Part 4

Feedback from Massive Stars

https://doi.org/10.1017/S0074180900212965 Published online by Cambridge University Press

LOC and SOC, plenty of feedback. *From left:* Sergio Simón-Díaz, Miguel A. Urbaneja, Artemio Herrero, Luis Corral, Charo Villamariz, Mrs. van der Hucht, and Karel van der Hucht

https://doi.org/10.1017/S0074180900212965 Published online by Cambridge University Press

A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © 2003 IAU
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

Ring nebulae around massive stars throughout the Hertzsprung-Russell diagram

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Abstract. Massive stars evolve across the H-R diagram, losing mass along the way and forming a variety of ring nebulae. During the main sequence stage, the fast stellar wind sweeps up the ambient interstellar medium to form an interstellar bubble. After a massive star evolves into a red giant or a luminous blue variable, it loses mass copiously to form a circumstellar nebula. As it evolves further into a WR star, the fast WR wind sweeps up the previous mass loss and forms a circumstellar bubble. Observations of ring nebulae around massive stars not only are fascinating, but also are useful in providing templates to diagnose the progenitors of supernovae from their circumstellar nebulae. In this review, I will summarize the characteristics of ring nebulae around massive stars throughout the H-R diagram, show recent advances in X-ray observations of bubble interiors, and compare supernovae's circumstellar nebulae with known types of ring nebulae around massive stars.

1. Introduction

Since Johnson & Hogg (1965) reported the first three ring nebulae around Wolf-Rayet (WR) stars, nebulae of various shapes, sizes, and ionization conditions have been observed around massive stars of different spectral types, such as luminous blue variables (LBVs), blue supergiants (BSGs), and red supergiants (RSGs). As these various spectral types in the upper part of the Hertzsprung-Russell (H-R) diagram are strung together by the evolutionary tracks of massive stars, their surrounding nebulae must be evolutionarily related. This relationship was illustrated clearly by García-Segura, Langer, Mac Low (1996) and García-Segura, Mac Low, Langer (1996) in their hydrodynamic simulations of the formation of WR ring nebulae taking into account the evolution and mass loss history of the central stars.

In this review, I will cover three topics. First, I will present a gallery of ring nebulae around massive stars throughout the H-R diagram and compare them to García-Segura *et al.*'s framework of hydrodynamic evolution of circumstellar gas around massive stars. Second, I will report an X-ray view of the hot gas in the interiors of bubbles blown by massive stars, using *ROSAT*, *ASCA*, *Chandra* and *XMM-Newton* observations. Finally, I will compare the circumstellar nebulae observed around young supernovae (SNe) to those around massive stars and use the nebular properties to diagnose the spectral types of SN progenitors.

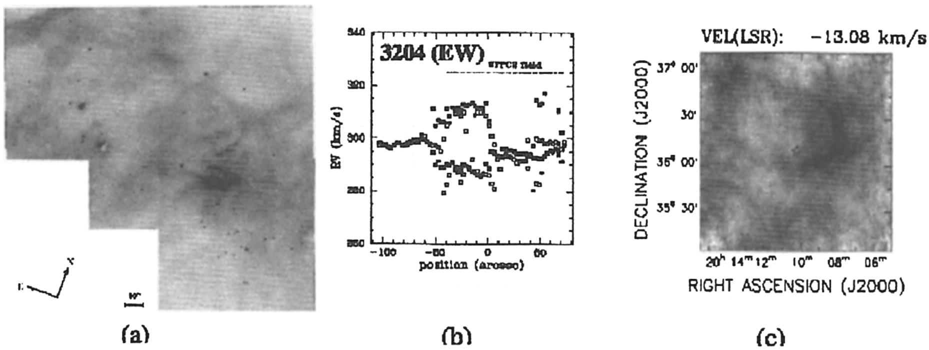

Figure 1. (a) *HST*-WFPC2 Hα image of interstellar bubbles in N 11; (b) velocity-position plot of an interstellar bubble in N 11B (from Nazé *et al.* 2001); (c) an H I interstellar bubble blown by the MS O-type progenitor of WR 134 (from Gervais & St-Louis 1999).

2. Gallery of ring nebulae around massive stars

The hydrodynamic models of ring nebulae around massive stars by García-Segura *et al.* considered two possible stellar evolution tracks from the main sequence (MS) to the WR phase: MS-O → LBV → WR, for a 60 $M_\odot$ star; MS-O → RSG → WR, for a 35 $M_\odot$ star. Stars at these different evolutionary stages expel stellar material in the following ways: MS O-type stars possess tenuous, fast winds with terminal velocities of 1 000 - 2 000 km s^{-1}; RSGs have copious, slow winds with velocities typically a few 10's km s^{-1}; LBVs have outbursts or winds at modest velocities that depend on the stellar luminosities; WR stars have the most powerful stellar winds with both large mass loss rates, $\sim 10^{-5}\,M_\odot\,yr^{-1}$, and high wind velocity, up to 3 000 km s^{-1}. These stellar winds interact with the ambient medium and form ring nebulae with distinct characteristics for each type of central stars.

2.1. Main sequence O-type stars — interstellar bubbles

The fast stellar wind of a MS O-type star sweeps up the ambient interstellar medium (ISM) to form an *interstellar bubble* (Weaver *et al.* 1977), which consists of a dense shell of interstellar material. Intuitively, we would expect around most O-type stars an interstellar bubble similar to the Bubble Nebula (NGC 7635) to be visible; however, hardly any O-type stars in H II regions have ring nebulae, suggesting that these interstellar bubbles are rare. This puzzle is recently solved by observations of the young H II region N 11B in the Large Magellanic Cloud (LMC). While no ring nebulae can be identified morphologically, long-slit high-dispersion spectra have revealed expanding shells around single or groups of O-type stars (see Figure 1a,b; Nazé *et al.* 2001). Their expansion velocities, typically 10 - 15 km s^{-1}, are not much higher than the isothermal sound velocity of the 10^4 K ionized gas in the H II region, and consequently cannot produce strong shock compression. Lacking large density enhancements, these slowly expanding interstellar bubbles do not have visible ring nebulae.

Interstellar bubbles blown by MS O-type stars may become morphologically identifiable at later evolutionary stages when the central stars can no longer

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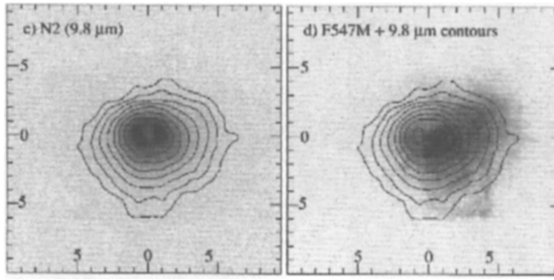

Figure 2. The circumstellar nebula of VY CMa. *Left:* 9.8 μm image of VY CMa (M5e Ia). *Right:* *HST*-WFPC2 F547M image of VY CMa overlaid by 9.8 μm contours (adopted from Smith *et al.* 2001).

ionize the bubble shells and the surrounding ISM. A 10 km s^{-1} expanding shell in a 100 K neutral H I medium (isothermal sound velocity $\sim$1 km s^{-1}) is highly supersonic, thus can generate strong compression and produce an identifiable shell morphology. Such recombined interstellar bubbles have been observed as H I shells around WR stars (Cappa, these Proceedings and references therein). A beautiful H I shell around WR 134 in our Galaxy reported by Gervais & St-Louis (1999) is reproduced in Figure 1c.

2.2. Red supergiants — circumstellar nebulae

Evolved massive stars at the RSG phase lose mass via slow winds and form circumstellar nebulae. Because of the high dust content, these circumstellar nebulae are best observed through the optical continuum scattered by dust or the thermal IR continuum emitted by dust. This is illustrated by VY CMa (M5e Ia) in Figure 2. The optical reflection nebula of VY CMa, visible to a radius of 9 000 AU (for a distance of 1.5 kpc), is asymmetric about the central star. The presence of bright arcs indicates that localized ejection of stellar material may have occurred on the stellar surface (Smith *et al.* 2001). More details on mass loss and circumstellar nebulae of RSGs are reviewed by Humphreys (these Proceedings).

2.3. Luminous Blue Variables — circumstellar bubbles

The name LBV has been used for both the extreme case of η Car and the less luminous S Doradus variables. The Ofpe/WN9 stars have also been loosely called LBVs. The circumstellar nebulae of LBVs have been reviewed by Nota *et al.* (1995). Using the heavy element abundances of LBV nebulae, Smith *et al.* (1998) suggest that LBVs have gone through a brief RSG phase, while Lamers *et al.* (2001) demonstrate that the nebulae are ejected during the blue supergiant (BSG) phase and that the LBVs have never gone through a RSG phase.

Most circumstellar nebulae around LBVs are small, $<$2 pc in diameter, expanding shells with v_{exp} of few 10 km s^{-1} (Nota *et al.* 1995; Weis these Proceedings). Many LBV nebulae in the Galaxy and in the Magellanic Clouds have been studied recently by, *e.g.*, Nota *et al.* (1996, 1997), Pasquali *et al.* (1997, 1999), and Weis (these Proceedings and references therein). A large compilation of images of LBV nebulae were presented in the poster by Weis in this meeting.

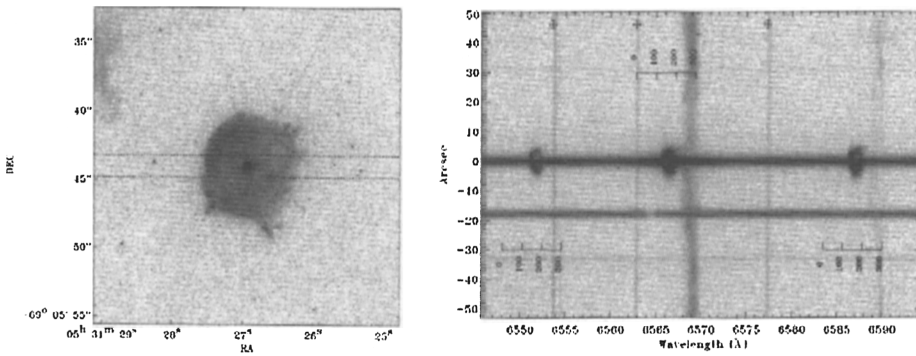

Figure 3. The runaway LBV S 119 and its circumstellar nebula. *Left: HST*-WFPC2 image in the Hα line. *Right:* long-slit echellogram of the Hα and [N II] lines. The ionized ISM of the LMC is detected at heliocentric velocities of 220 - 290 km s^{-1} along the entire slit length. The circumstellar nebula of S 119 showns an expanding shell structure centered at ∼ 160 km s^{-1} with a line splitting of 46 km s^{-1} (adopted from Danforth & Chu 2001).

Figure 3 shows the intriguing runaway LBV S 119 and its nebula in the LMC; the interstellar absorption lines in the *FUSE* spectrum of S 119 have established unambiguously that it is in the LMC (Danforth & Chu 2001).

2.4. Wolf-Rayet stars — interstellar/circumstellar bubbles

In the last decade, sensitive surveys of WR ring nebulae have been made using CCD cameras with interference filters for the Galaxy (Miller & Chu 1993; Marston *et al.* 1994a,b; Marston 1997) and the Magellanic Clouds (Dopita *et al.* 1994). The identification criteria in these surveys are similar to those used in the 70's and 80's. Based on nebular dynamics, Chu (1981) find three types of WR ring nebulae: R-type nebulae are not dynamically shaped by the WR stars, W-type nebulae are bubbles blown by the WR stars, and E-type nebulae are ejecta nebulae.

García-Segura *et al.* (1996a,b) show that a WR star is surrounded by an inner circumstellar bubble and an outer interstellar bubble. The interstellar bubble was blown by the progenitor of the WR star at the MS phase, while the circumstellar bubble is blown by the WR star in the circumstellar nebula ejected by the progenitor of the WR star at the RSG or LBV phase. Both the E-type and W-type WR ring nebulae refer to the circumstellar bubbles. If the circumstellar bubble is too tenuous to be detected, then the outer interstellar bubble may be ionized and become a R-type WR ring nebula.

It is thus clear that the three types of WR ring nebulae defined by Chu (1981) are not mutually exclusive. In particular, there is no physical distinction between W-type and E-type nebulae. Bearing in mind that the optically identified ring nebulae around WR stars may refer to either the circumstellar bubbles or the interstellar bubbles, it is thus meaningless to make statistical statements about 'the percentage of WR stars in visible ring nebulae', unless distinction is made between the circumstellar and interstellar cases.

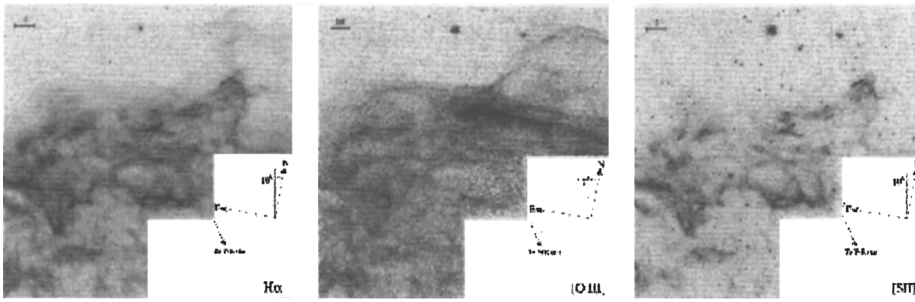

Figure 4. *HST*-WFPC2 images of NGC 6888 in Hα, [O III] and [S II] lines (from Moore *et al.* 2000).

WR ring nebulae have been studied in multiple wavelengths. Using the differences in Hα and [O III] images, Gruendl *et al.* (2000) presented a morphological diagnostic for dynamical evolution of WR bubbles. The most dramatic contrast between Hα and [O III] morphology is illustrated in the *HST*-WFPC2 images of NGC 6888 in Figure 4 (Moore, Hester & Scowen 2000). H I 21-cm line observations have revealed neutral gas shells of diameters a few 10 pc around WR stars; the properties of these shells are consistent with those expected in the interstellar bubbles blown by the MS progenitors (see review by Cappa in these Proceedings).

Observations of molecular gas associated with WR ring nebulae have yielded many intriguing results: (*i*) circumstellar CO associated with WR 16 (Marston *et al.* 1999) and possibly NGC 6888 (Rizzo *et al.* in these Proceedings); (*ii*) complex molecules and shock-excited interstellar H_2 and NH_3 in NGC 2359 (St-Louis *et al.* 1998; Rizzo, Martín-Pintado & Henkel 2001); and (*iii*) interstellar molecular gas around NGC 3199 (Marston 2001; these Proceedings).

A recent inventory of Galactic WR ring nebulae can be found in the VIIth Galactic WR catalogue by van der Hucht (2001).

2.5. Blue supergiants and massive binaries — circumstellar nebulae

The BSG phase has no unique meaning. Any massive star that is blue and luminous is called a BSG. If it varies, then it is called a LBV. The existence of a close binary companion can make the nature of a BSG even more mysterious. A small number of circumstellar nebulae around BSGs have been identified. Ironically, almost all of them have something peculiar about either the spectral properties of the stars or the physical structure of the nebulae. Below are a few examples.

NGC 6164-5 around HD 148937 consists of a small (2.6×1.9 pc) S-shaped circumstellar nebula and a filamentary interstellar ring nebula (∼10 pc in diameter) inside a large dusty cavity structure (Leitherer & Chavarría-K. 1987). Clearly, HD 148937 is an evolved star, but its spectral type, O6.5f?p, is peculiar and it shows well-marked emission in C III and N III lines that are not seen in normal Of stars (Walborn 1972). What is the evolutionary status of HD 148937?

Sk−69 202 (B3 I), the progenitor of SN 1987A, and Sher 25 (B1.5 I) are both BSGs and have circumstellar ring nebulae of similar size and morphol-

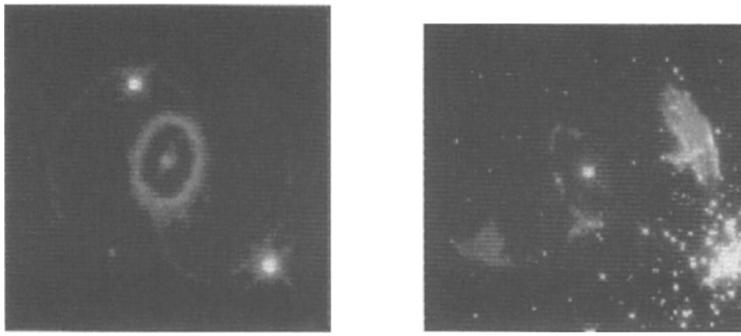

Figure 5. *Left:* SN 1987A and the circumstellar nebula of its B3 I progenitor Sk−69 202. *Right:* Sher 25, a B1.5 I star, and its circumstellar nebula. Both inner rings are 0.4 pc in diameter.

ogy (Brandner *et al.* 1997a,b). The hourglass morphology of these two rings are uncommon among known ring nebulae around massive stars; in fact, no other ring nebulae have such a morphology. Do these ring nebulae provide circumstellar or circumstantial evidence for a similar evolutionary status between these two BSGs?

Podsiadlowski, Joss & Hsu (1992) have proposed that Sk−69 202 is a product of a massive interacting binary. Their model explains the BSG spectral type of the star and the formation of the equatorial ring in the circumstellar nebula. Interestingly, a compact circumstellar nebula has been observed around the massive eclipsing binary RY Scuti (Smith *et al.* 1999); another circumstellar nebula has been detected around the B[e] supergiant R 4 and is suggested to be ejected during a binary merger process (Pasquali *et al.* 2000). These circumstellar nebulae clearly have different formation mechanisms from those around single massive stars. The circumstellar nebula of Sher 25, resembling that around Sk−69 202, most likely has a similar formation mechanism, which then requires Sher 25 to involve a massive interacting binary. Unless observations of Sher 25 can exclude this possibility, the ring nebula of Sher 25 provides circumstellar evidence that it is similar to Sk−69 202.

2.6. Observations *versus* expectations

Observations of ring nebulae around single massive stars with known evolutionary status generally agree with expectations:
(*a*) MS O-type stars blow interstellar bubbles of sizes $\sim$ a few $\times 10$ pc,
(*b*) RSGs are surrounded by circumstellar nebulae of sizes a few $\times 10^3$ AU,
(*c*) LBVs have small circumstellar bubbles with radius $\leq$1 pc,
(*d*) WR stars have larger circumstellar bubbles, a few pc in size, surrounded by interstellar bubbles blown by their progenitors at MS stage.

The circumstellar nebulae, consisting of material ejected by the stars, are N-enriched and can be diagnosed by a high [N II]/Hα ratio. LBVs may evolve into WR stars, and the sizes of their circumstellar bubbles (Chu, Weis & Garnett 1999) support this evolutionary sequence.

