Interestingly, they found that the radial slope of the emission was consistent with the assumption that the emission was due to a continuous ejection of small shells with constant average mass-loss rate This is different from all other known cases of circumstellar shells around LBV's where the emission arises in a detached shell.

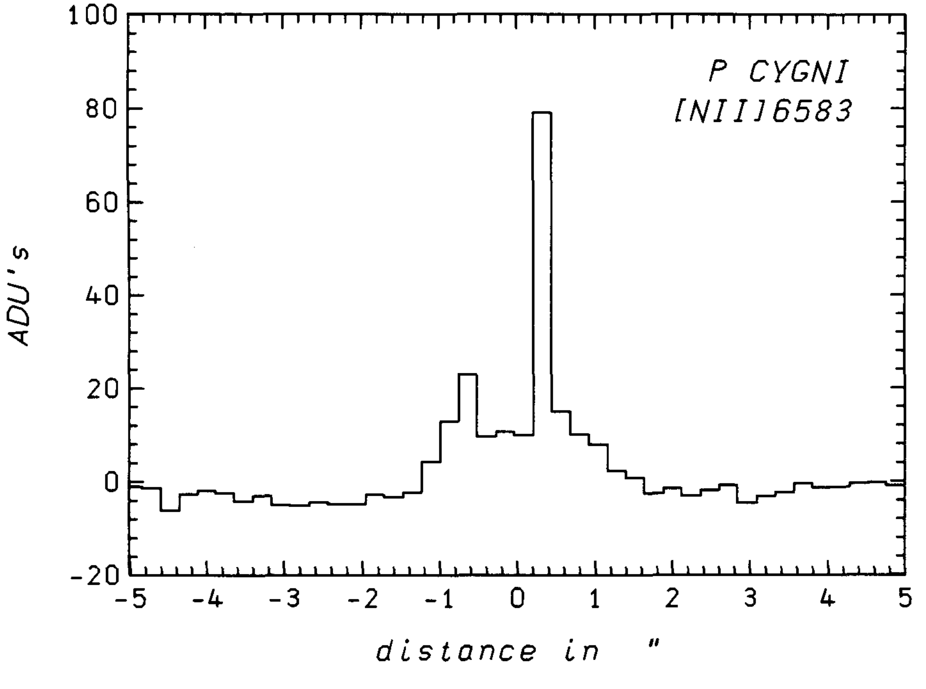

Figure 1: Difference of the line and continuum cross-dispersion profiles of a long-slit spectrogram of P Cygni in the line [NII]λ6583 and in the neighboring continuum. The difference from zero is not considered to be significant. One ADU very roughly corresponds to $\approx 5\,10^{-13}$ erg cm^{-2} s^{-1} arcsec^{-2}.

I observed, together with F.-J. Zickgraf, P Cyg with the coudé spectrograph of the 2.2m telescope of the DSAZ at Calar Alto, Spain in Sep. 1987 using the coudé spectrograph with the f/12 camera which gives a reciprocal linear dispersion of about 2.2 Å/mm in second order. The slit was opened to about $0\farcs5$.

We compared the cross-dispersion profile around the [NII]λ6583 line with cross-dispersion profiles around this wavelength. The cross-dispersion profile was averaged from 6580.5 to 6586.5 Å to give the spatial profile in the line and from 6574 to 6580 and 6587 to 6593 to give the spatial profile in the adjacent continuum (average of the flux in a 0.1 Å wavelength bin). Assuming that the shell emission is negligible close to the center of the profile, we matched both profiles in the central pixels. The difference *line-continuum* of the spatial profiles is shown in Figure 1.

The difference from zero is typically smaller than 1% of the total flux and not considered significant. The absolute calibration in line fluxes is difficult since it depends on assumptions about slit losses and the line profile from the shell. One ADU very roughly corresponds to $\approx 5\,10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,arcsec^{-2}}$. The upper limit is then (at distances larger than $\approx 2''$) $\approx 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,arcsec^{-2}}$. LZ measured $\approx 5\,10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,arcsec^{-2}}$ at $2''$, decreasing with the distance to the power of -3. This is significantly larger than the upper limit derived from the data shown in Figure 1.

How can the discrepancy be explained? LZ determine the radial profile averaged over all position angles, where we have only the profile at one position angle. A strongly flattened nebula could thus explain the difference. It is unlikely, however, that LZ would not have noticed such a nebula. A more likely explanation for the effect is that LZ seriously undersampled their images: LZ mention a seeing (FWHM) of $0\farcs6$ with a pixel size of $0\farcs46$. In such circumstances the radial profile of the star close to the center is very poorly determined and it strongly depends on the center of the star with respect to the center of the pixels. Since LZ compared the radial profiles of P Cygni with the profiles of a comparison star, a slightly different placement of the stars with respect to the center of the pixels may change the radial profile in the center drastically. We would then expect that the two radial profiles of the logarithm of the brightness are parallel outside the central pixels. This seems indeed to be the case, at least within the error bars given by LZ. Thus there is no convincing evidence that P Cygni is surrounded by an extended emission region. A more thorough search may be worthwhile.

3 Objects in the Magellanic Clouds and beyond

3.1 Spectroscopy

Nebular emission lines of circumstellar origin are very frequently observed in spectra of emission-line stars (see e.g. Stahl and Wolf, 1986). The strongest lines usually are [NII]$\lambda\lambda$6548, 6583. In almost all cases, the lines are narrow (typically FWHM $\approx$ 40 $\mathrm{km\,s^{-1}}$. All the known S Dor-variables in the LMC show these emission lines (see Figure 2). The B[e]-supergiants also frequently have [NII] lines, but in these stars

[OI]$\lambda\lambda$6300, 6363 are the dominant forbidden lines (see also Zickgraf, this volume). Other emission-line stars also frequently have forbidden emission lines. In some cases the electron density of the shell can be determined from diagnostic line ratios. The range of densities is large, from $\leq 10^3\,\mathrm{cm}^{-3}$ to $\approx 10^7\,\mathrm{cm}^{-3}$. In the high density nebulae, [NII]λ5755 is strong.

For most stars of this sample not much is known about the origin of the forbidden lines. In the B[e] supergiants, the forbidden lines are assumed to originate in the outer parts of the circumstellar disk. In very few cases the nebulosities have been spatially resolved.

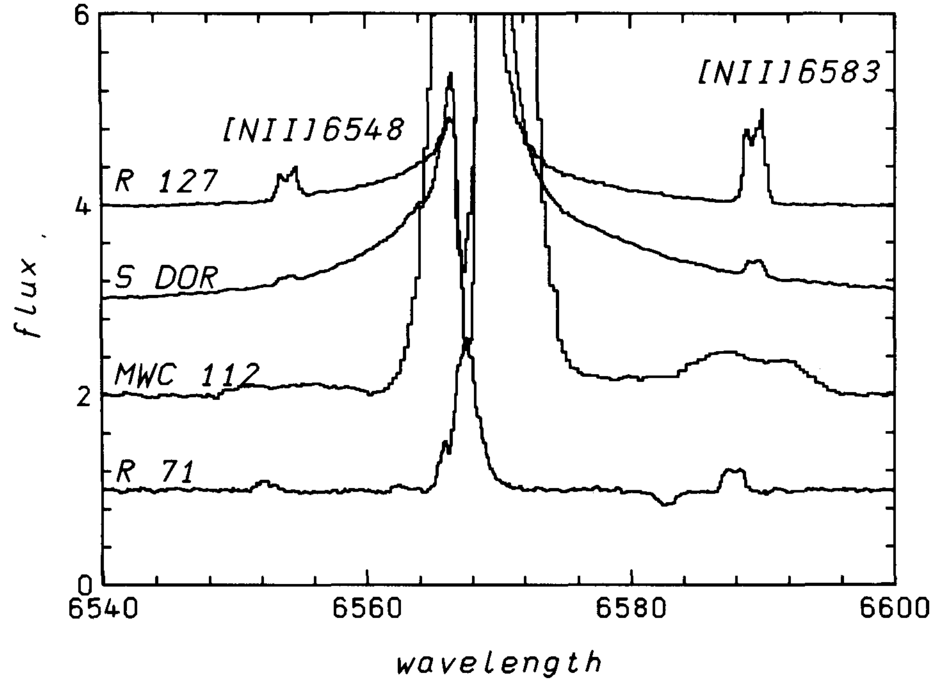

Figure 2: The wavelength region around Hα and [NII]$\lambda\lambda$6548, 6583 in the known S Dor variables in the LMC. All stars have the [NII] emission lines which are split in two components. In all cases except MWC 112 the lines are narrow with a FWHM of only about 40 $\mathrm{km\,s^{-1}}$. MWC 112 has much wider forbidden lines.

3.2 Imaging

Scaling the nebula around AG Car to the distance of the LMC, we expect an angular size of a few arcseconds. Although this should be easy to resolve from the ground, the

https://doi.org/10.1017/S0252921100004401 Published online by Cambridge University Press

emission is close to a bright star and so the detection of such shells is difficult due to the small contrast. Only the brightest shells can be expected to be seen. I conducted a survey of direct imaging in narrow-band filters of luminous emission-line stars in the Magellanic Clouds. Part of the results have been published by Stahl (1987). A larger sample has actually been observed. Only 2 out of 24 objects observed could be resolved. These objects are R 127 and S 61 (=Sk-67 266). These two objects have already been found by Walborn (1982) to show strong [NII]$\lambda\lambda$6548, 6583 emission lines. The two resolved objects appear to be objects similar to the AG Car nebula, even more similar, if the larger distance to AG Car is adopted.Some of the unresolved objects in the MC's may also have extended emission, which is just too faint to be seen against the background of the bright star.

