Circumstellar Ring Nebulae around Early B Supergiants

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Abstract. The rings around SN 1987A were shaped by the B3I progenitor Sk$-69°$202 and ionized by the UV flash of the supernova. No ring nebulae around B supergiants were known prior to the discovery of SN 1987A's rings. To determine the frequency of ring nebulae around B supergiants and to search for living counterparts of Sk$-69°$202, we have made three pilot searches for ring nebulae around B supergiants in the Galaxy, in 30 Doradus, and in the Small Magellanic Cloud. All three searches yielded negative results, confirming that ring nebulae around B supergiants are rarely seen. We have serendipitously found a circumstellar ring around the B1.5I star Sher 25 in the giant H II region NGC 3603 in the Galaxy. The similarities between this ring and SN 1987A's inner ring suggest that Sher 25 is a Galactic counterpart of Sk$-69°$202.

1. Introduction

SN 1987A in the Large Magellanic Cloud (LMC) has sparked tremendous excitement and interest, as its progenitor Sk$-69°$202 has a known spectral type – a B3 supergiant (Rousseau et al. 1978). This may place essential constraints on stellar evolutionary models. However, it was not certain whether Sk$-69°$202 was a run-of-the-mill B supergiant that had evolved past the red supergiant phase or an exotic product of a binary system that had gone through common-envelope evolution (Podsiadlowski 1992). Because no high-quality, high-resolution spectra of Sk$-69°$202 exist, it is difficult to empirically determine the real nature of Sk$-69°$202 or to spectroscopically identify stars with a similar nature.

The detection of circumstellar rings around SN 1987A (Wampler et al. 1990; Burrows et al. 1995) has provided an opportunity to peer into the mass loss history of Sk$-69°$202. The rings not only promise spectacular fireworks upon impact by the supernova ejecta, but also offer an invaluable template with which we may identify living counterparts of Sk$-69°$202. However, ring nebulae around B supergiants were essentially unheard of prior to the discovery of SN 1987A's rings. There had not been any survey of ring nebulae around B supergiants, presumably because B supergiants do not have conspicuous properties such as copious stellar wind, violent outburst, or powerful ionizing flux. