R4 and its circumstellar nebula: evidence for a binary merger?[1]

A. Pasquali

ESO/ST-ECF, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

A. Nota [2]

STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA

N. Langer

Institut für Physik, Universität Potsdam, Postfach 601553, D-14415 Potsdam, Germany

R.E. Schulte-Ladbeck

University of Pittsburgh, Pittsburgh, PA 15260

M. Clampin

STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA

Received ______________________; accepted ______________________

---

[1]Based on observations obtained at the European Southern Observatory, La Silla

[2]Affiliated with the Astrophysics Division, Space Science Department of the European Space Agency

ABSTRACT

We present new, NTT longslit spectroscopy of the B[e] supergiant in the binary system R4 in the Small Magellanic Cloud. The data show extended, forbidden N and S emissions which are typical signatures of circumstellar matter. Their extension along the space axis of the slit defines an angular size of 8.6″ which translates into a linear size of 2.4 pc. The N emission lines also show the velocity structure of a bipolar outflow expanding at 100 km s^{-1} on average. This implies that, for a measured radius of 1.2 pc, the outflow originated about 1.2 $\times 10^4$ yr ago. The line flux ratio [NII]6584/[SII]6717 indicates that the nebula is nitrogen enriched and therefore it has been ejected from the central star.

This is the first bipolar, ejection nebula detected around a well-established B[e] supergiant. The bipolar morphology and the chemical enrichment shown by the nebula associated with R4 are consistent with the picture of a binary merger (Langer & Heger 1998), in which R4 was originally a system composed by a close pair and a third star (the observed A companion). The close pair merged into a single star and the merging process produced a circumstellar nebula that was later shaped by the ensueing B star wind.

Since the bipolar morphology, the kinematics and the enriched chemical composition make the nebula surrounding R4 very similar to the observed LBV nebulae, our findings imply that at least a few LBV outbursts and nebulae might well be the result of the merging process of two massive stars.

Subject headings: B[e] supergiants — Luminous Blue Variables — Circumstellar medium

1. Introduction

The class of B[e] supergiants consists of about 20 luminous evolved B stars with a rich emission line spectrum and a strong infrared excess (Zickgraf et al. 1986, Lamers et al. 1998). Most of the confirmed members of this class are located in the Magellanic Clouds, mainly for two reasons: the luminosities of the Galactic objects cannot be precisely determined due to the uncertain distances, and the difficulty to resolve the objects of this class from other B-type emission line stars (Be stars, Herbig Be stars, and other types of B[e] stars).

Gummersbach et al. (1995) were able to place 14 Magellanic Cloud B[e] supergiants in the HR diagram. There, they appear to define two distinct groups, one at relatively low luminosity ($L \lesssim 10^5\,\mathrm{L}_\odot$) and low effective temperature (log $T_{\rm eff} \lesssim 15\,000\,\mathrm{K}$), and the other at higher luminosities ($L \gtrsim 10^5\,\mathrm{L}_\odot$) and temperatures (log $T_{\rm eff} \simeq 12\,000\,\mathrm{K} - 30\,000\,\mathrm{K}$).

The spectral properties of the B[e] supergiants are best explained within the model by Zickgraf et al. (1985), who propose that these stars have a two component wind: a fast polar wind responsible for the high excitation UV resonance lines, and an equatorial slow and cool wind producing the narrow permitted and forbidden lines. The equatorial wind is associated with the highest mass-loss rate and usually identified with an outflowing disk where dust can condense and emit at infrared wavelengths. Such disk might be produced by rotational wind compression (Bjorkman & Cassinelli 1993, Bjorkman 1999). Nevertheless, it remains to be shown that disk inhibition due to non-radial components of the wind driving line force and gravity darkening (Owocki & Gayley 1998) can be overcome, perhaps by a combination of rotational compression and wind bi-stability proposed by Lamers & Pauldrach (1991) which predicts a sudden increase in the wind mass flux and decrease in the wind velocity at a critical temperature ($\sim 20\,000\,\mathrm{K}$) when the stellar surface temperature decreases gradually from the pole towards the equator.

Langer & Heger (1998) have connected the B[e] supergiant stage with phases in the evolution of rotating massive stars during which the star can possibly reach the Ω-limit, i.e. its surface rotation rate (which also takes into account the radiation force of the star) is able to destabilize the stellar surface at the equator (Langer 1997). They found that the most luminous and hot B[e] stars might be related to core hydrogen burning models which arrive at the Ω-limit due to increasing surface opacities during their main sequence evolution, which is possible for stars relatively close to the Eddington-limit even if they are slow rotators (Langer 1998). They proposed further that stars below $\sim 10^5\,L_\odot$ could reach the Ω-limit during core helium burning (on the so called blue loops) due to efficient angular momentum transport from the stellar interior to the stellar surface during this phase (Heger & Langer 1998). Finally, the outbursts of Luminous Blue Variables have been associated with these stars hitting the Ω-limit (Langer 1997, Langer et al. 1999), a conjecture which is strongly supported by the bi-polarity of virtually all circumstellar nebulae of LBVs (Nota et al. 1995).

Whether all massive stars go through a B[e] supergiant stage, and whether they are connected to Luminous Blue Variables is unclear. Empirically, the distribution of the group of luminous B[e] supergiants in the HR diagram overlaps with that of the LBVs (Bohannan 1997). A connection between B[e] supergiants and LBV stars has been early suggested by Shore (1990) and Schulte-Ladbeck & Clayton (1993) from their analysis of S22, in the Large Magellanic Cloud. Classified as a B[e] supergiant by Zickgraf et al. (1986), S22 shows an intrinsic polarization of 0.52 % due to electron scattering in an aspherical wind. The polarization degree is variable and this is probably linked to variations in the mass-loss rate of the star (Schulte-Ladbeck & Clayton 1993). A similar result has been found for the galactic LBV HR Carinae, which is characterized by an intrinsic continuum polarization of about 0.4%, possibly variable (Clampin et al. 1995). This can again be explained as due to a non-spherical wind geometry (the presence of a circumstellar disk has been also discussed by Nota et al. 1997) and a time dependent mass loss rate. In addition, Shore (1990) has detected almost a factor of two variation in the UV flux of S22 longward of 1600 Å and a factor between 2 and 3 variation shortward of 1600 Å. The amplitude of the UV variability is quite similar to that observed in LBVs during their shell ejection phase (Pasquali & Nota 1999).

As an alternative approach, to study the occurrence of the LBV phase in the evolution of massive stars, we have undertaken a longslit spectroscopy campaign of galactic and MC evolved supergiants whose stellar properties (M_{Bol} and Log T_{eff}) are in the range set by confirmed LBVs. The aim of the observations is to detect the presence of circumstellar nebulae and to determine whether these are ejected by the star and possibly establish an evolutionary connection with LBVs.

Here, we present the first results obtained for the R4, in the Small Magellanic Cloud. With $L \simeq 10^5\,L_\odot$ and $T_{eff} \lesssim 27\,000\,K$ (Zickgraf et al. 1996), R4 is the hottest and least luminous star within the high luminosity group of B[e] supergiants. Zickgraf et al. showed that R4 is a spectroscopic binary (a = 23 A.U.) comprising a B[e] supergiant with spectrophotometric variability characteristic of a LBV, and an evolved A type companion star which is about 10 times less luminous ($10^4\,L_\odot$). In Sect. 2 we present the spectroscopic data taken for R4, while in Sect. 3 we describe the results obtained from our observations. A discussion of our results, of the implications for the evolutionary history of R4, and of the connection of B[e] supergiants with LBVs follows in Sect. 4.

2. Observations and data reduction

We observed R4 at the 3.5m ESO/NTT telescope, on the nights of July 27 - 30, 1998. We used the EMMI spectrograph in the REMD (Red Medium Dispersion) configuration and acquired longslit spectra through gratings 6 and 7 in the following wavelength ranges: 4470 - 5820 Å, 5080 - 6420 Å and 6240 - 6870 Å. We observed in three different positions: on the star, at 3″ North and 3″ South, respectively. These two offsets were computed by translating the typical linear sizes of known LBV nebulae into angular sizes at the SMC distance (57.5 Kpc, van den Bergh 1989), in order to be able to detect a circumstellar nebula, if present, when no high-resolution imaging could be performed. We employed a 1″ x 180″ longslit oriented East - West in all the cases but in the 4470 - 5820 Å spectrum, for which the slit had been oriented North - South. The complete journal of the observations is reported in Table 1, where the wavelength range, the dispersion and effective resolution, the exposure time and the offset are summarized for each spectrum. The red arm of EMMI was equipped with a TK2048EB4 CCD, whose spatial scale is 0.27″ per pixel.

We obtained the usual set of bias and flat-field images, together with comparison spectra of HeAr for the wavelength calibration. The spectra were first cleaned to remove cosmic rays and bad columns, and then corrected for bias and flat-fielded. Their subsequent reduction was performed following the procedure outlined in the IRAF LONGSLIT package. We modeled the sky background in each frame by fitting a surface described by Chebyshev polinomials of low order in X and Y. This surface was then subtracted from the frame itself. The wavelength calibration was achieved in three steps: first, we identified the emission lines at the central row of the comparison spectrum and derived the dispersion correction by fitting a Chebyshev function of order 3. The same lines were then reidentified across the entire frame adopting a step of 2 rows and readjusting the dispersion correction if necessary. Finally, the dispersion corrections obtained through the frame were fitted into a surface using Chebyshev polynomials of order 5. This surface was then applied to each spectrum for the final wavelength calibration. The same procedure was of course repeated for each grating. The effective resolution is reported in Column 5 of Table 1 for each grating: a FWHM = 2.72 and 2.36 Å corresponds to a velocity resolution of 84 and 61 km s^{-1} at Hβ

and [NII]λ5755 respectively, while a FWHM of 1.12 Å defines a velocity resolution of 25 km s^{-1} at Hα. Measurements of the sky lines indicate that the wavelength calibration is certain at $\pm$ 10 km s^{-1} at any position within the longslit spectra.

3. Results

3.1. Nebular kinematics

The long-slit spectra of the R4 region show the presence of extended nebular lines, such as [NII] $\lambda\lambda$6548, 6584 and [SII] $\lambda\lambda$6717, 6731. These lines show a well defined spatial extension and velocity structure, clearly distinguishable from the underlying emission due to the local interstellar medium. We show in Figure 1 the [NII] λ6584 line as detected at the position 3$''$ North with respect to the star (top panel), and 3$''$ South (bottom panel). The spatial extent of the nebular emission is approximately 32 pixels, which corresponds to an angular size of 8.6$''$ (given the EMMI/CCD spatial scale of 1 pixel = 0.27$''$) and to a linear size of 2.4 pc, in the assumption of a distance for the SMC of 57.5 Kpc (van den Bergh 1989). The peculiar velocity structure of the nebular lines can be immediately noted in a quick look inspection of the two-dimensional spectra: while at 3$''$ North the bulk of the emission is redshifted, at 3$''$ South the line is blueshifted. A remarkable symmetry is present, both along the spatial direction (North compared with South), and in the velocity structure (redshifted versus blueshifted).

We used the [NII]λ6584 line to derive the nebular radial velocity map at the two offset pointings. We binned the spectra by a factor of 2 along the spatial axis (2 pixels corresponding to 0.54$''$) and extracted an individual spectrum from each bin. We measured the peak wavelengths in the [NII] profile by multi-gaussian fitting and computed the corresponding radial expansion velocities. Our fits are characterized by a typical error of $\pm$

4 km s^{-1}. In this wavelength region, the spectra have a velocity resolution of $\simeq$ 25 km s^{-1} and the absolute wavelength calibration is within $\pm$ 10 km s^{-1} across the entire slit. The derived radial velocities, corrected for the heliocentric motion, have been plotted in Figure 2 as a function of distance from the star, in arcseconds, for both slit positions (3$''$ North - top panel; 3$''$ South - bottom panel). On the abscissae, East is to the left and West is to the right. The star is at position 0.

From Figure 2 it is clear that the local interstellar medium dominates the velocity distribution at distances larger than $|5|''$ from the star, since we measure the mean radial velocity of this overall motion to be 110 km s^{-1}, in agreement with the Fabry-Perot Hα observations of le Coarer et al. (1993). However, in the distance range -5$''$ $<$ d $<$ 5$''$ from the star, two additional components are clearly resolved: at the position 3$''$ North we find a component which is redshifted, and spans between 200 and 280 km s^{-1}, covering the entire spatial range. At the position 3$''$ South, a second component is also present, which varies between 20 and 90 km s^{-1}. This component extends between 4$''$ E and 4$''$ W from the star.

The remarkable symmetry of these radial velocity structures can be better appreciated in Figure 3 (top panel) where we have plotted on the same spatial scale the two velocity profiles obtained at the two positions. First, we notice that the northern velocity distribution mirrors the southern. The N component displays two radial velocity maxima at $\simeq$ 2.5$''$ E and $\simeq$ 1.5$''$ W. In correspondence to the same two positions, the S component shows two radial velocity minima. The N component reaches radial velocity minima in correspondence to the star and at the outer boundaries of its spatial extension. The S component follows a symmetrical trend. The peak-to-peak radial velocity amplitude of both components is very similar ($\simeq$ 80 km s^{-1}). In addition, there is symmetry between the E and W regions of the nebula with respect to the central star. Indeed, the eastern portion of both velocity curves, when folded, significantly overlaps the western.

The observed velocity structure is likely to be indicative of a nebula surrounding R4. The nebula is dynamically associated with the central star, for which Zickgraf et al. (1996) determined a radial velocity of 147 km s^{-1}, and most likely has been ejected by R4 in a previous phase. Therefore, with respect to the central star, the northern component of the nebula turns out to be red-shifted by 84 km s^{-1} while the southern is blue-shifted by 118 km s^{-1} on average. Assuming a mean expansion velocity of 100 km s^{-1} and a full linear size of 2.4 pc, we derive a dynamical age of the nebula of $\sim 1.2 \times 10^4$ yr.

Without a direct image, and on the basis of kinematics considerations alone, it is difficult to make definite conclusions on its structure. Compared with the information available on nebulae around LBVs, the nebula around R4 appears more complicated in nature. From the kinematics, it is fair to conclude that:

- the nebula is *not* a simple expanding shell. An expanding shell would result in a radial velocity map which has maximum dispersion in correspondence to the position of the star, and minimum velocity at the shell boundaries (eg. AG Car: Smith 1991, Nota et al. 1992).
- the nebula is not strictly bipolar. Compared with the radial velocity maps derived for HR Car, a prototypical bipolar outflow (Nota et al. 1997), the situation is very different: in the case of HR Car, there is a clear demarcation between the two sides of the bipolar outflow, with the redshifted region limited to the NW quadrant, and the blueshifted to the SE quadrant (see Figure 9 in Nota et al. 1997).

In order to provide a consistent explanation for the radial velocity maxima and minima observed in the R4, a more complicated structure needs to be invoked, which is symmetrical around two axes. In the bottom panel of Figure 3, we provide a cartoon of one possible structure, in which a cloverleaf morphology is aligned with the peculiar radial velocity features. In this proposed structure, the outflow occurs in four directions along two axes, perpendicular to each other, and oriented at a PA $\simeq 45^o$. This complicated structure, although speculative, has been observed in planetary nebulae. Only a direct image will confirm whether such speculation is correct.

3.2. Nebular composition

In addition to the kinematical properties, the nebular lines provide also some information on the chemical composition of the nebula. We have computed the line ratio [NII]6584/[SII]6717 for the R4 nebula and the local interstellar medium from the long-exposure spectra which we corrected for atmospheric extinction. We derived a ratio [NII]6584/[SII]6717 of about 3 (in agreement also with the data of Zickgraf et al. 1996) and 0.3 for the R4 nebula and the local interstellar medium, respectively. Such result is inconsistent with the same line ratio measured in HII regions and SN remnants in the SMC by Russell & Dopita (1990). Typically, the [NII]6584/[SII]6717 ratio is 0.6 for the HII regions (with one exception: N84C is characterized by a value of 2.4) and varies between 0.2 and 0.4 in the case of SNR, independently of the position in the galaxy. A [NII]6584/[SII]6717 value of 0.3 is considered to reflect the intrinsic lower N content of the SMC with respect to the Galaxy and the LMC. We may then conclude that the R4 nebula is N-enriched by a factor 10 with respect to both the local interstellar medium and HII regions/SN remnants.

4. Discussion

From Section 3, we conclude that R4 is surrounded by a bipolar circumstellar nebula, nitrogen enriched, with a dynamical age of $\sim 1.2 \times 10^4$yr. This nebula appears to have been ejected from the central star, and its morphological, kinematic and chemical properties are comparable to the average properties of LBV nebulae (cf., Nota et al. 1995). Although Esteban & Fernandez (1998) have detected a circumstellar nebula around the galactic B[e] star MCW 137 which appears not to be chemically enriched, our findings for R4 provide the first evidence for an ejected nebula around a B[e] supergiant.

4.1. The progenitor evolution of R4

In order to investigate the implications of our finding for the connection of B[e] supergiants and LBVs, let us recall the proposed evolutionary scenarios for the B[e] supergiants. Table 3 summarises the expected stellar and circumstellar nebula properties of B[e] supergiants according to the very massive main sequence star scenario, the blue loop scenario and the binary merger scenario (Langer & Heger 1998).

In the first scenario, the star reaches the Ω-limit (cf. Section 1) during its main sequence evolution due to its high luminosity, i.e. its proximity to the Eddington limit (Langer 1998). This appears possible only for the most massive stars. Since at low metallicities the Eddington-limit is even higher at higher luminosity than for young stars in the solar neighborhood (Ulmer & Fitzpatrik 1998), this scenario would require an extraordinarily fast rotation to apply to the case of R4.

In the second scenario, the star reaches the Ω-limit on a blue loop evolving off the Hayashi line during core helium burning (Heger & Langer 1998). This scenario can not apply to R4 since stars on blue loops do not exceed effective temperatures of $\sim 20\,000\,\mathrm{K}$ (cf. Langer & Maeder 1995), i.e., the blue loops never extend to the main sequence band.

In the third scenario, an equatorial disk or ring is created by mass overflow through the second Lagrangian point in a close binary system in the course of a close binary merger.

This scenario was supposed to be most appropriate for the case of R4 by Langer & Heger (1998) for the following reasons. The B[e] supergiant R4 has an evolved A type companion star with a mass of about $12.9\,\mathrm{M}_{\odot}$ (Zickgraf et al. 1996). While the B[e] star mass has been determined to a similar value ($\sim 13.2\,\mathrm{M}_{\odot}$) its bolometric luminosity outshines that of the A star by a factor of ~ 10. Zickgraf et al. conclude from the high luminosity of R4 ($\sim 10^5\,\mathrm{L}_{\odot}$), and from its strong surface enrichment in CNO processed material, that it must have lost large amounts of mass in a previous red supergiant phase.

However, as noted by Langer & Heger (1998), even if a $\sim 20\,\mathrm{M}_{\odot}$ red supergiant at the very low metallicity of the SMC had lost about $10\,\mathrm{M}_{\odot}$ via its stellar wind (which appears unlikely for several reasons; e.g., the large envelope mass of the progenitor of supernova 1987A), there would remain a basic puzzle in the R4 binary system. The A star is clearly beyond core hydrogen exhaustion: how then can the B star have an *evolved* companion which is ten times less luminous? The B star should have long exhausted its fuel and exploded as a supernova. Clearly, binary mass transfer must have occured in this system. Now, the orbital separation in the system is presently about 23 A.U. or $5000\,\mathrm{R}_{\odot}$ (Zickgraf et al. 1996), which may be too large to allow any mass transfer from the A star to the B star. Also, mass transfer in very wide systems is supposed to be unstable and would not leave the two stars at a large separation (e.g., Podsiadlowski et al. 1992), and can therefore be excluded.

A viable binary scenario for R4 may be that the B[e] star has been formed by a recent binary merger, and the A star is not involved in any mass transfer but only serves as a suitable clock (Langer & Heger 1998). Wellstein et al. (2000) find in a parameter study of binary evolution models that a system which starts out with a $12\,\mathrm{M}_{\odot}$ and a $11\,\mathrm{M}_{\odot}$ star on a 40 day orbit would evolve into contact after core hydrogen exhaustion in the $12\,\mathrm{M}_{\odot}$ star, which leads to mass overflow through the outer Lagrangian point L_2 and then most likely to a merger. The L_2 overflow, which is likely to comprise several solar masses of material (Wellstein et al. 2000), gives rise to a circumstellar nebula, which is then shaped by the ensueing B star wind, like the Homunculus nebula around η Carinae in the wind interaction scenario of Langer et al. (1999). The large amount of angular momentum in the stellar merger remnant may lead to a disk wind according to the Bjorkman-Cassinelli mechanism, which then is responsible for the B[e] morphology of the stellar spectrum. Furthermore, the merger star would be expected to contain an overly large helium fraction in its interior — which would give it an unusually large L/M-ratio — and a surface strongly enriched in CNO products.

That all these details are observational facts makes R4 the strongest massive star candidate for a binary merger. Within this picture, the system started out as a triple system with three very similar stars, a close pair of, say, $12\,M_\odot$ and $11\,M_\odot$, in a wide orbit with a $\sim 13\,M_\odot$ star. Soon after the latter has evolved off the main sequence into an A type supergiant, the close pair would merge to form the B[e] supergiant, about 1.2×10^4 yr ago.

4.2. Implications for other B[e] supergiants and LBVs

In order to understand the relevance of R4 for massive stars in general, we should establish whether R4 is a peculiar or a typical B[e] supergiant. The latter case would have the dramatic implication that most B[e] supergiants might be the result of a binary merger. However, there are at least two arguments against this proposition. First, R4 has an extreme location in the HR diagram compared to all other B[e] supergiants in that its location is by far the closest to the main sequence band. Zickgraf et al. (1996) compared it with evolutionary tracks of Charbonnel et al. (1993), where R4 falls exactly on the terminal age main sequence of a $20\,M_\odot$ track. Second, R4 is today the only B[e] supergiant with an ejected circumstellar nebula. Before generalizing the evolutionary scenario of its progenitor, one would certainly want to detect more examples with ejected nebulae.

On the other hand, the similarity of the properties of the R4 nebula and that of LBV nebulae in general — which provides a remarkably homogeneous class — is striking. These nebulae are all very similar in terms of morphological and physical properties. They are all typically 1 parsec in size, with morphologies which are mildly to extremely bipolar. They expand in the surrounding medium with velocities of the order of 50 – 100 km s^{-1}. Their size and expansion velocities identify dynamical timescales which are of the order of several thousand of years. Densities are generally found to be low (500 - 1000 cm^{-3}) and so are temperatures, found in the range 5000 - 10000 K. In terms of overall physical and chemical properties, the nebula surrounding R4 would fit this category well. However, two facts preclude the possibility that the R4 nebula and all LBV nebulae have been formed the same way. The first is R4's location in the HR diagram, which of all the stars in the group of luminous B[e] supergiants is farthest away from the LBV regime. The second, even stronger argument is the fact that some LBV nebulae appear to have multiple shells (Nota et al. 2000) and thus the central stars most likely experienced multiple outbursts, which appears not possible within the binary merger scenario.

Although we argue that not all B[e] supergiants are formed by stellar mergers, we conclude that at least two intrinsically very different nebula formation mechanisms, the binary merger and the single star LBV outburst mechanism, can produce nebulae with very similar properties. Seemingly, the prerequisites for the nebular structure are the same in both cases, i.e. a massive disk ejected by the central star which is then shaped by its strong wind. While the disk forms through the L_2-Roche lobe overflow in the case of the merger (hardcore hydrodynamic calculations for such events exist so far only for low mass stars, which, however, support the general idea; cf. Yorke et al. 1995), it may be formed through rotational wind compression (Bjorkman & Cassinelli 1993) in the single star case (cf. Langer et al. 1999).

5. Conclusions

Our longslit spectroscopic observations reveal that R4 is embedded in a circumstellar nebula whose full spatial extension is 8.6″, i.e. 2.4 pc at the SMC distance of 57.5 Kpc (van den Bergh 1989). The emission lines show a significant structure in velocity indicating that the nebula is expanding at 100 km s^{-1} on average. This implies a dynamical age of 1.2×10^4 yr. The radial velocity maps obtained for the nebula at 3″ North and 3″ South from the central star are characterized by two velocity maxima and two velocity minima, respectively, located at the same positions with respect to the star. Hence, the two velocity distribution appear to be symmetric not only in the velocity field but also along the E-W direction (cf. Figure 3). Such a symmetry excludes that the R4 nebula is either a simple expanding shell (i.e. AG Car) or a simple bipolar outflow (i.e. HR Car). It rather suggests a cloverleaf morphology, where the outflow occurs in four directions along two axes, perpendicular to each other and oriented at PA $\simeq 45^o$.

Since the line flux ratio [NII]6584/[SII]6717 is almost independent of electron temperature and density, it can be used to estimate any overabundance of nitrogen with respect to the "unprocessed" sulphur. The nebular [NII]6584/[SII]6717 ratio turns out to be 3 against a value of 0.3 as measured for the local interstellar medium in the same observed spectra, and a value between 0.6 and 0.2 as derived for HII regions and SN remnants in the SMC by Russell & Dopita (1990). This factor of 10 discrepancy clearly indicates that the R4 nebula is nitrogen enriched and therefore, since it is also kinematically associated with the central B[e] supergiant, it is an ejected nebula. *R4 is surrounded by a bipolar and N-enriched nebula, ejected from the central star, whose morphological, kinematical and chemical properties well compare with the mean properties of LBV nebulae.*

We have shown that the central star most likely formed through a binary merger, as proposed by Langer & Heger (1998). This makes R4 the strongest observational counterpart of such event among massive stars, which has long been sought for. E.g., in a comprehensive binary and single star evolution and population sysnthesis study, Podsiadlowski et al. (1992) conclude that $\sim 25\%$ of all massive binaries undergo a merging process, most likely so just after the initially more massive star has terminated core hydrogen burning.

In Section 4.2, we concluded from the properties of R4 that two distinct mechanisms can form circumstellar nebulae of exactly that type found around LBVs. This has two consequences. First, it implies that some LBV outbursts and nebulae may in fact be due to the merging process of two massive stars. The predicted amount of expected binary mergers (see above) implies that this is in fact likely. Second, it may deepen the understanding of why bipolar circumstellar nebulae are such a frequent phenomenon. E.g., what holds for massive stars may be true for the progenitors of planetary nebulae, and in the end the dispute of whether bipolar planetaries are formed through binaries (e.g., Soker 1998) or single stars (e.g., García-Segura et al. 1999) may end in a draw.

We conclude by urging for imaging observations of the R4 nebula. They will not only provide for the first time the morphological details of a nebula ejected by a massive stellar merger and will thereby allow to constrain the hydrodynamical processes at work in such phenomenon, but it will perhaps reveal clues of how to empirically discriminate binary and single star ejection mechanisms and thus allow for a better understanding of bipolar circumstellar nebulae in general.

The authors wish to thank Guillermo García-Segura and the staff of the Tonantzintla Institute for their hospitality during their visit where this project was perceived. AP, AN and MC would like to thank STScI and ST-ECF for their hospitality during their visits where the paper was finalized. NL acknowledges supporting from the Deutsche

Forschungsgemeinschaft through grants La 587/15-1 and 16-1. RSL acknowledges funding from the HST grant to GO proposal 6540.

REFERENCES

Bjorkman, J.E. 1999, in Variable and Non-spherical Stellar Winds in Luminous Hot Stars, eds. B. Wolf, O. Stahl & A.W. Fullerton, Lecture Notes in Physics (Springer: Heidelberg), p. 121

Bjorkman, J.E., Cassinelli, J.P. 1993, ApJ, 409, 429

Bohannan, B. 1997, in Luminous Blue Variables: Massive Stars in Transition, eds. A. Nota & H.J.G.L.M. Lamers, ASP Conf. Ser., 120, p. 3

Charbonnel, C., Meynet, G., Maeder, A., Schaller, G., Schaerer, D. 1993, A&AS, 101, 415

Clampin, M., Schulte-Ladbeck, R.E., Nota, A., Robberto, M., Paresce, F., Clayton, G.C. 1995, ApJ, 448, 788

Esteban, C., Fernandez, M. 1998, MNRAS, 298, 185

García-Segura, G., Langer, N., Różyczka, N., Franco J. 1999, ApJ 517, 767

Gummersbach, C.A., Zickgraf, F.-J., Wolf, B. 1995, A&A, 302, 409

Heger, A., Langer, N. 1998, A&A 334, 210

Lamers, H.J.G.L.M., Pauldrach, A.W. 1991, A&A, 244, L5

Lamers, H.J.G.L.M., Zickgraf, F.-J., de Winter, D., Houziaux, L., Zorec, J. 1998, A&A, 340, 117

Langer, N. 1997, in Luminous Blue Variables: Massive Stars in Transition, eds. A. Nota & H.J.G.L.M. Lamers, ASP Conf. Ser., 120, p. 83

Langer, N. 1998, A&A 329, 551

Langer, N., Maeder A. 1995, A&A 295, 685

Langer, N., Heger, A. 1998, in B[e] Stars, eds. A.M. Hubert & C. Jaschek, ASSL, 233, p. 235

Langer, N., García-Segura, G., Mac Low, M.-M. 1999, ApJ 520, L49

le Coarer, E., Rosado, M., Georgelin, Y., Viale, A., Goldes, G. 1993, A&A, 280, 365

Nota, A. et al. 2000, in prep.

Nota, A., Leitherer, C., Clampin, M., Greenfield, P., Golimowski, D.A. 1992, ApJ, 398, 621

Nota, A., Livio, M., Clampin, M., Schulte-Ladbeck, R.E. 1995, ApJ, 448, 788

Nota, A., Smith, L.J., Pasquali, A., Clampin, M., Stroud, M. 1997, ApJ, 486, 338

Owocki, S.P., Gayley, K.G. 1998, in Boulder-Munich II: Properties of Hot, Luminous Stars, ed. I.D. Howarth, ASP Conf. Ser., 131, p. 237

Pasquali, A., Nota, A. 1999, MEM SAIt, in press

Podsiadlowski Ph., Joss P.C., Hsu J.J.L. 1992, ApJ 391, 246

Russell, S.C., Dopita, M.A. 1990, ApJS, 74 93

Schulte-Ladbeck, R.E., Clayton, G.C. 1993, AJ, 106, 790

Shore, S.N. 1990, IAU Circ., 5005, 1

Smith, L.J. 1991, in IAU Symp. 143, Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, eds. K.A. van der Hucht & B. Hidayat (Dordrecht: Kluwer), p. 385

Soker, N. 1998, ApJ 496, 833

Ulmer, A., Fitzpatrick, E.L. 1998, ApJ 520, 200

van den Bergh, S. 1989, A&AR, 1, 111

Wellstein S., Braun H., Langer N. 2000, in prep. for A&A

Yorke H.W., Bodenheimer P., Taam R.E. 1995, ApJ 451, 308

Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., Klare, G. 1985, A&A, 143, 421

Zickgraf, F.-J., Wolf, B., Stahl, O., Leitherer, C., Appenzeller, I. 1986, A&A, 163, 119

Zickgraf, F.-J., Kovacs, J., Wolf, B., Stahl, O., Kaufer, A., Appenzeller, I. 1996, A&A, 309, 505

This manuscript was prepared with the AAS LaTeX macros v4.0.

Table 1. Journal of the observations.

Date (1998)	Grating	λ range (in Å)	Dispersion (in Å/pix)	Resolution (FWHM in Å)	Exp. Time (in s)	Location
July 30	7	4470 - 5820	0.66	2.72	1800	on the star
July 31	7	5080 - 6420	0.66	2.36	1500	$3''$ North
”	6	6240 - 6870	0.31	1.12	60	$3''$ North
”	”	”	”	”	1800	”
”	”	”	”	”	80	on the star
”	”	”	”	”	60	$3''$ South
”	”	”	”	”	1800	”

Table 2. Comparison of observable properties predicted by the three B[e] supergiant evolutionary scenarios discussed in this paper (cf. Langer & Heger 1998).

colhead	very massive main sequence star at the Ω-limit	supergiant on blueward excursion from Hayashi line	single star remnant of binary merger
log $T_{\rm eff}$	$\gtrsim 20\,000$ K	$\lesssim 20\,000$ K	$10\,000$ K ... $30\,000$ K
luminosity	$\gtrsim 10^5\,L_\odot$	$\lesssim 10^5\,L_\odot$	$\gtrsim 10^4\,L_\odot$
time scale	some 10^5yr	some 10^4yr	(?)
time integr. disk mass	$\sim 5\,M_\odot$	$\sim 0.1\,M_\odot$	$\sim 5\,M_\odot$(?)
nebular chem. composition	non-enriched to moderately enriched	moderately enriched	strongly enriched

Fig. 1.— Top panel: the [NII]λ6584 line as it appears in the longslit spectrum taken at $3''$ North. Wavelength is on the abscissae axis, increasing from left to right, while the spatial direction is on the ordinates axis. Bottom panel: the [NII]λ6584 line in the longslit spectrum taken at $3''$ South.

Fig. 2.— Top panel: radial velocities (in the heliocentric system) measured from the [NII]λ6584 as a function of position with respect to the star (at 0), in the longslit spectrum at $3''$ North. Bottom panel: radial velocities measured from the same line in the longslit spectrum obtained at $3''$ South. The cross represents the star velocity of 147 km s^{-1} as derived by Zickgraf et al. (1996).

Fig. 3.— A cartoon of the R4 nebula. The speculated structure is of a cloverleaf, where the outflow occurs in four directions along two axis, perpendicular to each other and oriented at PA $\simeq 45^o$ (bottom panel). This structure is aligned with the two velocity maxima in the spatial distribution of radial velocities obtained at $3''$ North and with the two velocity minima of the radial velocity map measured at $3''$ South (top panel).