Only R 127 is a known LBV, but S 61 is probably spectroscopically almost a twin to R 127 in minimum (Walborn, 1982). The failure to resolve the other objects may be partly due to the limited sensitivity of the observations. However, some nebulae are probably very small.

3.3 High-density nebulae

This shall be demonstrated with the star MWC 112, which is surrounded by a high-density nebula. In addition to the [NII] lines around Hα, MWC 112 also has rather strong [FeIII] lines. The following analysis is due to Kris Davidson and will be published in more detail elsewhere. From the intensity ratio of the [FeIII] lines a likely nebular electron density of $\approx 10^7\,\mathrm{cm}^{-3}$ can be derived. The mass of the gas can be found from the [NII]λ6583 line ($\approx 10^{-3.5}\,\mathrm{M}_\odot$), assuming abundances appropriate for CNO processed matter. From the density and the mass a volume can be inferred and thus a minimum radius ($\approx 10^{15.2}\,\mathrm{cm}$) for the shell. For this radius, the travel time is of the order of only a few years. Thus, the nebula is clearly different from the large shells observed around AG Car and R 127. The most likely origin of the nebular lines is in this case a shock where the present high-velocity wind shocks the matter expelled in an outburst a few years ago.

3.4 The Hubble-Sandage variables in M31 and M33

Nebular emission lines have also been found in the spectra of the Hubble-Sandage variables in M31 and M33 (see Humphreys et al., this volume), demonstrating again that these objects are physically very similar to the S Dor variables. AE And is the most extreme case among the HS-variables, showing extremely strong nebular emission lines.

4 Chemical abundances and relation to other objects

Our knowledge about the chemical abundances of the ejecta is rather limited. The outer condensations of the η Car nebula have been studied by Davidson et al. (1982). They found a very high abundance of N with respect to O and C, consistent with

CNO-processed matter. S 61 has been analysed by Walborn (1982) and was also found to be N-rich and O-poor, if compared with LMC HII regions. The AG Car nebula has recently been analyzed by Dufour and Mitra (1987). They also give an O/H underabundance. So, from this limited number of observations, there is evidence for CNO-processed matter in the nebulae.

Since the LBV's may evolve to WR stars, one may suspect that the circumstellar shells around LBV's evolve to the well-known ring nebulae surrounding some WR stars. However, these nebulae are in most cases much more massive than the LBV nebulae and may consist mainly of swept-up interstellar matter. The bipolar nebula around the Of?p star HD 148937 may also be related to the nebulae around the LBV's. It is also N-rich (Leitherer and Chavarria, 1987; Dufour et al., 1988).

The bipolar structure of the nebula around HD 148937 may also be related to the double-peak structure seen in the spectra of the nebular lines of the LBV's in the LMC. In fact, there is ample evidence for bipolar ejection of the nebulae. The cause of this bipolarity is unclear. It is also not clear, why the nebular lines are so narrow in almost all cases.

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DISCUSSION

Schulte-Ladbeck: Franz-Josef Zickgraf and I have measured linear polarization as a function of wavelength for a number of Galactic B[e] stars, and the results are indicative of the presence of circumstellar disks (paper submitted to *Astr.& Astrophys.*).

Lamers: Recent observations of the radio arc around P Cygni indicate that the arc is due to thermal radiation (Baars & Wendker 1987: *Astr.& Astrophys.* **181**, 210).

Heap: What is the evidence **against** AG Carinae being the central star of a planetary nebula?

Stahl: I think everybody agrees that the distance to AG Carinae, though uncertain, is at least 2.5 kpc. Therefore the bolometric luminosity is brighter than -8, significantly more luminous than central stars of planetary nebulae.

Davidson: Some of your objects have [N II] profiles that are flat-topped at first glance, double-peaked on closer examination, with low velocities in most cases but faster in the case of MWC 112. As you have remarked sometimes, these profiles hint at bipolar or axial structure. But it's worth mentioning that the precise form of this axial symmetry is not obvious. In particular, the [N II] does not necessarily have to be in an equatorial disk; similar line profiles might originate in a symmetrically incomplete expanding shell. I say this because hypothetical disks sometimes have embarrassingly small volumes for emitting forbidden lines, especially if orbit-velocity assumptions require them to be only a few a.u. across.