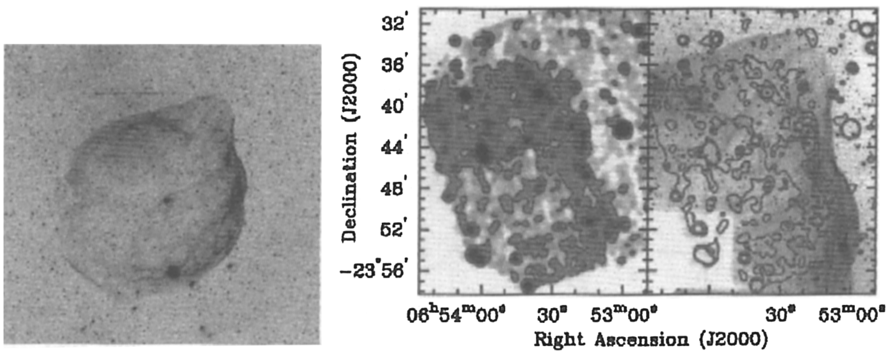

Figure 6. [O III] (*left*), XMM X-ray (*middle*), and X-ray contours over [O III] images of S 308. The [O III] image was taken by Chris Smith with the Curtis Schmidt telescope. The X-ray image covers only the NW quadrant of S 308.

On the other hand, ring nebulae around massive stars with uncertain evolutionary status, such as BSGs, show complex structures that are not completely understood. This is an area that needs a lot of future work. Ring nebulae around close massive binaries also need to be studied.

3. X-ray views of ring nebulae

Bubbles blown by massive stars ought to be filled by shocked fast stellar wind at X-ray-emitting temperatures (Weaver *et al.* 1977). The first detection of diffuse X-ray emission from the hot gas in a bubble interior was made by Einstein IPC observations of NGC 6888 (Bochkarev 1988). *ROSAT*-PSPC observations of several WR ring nebulae detected only NGC 6888 and S 308 (Chu 1994). The X-ray emission from NGC 6888 is brighter toward the dense shell rim, and the X-ray spectrum indicates a plasma temperature of 1.6×10^6 K (Wrigge, Wendker, Wisotzki 1994). *ROSAT*-PSPC observations of S 308 is severely affected by the occultation ring, making the extraction of X-ray spectrum difficult and unreliable (Wrigge 1999). *ASCA* observations of NGC 6888 show an additional faint component at 8×10^6 K (Wrigge *et al.* 1998).

The advent of *Chandra* and *XMM-Newton* finally makes it possible to study the distribution and physical conditions of the hot gas in bubble interiors. To date, NGC 6888 has been awarded a 100 ks *Chandra*-ACIS-S observation in Cycle 4, and S 308 has recently been observed with *XMM-Newton* (Chu *et al.* 2003). Figure 6 shows the X-ray image of the northwest quadrant of S 308. For the first time, the relative locations of the interior hot gas and the cool shell are resolved! A gap of 0.5 pc between the boundary of hot gas and the leading edge of the cool, dense bubble shell is observed; this gap would correspond to the interface region where heat conduction takes place.

It is interesting to compare the hot interior of S 308 to those of planetary nebulae (PNe). The progenitors of PNe have initial masses up to $\sim 10\,M_\odot$, which corresponds to mid-B type stars, which are qualified as 'massive stars'. PNe are believed to be formed by the current fast stellar winds interacting with the former slow winds at the AGB phase (Kwok 1983), a mechanism almost

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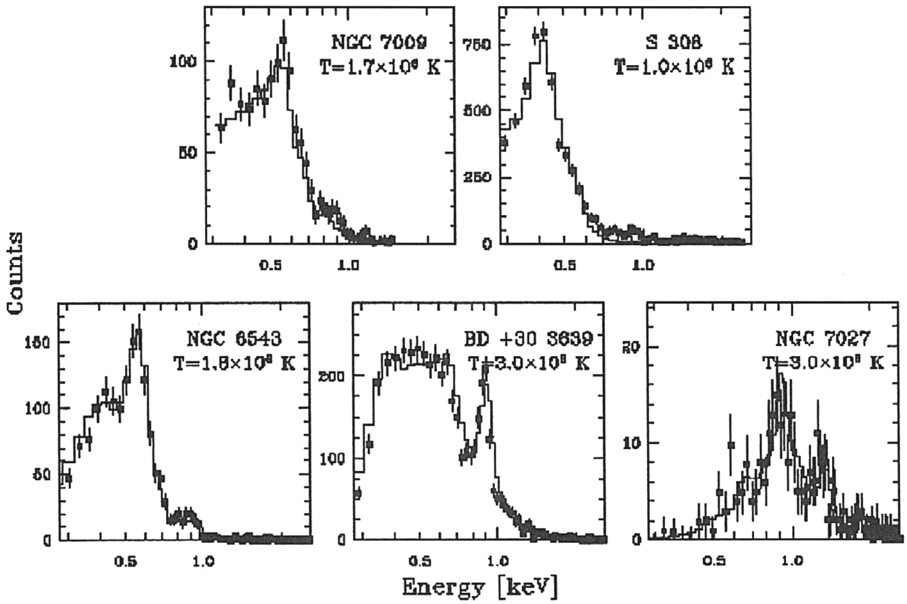

Figure 7. X-ray spectra of shocked fast stellar winds. *Top row:* spectra taken with *XMM-Newton*; *bottom row:* taken with *Chandra*. S 308 is a WR bubble, while the others are planetary nebulae. The nebula name and plasma temperature derived from spectral fits are marked in each panel.

identical to that for the formation of a WR bubble with a RSG progenitor (García-Segura *et al.* 1996). Diffuse X-ray emission has been detected in four PNe (Chu, Guerrero, & Gruendl 2002, and references therein). Figure 7 shows that the hot gas in PN interiors has temperatures of 2 - 3$\times10^6$ K, while S 308 has the coolest interior, only $\sim$1$\times10^6$ K. These temperatures are much lower than the post-shock temperature for a 1000 - 3000 km s^{-1} fast wind. Clearly, mixing with the cool nebular material has taken place (*e.g.*, Pittard *et al.* 2001a,b). More X-ray observations of ring nebulae around massive stars are needed to constrain bubble models.

4. Ring nebulae after the supernova explosion

One of the most intriguing questions about massive stellar evolution is: 'At what locations in the H-R diagram do massive stars explode as SNe?" Only two SNe's progenitors have adequate data to estimate their spectral type: B3 I for SN 1987A (Walborn *et al.* 1989) and K0 I for SN 1993J (Aldering, Humphreys & Richmond 1994). Mass limits of SN progenitors have been estimated from photometric measurements using pre-explosion images (Smartt *et al.* 2001, 2002; Smartt, these Proceedings).

An alternative way to estimate a SN progenitor's spectral type is through the physical properties of the circumstellar nebulae, which can be identified by narrow emission lines in high-dispersion spectra of SNe. The expansion of the

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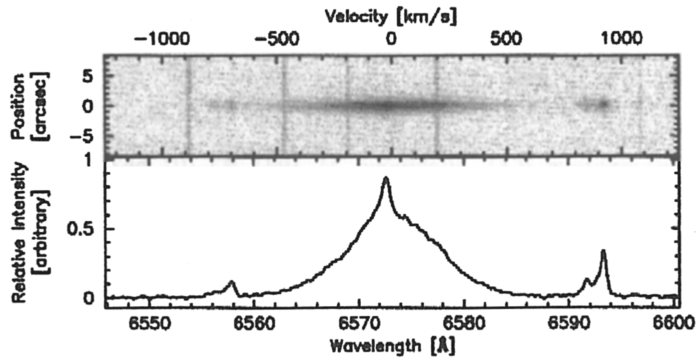

Figure 8. High-dispersion spectrum of SN 1978K at the Hα line region. The broad Hα line originates from the SN ejecta, while the narrow Hα and [N II] $\lambda\lambda$6548, 6583 lines originate from a circumstellar nebula (from Gruendl *et al.* 2002).

nebula can be derived from the widths of line profiles, and the nebular density and temperature can be derived from the [O III] and [N II] lines. A variety of circumstellar nebulae have been observed.

