RING NEBULA AND BIPOLAR OUTFLOWS ASSOCIATED WITH THE B1.5 SUPERGIANT SHER 25 IN NGC 3603

WOLFGANG BRANDNER,2 EVA K. GREBEL,2,3 YOU-HUA CHU,3,5 AND KERSTIN WEIS3,4,5

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ABSTRACT
We have identified a ring-shaped emission-line nebula and a possible bipolar outflow centered on the B1.5 supergiant Sher 25 in the Galactic giant H II region NGC 3603 (distance 6 kpc). The clumpy ring around Sher 25 appears to be tilted by 64° against the plane of the sky. Its semimajor axis (position angle ≈165°) is 6.9 long, which corresponds to a ring diameter of 0.4 pc. The bipolar outflow filaments, presumably located above and below the ring plane on either side of Sher 25, show a separation of ≈0.5 pc from the central star.

High-resolution spectra show that the ring has a systemic velocity of $V_{\text{LSR}} = +19$ km s$^{-1}$ and a deprojected expansion velocity of 20 km s$^{-1}$, and that one of the bipolar filaments has an outflow speed of ~83 km s$^{-1}$. The spectra also show a high [N II]/Hα ratio, suggestive of strong N enrichment. Sher 25 must be an evolved blue supergiant (BSG) past the red supergiant (RSG) stage. We find that the ratio of equatorial to polar mass-loss rate during the RSG phase was ≈16. We discuss the results in the framework of RSG-BSG wind evolutionary models.

We compare Sher 25 to the progenitor of SN 1987A, which it resembles in many aspects.

Subject heading: ISM: individual (NGC 3603) — stars: evolution — stars: individual (Sher 25) — stars: mass-loss — supergiants — supernovae: individual (SN 1987A)

1. THE BLUE SUPERGIANT SHER 25 IN NGC 3603
Sher 25 (Sher 1965) is a B1.5 Iab supergiant (Moffat 1983) similar to Sk $-69^h 202$, the progenitor of SN 1987A. Sher 25 has a visual magnitude of $V \approx 12.2–12.3$ mag (e.g., van den Bergh 1978). It is located at ≈20° north of HD 97950, the core of the ≈4 Myr old cluster at the center of the Galactic giant H II region NGC 3603 at a distance of 6–7 kpc (Clayton 1986; Melnick, Tapia, & Terlevich 1989). Based on UVB CCD photometry of Sher 25, Melnick et al. derived a visual extinction $A_V \approx 5$ mag and a distance modulus consistent with Sher 25 being associated with NGC 3603.

In a recent search for emission-line objects in NGC 3603 (Brandner et al. 1997), we found a clumpy ring and a bipolar nebula around Sher 25. This ring is similar to that around SN 1987A in both size and morphology. Follow-up spectroscopy shows N enrichment in the nebula around Sher 25, suggesting that Sher 25 is at a similar evolutionary stage to Sk $-69^h 202$. In this Letter, we report our observations (§2), discuss the physical structure of the nebula around Sher 25 (§3) and the evidence for Sher 25 being associated with NGC 3603 (§4), and compare it to SN 1987A (§5).

2. OBSERVATIONS
Hα and R images of an 8’ × 8’ field centered on NGC 3603 were obtained at the ESO New Technology Telescope (NTT) on 1995 February 8 with the red arm of the ESO Multi-Mode Instrument and a 2k Tek CCD (ESO 36). We used a narrow-band Hα filter (Δλ = 1.8 nm) and a broadband R filter for continuum subtraction. Photometric VRI observations and an Hα+[N II] image (Δλ = 6.2 nm) were obtained on 1995 March 2 with the CCD camera at the Danish 1.54 m telescope. The Hα+[N II] image of the central cluster in NGC 3603 and its surroundings is displayed in Figure 1 (Pl. L8). Figure 2 (Pl. L9) shows a continuum-subtracted Hα NTT image centered on Sher 25. The residuals (bright features) are due to charge bleeding as the brightest stars were saturated in the R image. Figure 3 shows the location of the blue supergiant (BSG) Sher 25 above and to the red of the main-sequence turnoff. The stars well above the main sequence are (blended) Wolf-Rayet and early type O stars located in the very center of the cluster.

Long-slit echelle spectra of the eastern cap and the ring were obtained on 1996 January 10 at the Cerro Tololo Inter-American Observatory 4 m telescope. The echelle spectrograph was equipped with a 2k Tek CCD. The slit orientation was east-west (dashed line in Fig. 2), and the slit width was 1.6. We adopted rest wavelengths in air of 654.81 and 658.36 nm for the two forbidden [N II] lines $^2P_{1/2}^1-D_2$ and $^2P_{1/2}^3-D_2$ (e.g., Moore 1959). Relative velocities are accurate to about 0.2 km s$^{-1}$. The absolute calibration with respect to the local standard of rest (LSR) has an uncertainty of about 2–4 km s$^{-1}$. Figure 4 (Pl. L10) shows the two-dimensional spectra in the region of the Hα and [N II] lines. At the position where the slit intersects the ring the two distinct velocity components are clearly visible.

3. INNER RING AND OUTFLOW FILAMENTS AROUND SHER 25
A tilted ring around Sher 25 can be clearly seen in Figures 1 and 2. The semimajor and semiminor axes are 6.9 and 3.05, respectively. Assuming a circular ring geometry, we derive an inclination angle of 64° with respect to the sky plane along the position angle ≈165°. The linear diameter of the ring is 0.4 pc, for a distance of 6 kpc. The relative velocity difference between the two ring components intersected by the slit is 32 km s$^{-1}$ (see Fig. 5). Taking projection effects into account, we derive a deprojected expansion velocity of 20 km s$^{-1}$ for the ring and a systemic velocity of $V_{\text{LSR}} = +19$ km s$^{-1}$. This value...
agrees well with radial velocities of molecular cloud cores south of NGC 3603 (112 km s\(^{-1}\) to 116 km s\(^{-1}\); Nürnberg 1996, private communication) and supports Sher 25’s association with NGC 3603.

Bipolar filaments to the northeast and to the southwest of Sher 25 are also clearly visible in Figures 1 and 2. The northeast filament is not resolved into substructures. It is blueshifted by 36.2 km s\(^{-1}\) from the systemic velocity, indicating an outflow nature. The southwestern filament shows a complex structure with two apparent shock fronts. Lacking kinematic information, we cannot determine whether the southwestern filament is part of a larger three-dimensional structure, i.e., something hourglass-like. Nevertheless, it is very likely that these bipolar filaments are physically produced by a bipolar outflow. If the bipolar filaments of Sher 25 are located along an axis perpendicular to the plane defined by the ring, their physical separation from Sher 25 is about 0.5 pc (15′/cos 26° at 6 kpc). The deprojected expansion velocity of the northeastern filament is 283 km s\(^{-1}\).

The echelle spectra of the ring and the northeast outflow filament show a high [N II]/H\(\alpha\) ratio, compared to the background H\(\alpha\) region (see Table 1 and Fig. 5). Low-resolution spectra of the northeastern outflow filament indicate \(T_e \approx 7000 \pm 1000\) K and \(N_e \approx 9.8 \pm 0.3\) m\(^{-3}\). In a [O III]/H\(\beta\) versus [N II]/H\(\alpha\) diagram, the northeastern outflow filament is situated clearly outside the location of H\(\alpha\) regions or supernova remnants (Brandner et al. 1997). Thus, the high [N II]/H\(\alpha\) ratio is caused by an enhanced N abundance, indicating that at least the bipolar filaments around Sher 25 consist of stellar material enriched by the CNO cycle. Therefore, Sher 25 very likely is an evolved post–red supergiant (RSG).

Given the evolutionary stage of Sher 25, the surrounding nebula may be explained in the framework of interaction between RSG wind and BSG wind. A two-dimensional ringlike structure (as opposed to three-dimensional shells) can be produced if the density of the RSG wind is a strong function of polar angle, peaking along the equatorial plane and decreasing toward the poles (Blondin & Lundqvist 1993; Martin & Arnett 1995). A ring develops as the fast BSG wind sweeps up the dense RSG wind material. At the same time, the density gradient in the RSG wind allows the fast BSG wind to expand more easily in polar directions. This process might lead to an hourglass-shaped emission nebula as has been observed in the young planetary nebula MyCn 18 (Sahai, Trauger, & Evans 1995). The clumpy structure of the ring (see Fig. 2) very likely originates in Rayleigh-Taylor instabilities at the interface between the swept-up slow RSG wind and the fast BSG wind.

The expansion velocities and physical dimensions yield a

### TABLE 1

| Property | Sher 25 | Sk –69°202/SN 1987A |
|----------|---------|---------------------|
| \(d_{\text{inner ring}}\) | 0.4 pc | 0.4 pc* |
| \(v_{\text{inner ring}}\) | 20 km s\(^{-1}\) | 10 km s\(^{-1}\) b |
| \(v_{\text{poles}}\) | 83 km s\(^{-1}\) | |
| ([N II]/H\(\alpha\))\(\text{ring}\) | 0.9:1.2:1 | 4.2:1 c |
| ([N II]/H\(\alpha\))\(\text{poles}\) | 2.1:1 | 2.5:1 c |
| ([N II]/H\(\alpha\))\(\text{background}\) | 0.15:1 | 0.09:1 d |

*Panagia et al. 1991; Plait et al. 1995.
* Jakobsen et al. 1991.
* Panagia et al. 1996.
* Chu, unpublished.
dynamical age of \( \approx 9000 \) yr for the ring and \( \approx 6000 \) yr for the polar outflows. Applying a self-similarity solution for the interaction regions of colliding winds (e.g., Chevalier & Imanura 1983), we can carry out a crude analysis of the observed velocities. In the following we assume constant mass-loss rates and constant wind velocities for the slow wind and the fast wind, a stalled shock (pressure equilibrium) in a spherical symmetric fast wind, and an adiabatic (nonradiative) shock. The shock then expands with a velocity of

\[
v_{\text{shock}} \approx \left( \frac{M_{\text{sw}} v_{\text{sw}}}{M_{\text{fw}} v_{\text{fw}}} \right)^{1/2},
\]

where \( M_{\text{fw}}, M_{\text{sw}}, v_{\text{fw}}, \) and \( v_{\text{sw}} \) are mass-loss rate and wind velocity of the fast wind (fw) and the slow wind (sw), respectively.

If the fast wind is isotropic and does not show any variation in density as a function of polar angle, then the ratio of the expansion velocity of the polar outflow (83 km s\(^{-1}\)) to that of the ring (20 km s\(^{-1}\)) gives us directly the ratio of RSG mass loss in both directions: \( M_{\text{sw}}(90^{\circ})/M_{\text{fw}}(0^{\circ}) \approx 16:1 \). This is in reasonable agreement with the ratios of 20:1 and 10:1 computed for the progenitor of SN 1987A by Blondin & Lundqvist (1993) and by Martin & Arnett (1995), respectively. Assuming a fast wind velocity of 800 km s\(^{-1}\), a slow wind velocity of 50 km s\(^{-1}\), and a ratio of the slow wind and fast wind mass-loss rates along the stellar equator of 90:1 (6:1 in polar direction), one is able to reproduce the observed shock velocities in the framework of this very simplified model.

The center of the inner ring does not coincide with the position of Sher 25 (offset 1\(\alpha\)–2\(\alpha\)). This may be the result of a movement of Sher 25 relative to the surrounding ISM. Martin & Arnett (1995) pointed out that such a movement would produce asymmetric polar outflow structures, which in turn might explain the different appearance of the northeastern and southwestern polar outflow filaments of Sher 25. However, the interpretation of the filaments may be complicated by Sher 25’s apparent location at the edge of a windblown cavity excavated by the central cluster of NGC 3603 (Fig. 1). This cavity has a diameter of 2 pc and a dynamical age of 10\(^4\) yr (Clayton 1986), and it may have been created by the onset of the Wolf-Rayet phase of the three central stars of NGC 3603 (Drissen et al. 1995).

4. SHER 25 AND ITS RELATION TO NGC 3603

What evidence do we have that Sher 25 is indeed a member of the giant H II region NGC 3603? First, as discussed above, the systemic velocity of the ring is in good agreement with the line-of-sight velocities of the cloud cores south of HD 97950. Second, Sher 25 is not the only BSG in the NGC 3603 region. Spectroscopy by Moffat (1983) revealed two other BSGs in the vicinity of the cluster core (see Fig. 1). The locations of Sher 18 (O6 If) and Sher 23 (O9.5 Iab) are also indicated in our \( V \) versus \( V - I \) CMD (Fig. 3). The apparent lack of BSGs with similar reddening among the “field stars” (thin dots in Fig. 3) adds additional weight to the assumption that Sher 25 is associated with NGC 3603.

Could Sher 25 then have been born at the same time as the massive central stars of the cluster? This would require that Sher 25 originally had been at least as massive as these central stars and has gone through a violent luminous blue variable (LBV) phase with a total mass loss of more than 50% of its initial mass (i.e., \( \Sigma M_{\text{tot}} \approx 25 M_\odot \)) before it became a BSG. Indeed, kinematical age, expansion velocity, and abundances of Sher 25’s nebula are comparable to those of the AG Car nebula (see, e.g., Leitherer et al. 1994). With \( M_{\odot} \approx -9.1 \) mag, Sher 25’s luminosity is in the range of luminosities observed in other LBVs. Thus, an LBV evolutionary scenario for Sher 25 and its circumstellar surroundings cannot be entirely excluded.

The simultaneous presence of BSGs and stars of MK type O3 V (see Drissen et al. 1995) requires at least two distinct episodes of star formation in NGC 3603 separated by \( \approx 10 \) Myr. Moffat (1983) and Melnick et al. (1989) have already suggested that star formation in NGC 3603 might not have been coeval. The starburst in the dense cluster of NGC 3603 might have been initiated by the first generation of massive stars through their interaction with a dense cloud core. Subsequently, this cloud core developed into the present-day starburst. A similar evolutionary scenario has been suggested by Hyland et al. (1992) in order to explain the starburst in the 30 Dor region.

5. SHER 25 AND SN 1987A

Sher 25’s circumstellar nebula resembles that of SN 1987A in many aspects. Both objects have an equatorial ring and bipolar nebulae, and show high [N II]/\( \lambda 6583 \) ratios, indicating an enhanced N abundance. The N enrichment indicates that the rings and the bipolar nebulae consist of mass lost from the progenitor at an earlier evolutionary stage and swept up by the fast BSG wind. Surface enrichment with material processed by the CNO cycle typically occurs at the very end of the RSG phase within the last 10\(^4\) yr of RSG evolution.

Yet, differences exist. As shown in Table 1, the expansion velocities and [N II]/\( \lambda 6583 \) ratios are different. The [N II]/\( \lambda 6583 \) ratio of the nebula around Sher 25 is lower than the ratio observed in the outer northern ring around SN 1987A despite the lower N abundance in the LMC. Furthermore, Sher 25 exhibits a higher [N II]/\( \lambda 6583 \) ratio in the bipolar nebulae than in the ring, while SN 1987A shows an opposite trend.

The similarities between the nebulae seem to suggest that Sher 25 is at a similar evolutionary stage to that of the late progenitor of SN 1987A, Sk –69°202. However, the differences between the nebulae imply that their evolutionary histories differ. This may be because of the abundance differences between the young populations in the LMC and in the Milky Way, and because of mass differences between the two stars.

Sher 25 appears to have been in a rather stable BSG evolutionary phase during the past decades covered by photo-

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**TABLE 2**

PHOTOMETRIC OBSERVATIONS OF SHER 25

| Reference         | Date       | \( V \) (mag) | \( B - V \) (mag) | \( U - B \) (mag) |
|-------------------|------------|---------------|-------------------|-------------------|
| Sher 1965         | 1962       | 12.07         | 1.59              | 0.19              |
| van den Bergh 1978 | ...        | 12.08         | 1.59              | 0.19              |
| Moffat 1974       | 1972       | 12.27         | 1.36              | 0.10              |
| van den Bergh 1978 | ...        | 12.38         | 1.40              | 0.29              |
| Melnick et al. 1989 | 1985 Feb. | 12.20         | 1.42              | 0.13              |
| Moffat et al. 1994 | 1991 Feb. | ...           | ...               | ...               |
| This paper.       | 1995 March | 12.31         | ...               | ...               |

* Applying photometric transformations as derived by van den Bergh 1978.
* Using HST/PC1 Moffat, Drissen, & Shara 1994 measured \( B = 13.50 \) mag.
* \( V / R / I \) measurements: \( V - R = 1.03 \) mag, \( R - I = 1.03 \) mag.
metric measurements. Its photometry (Table 2) is quite heterogeneous owing to the variety of different measurement techniques used, crowding problems, and spatial variations in the strength of the nebular background emission. The overall amplitude of variation in \( V \) is less than 0.25 mag within the last 35 yr, and less than 0.1 mag over the last 25 yr. The progenitor of SN 1987A did not stand out as a variable star, either.

Will Sher 25 explode like Sk –69°202 in the near future? The presence of the ring around Sher 25, the N enrichment in the outflows, and the surface enrichment in metals all suggest that Sher 25 has passed through the RSG phase at least once and is now well within its final BSG phase, which may last a few times \( 10^4 \) yr in total depending on the initial stellar mass (see Martin & Arnett 1995). Evolutionary models for massive stars, however, still suffer from many unsolved problems, such as the amount of overshooting, semiconvection, mixing, and mass loss, the choice of convection criteria, and metallicity effects (see, e.g., Langer & Maeder 1995). At present, it is premature to predict whether Sher 25 will succeed Sk –69°202 and provide another spectacular supernova in the southern sky soon.

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Fig. 1.—Hα + [N \text{ II}] image (Danish 1.54 m telescope, exposure time 100 s, seeing 0'9) of NGC 3603. The windblown cavity around the central cluster is visible. The three BSGs in this field are marked. Sher 25 is located at the northern edge of the cavity.

Brandner et al. (see 475, L45)
Fig. 2.—Continuum-subtracted Hα image (NTT/EMMI, exposure time 10 minutes, seeing 1") of Sher 25 (α2000 = 11°15'7.8", δ2000 = −61°15'17"). The tilted ring around the BSG as well as the bipolar filaments located to the northeast and southwest of Sher 25 are visible. The position of the slit is indicated by a dashed line.

Brandner et al. (see 475, L45)
Fig. 4.—Two-dimensional high-resolution spectra of stellar ejecta associated with Sher 25. Two distinct velocity components where the slit intercepts the ring (B and C) are visible in H\(\alpha\) and \([\text{N II}]\).

Brandner et al. (see 475, L45)