Humphreys: You said very little about R71. Is there evidence for circumstellar ejecta around this star? It is the lowest-luminosity LBV and the one most likely to have been through a red supergiant stage. It does not have a ring nebula or shell, so far as I know. R71 does have a cool dust shell, possibly a remnant of a red supergiant stage.

Stahl: R 71 has [N II] λ6583 emission, not very strong. We could not spatially resolve this shell; maybe it is just slightly too small to resolve from the ground.

Walborn: (1) The two LMC stars with resolved shells, R 127 (= HDE 269858) and S61 (= Sk -67° 266), are also the two originally found to have the most similar Ofpe spectra and the strongest, velocity-doubled [N II] lines. (2) If the B[e] stars have strong circumstellar oxygen emission but not nitrogen, they may be less evolved than LBV's. η Car shows strong [N I] and [N II] but no [O I] or [O II] and this immediately suggests anomalous abundances. (3) MWC 112 (= HDE 269582) shows strong spectral variations, but I am not familiar with its light curve. What is its LBV pedigree?

Stahl: (1) That is true. (2) The B[e] stars are indeed probably not as nitrogen-rich as η Car. They show strong [O I] and no [N II]. I do not know about [N I], so the difference might be a difference in ionization. (3) Not much is known about the light curve of MWC 112. Hoffleit remarked in the *Harvard Annals*, 1933, that it is an irregular variable with an amplitude of one magnitude. We have begun to monitor it photometrically.

Hillier: Two comments. (1) HD 316285 shows P Cygni profiles and is even more extreme than P Cyg. It has broad [N II] and some [Fe II] lines, these being formed in the stellar wind. Broad [N II] λ6583 is present but is badly blended with the electron scattering wings of Hα. (2) In MWC 112, the [N II] lines are probably formed in the stellar wind. Since λ5755 and λ6583 have different critical densities for collisional de-excitation, you need to take their different formation regions into account.

Appenzeller: The [O I] and [N II] lines have highly different critical densities. Hence their ratio may reflect mainly different physical conditions in the B[e] shells, rather than different abundances. To learn something about the abundances, lines with similar critical densities should be compared.

Walborn: I agree; η Car shows strong [N I] and [N II] but no [O I] or [O II]. If a circumstellar shell shows [O I] but not [N I], it is probably not processed material.

Davidson: About these critical densities -- [N I] is a $2p^3$ configuration like [O II], so I suppose it has a slow transition probability and is collisionally de-excited at lower densities than [O I] which is a $2p^4$ configuration.

{Order-of-magnitude critical electron densities for collisional de-excitation are roughly $log\,(n_e^{crit}/cm^{-3}) \approx 3.5, 4.9, 6.3$, and 3.9 for [N I] λ5200, [N II] λ6583, [O I] λ6300, and [O II] λ3727 respectively.}

Hillier: The presence of oxygen is not necessarily inconsistent with enhanced nitrogen. In Maeder's models, you can get nitrogen enhancement through carbon depletion. The depletion of oxygen occurs on a longer time scale.

Maeder: It is worth remembering that before ejecting the CNO-processed material, the star must first eject its original outer solar-like-composition material.

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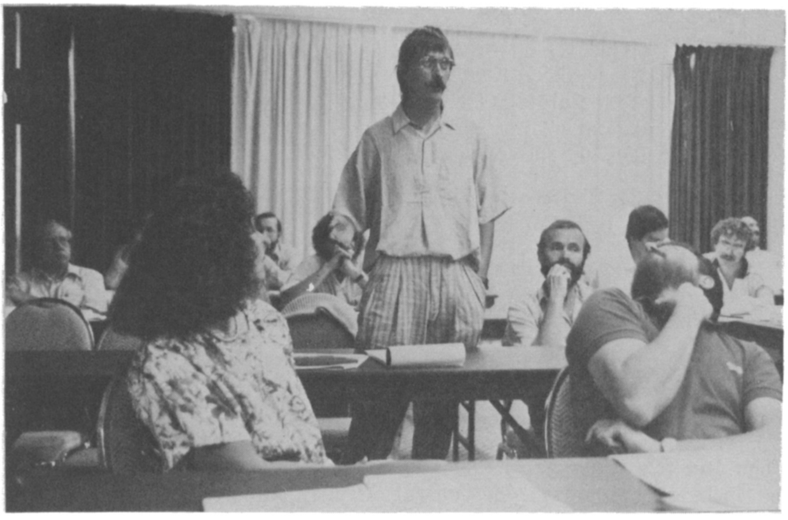

Werner Schmutz *et al.*

Humphreys, Rossi

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