SN 1997ab and SN 1997eg both showed a narrow P-Cygni Hα line, implying the existence of circumstellar nebulae with densities $> 10^7\,\mathrm{cm}^{-3}$ and expansion velocities 100 - 150 km s^{-1} (Salamanca *et al.* 1998; Salamanca, Terlevich & Tenorio-Tagle 2002). These narrow P-Cygni lines disappeared in observations made in March 1999, indicating that they are small (Gruendl *et al.* 2002). These circumstellar nebulae cannot be the RSG wind because the expansion velocities are too high. It is possible that these dense circumstellar nebulae are produced by a very dense SN progenitor wind, as the 'deathbed ejecta' (Chu 2001).

SN 1978K (Figure 8) shows narrow Hα and [N II] lines superposed on a broad Hα line from the SN ejecta (Chu *et al.* 1999; Gruendl *et al.* 2002). A lower limit on the nebular size can be derived from the age of the SN and the expansion velocity of the SN ejecta, while an upper limit of 2.2 pc is derived from the unresolved *HST*-WFPC2 image. The observed auroral to nebular line ratios of the [O III] and [N II] lines indicate a high density, $3 - 12\times10^5\,\mathrm{cm}^{-3}$ (Ryder *et al.* 1993). Such size and density are consistent with those of LBV nebulae. The progenitor of SN 1978K might have exploded at the LBV phase.

SN 1998S showed rapid variation in the narrow nebular line profiles during the first month after the SN explosion, indicating that the SN ejecta was plowed through a circumstellar nebula with a range of densities (Fassia *et al.* 2001). A year after the SN explosion, a narrow [O III] line persisted; the FWHM of this line indicates an expansion velocity < 25 km s^{-1} (Gruendl *et al.* 2002). The lack of [N II] counterpart suggests an interstellar origin. Thus, this narrow [O III] line might originate from an interstellar bubble.

Monitoring observations of SN 1987A have proven useful in revealing the interaction between the SN ejecta and the circumstellar nebula. Likewise, monitoring observations of extragalactic SNe with narrow nebular lines would also be very useful in determining the size of the circumstellar nebula. By comparing the density and size of a SN's circumstellar nebula to those of ring nebular around massive stars, it is then possible to gain insight into the nature of the SN progenitor.

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Discussion

OEY: Are abundance enhancements seen in circumstellar bubbles?

CHU: Yes, circumstellar bubbles are in fact confirmed to contain stellar material, because of their abundance enrichments.

SONNEBORN: I repeat my comment from Monday, that the similarity between Sher 25 and the SN 1987A circumstellar rings cannot be established, until spectroscopy of the Sher 25 ring can measure its CNO abundances. The ring may be circumstellar, but the evidence for it being a SN 1987A analogue is circumstantial.

CHU: The high [N II]/Hα ratio of Sher 25's rings is indicative that its N abundance is enhanced. The morphology and size of SN 1987A's and Sher 25's rings are so unique, unparalleled by any other ring nebulae, that they are most likely formed in a similar fashion, because the central stars have similar mass loss history and evoltion. I maintain that the evidence is circumstellar, rather than circumstantial.

MAÍZ-APELLÁNIZ: You showed that in the region of N 11B there is a kinetically-observed splitting of the [N II] lines. However, no morphological bubbles are observed in Hα (or [O III]): behind the bubble is an intense H II region on the surface of a molecular cloud (as detected in CO). Therefore, all weak morphological structures (such as a bubble) are completely washed out against the bright Hα or [O III] background. The bubbles could be imaged, but only in low-excitation lines such as [N II] or [S II].

CHU: The [N II] lines show two equally bright velocity components, indicating similar density in both the approaching and receding sides of the bubble. The lack of a bright stationary component suggests that the bubble does not reside against a brighter H II region; the bubble itself is the H II region.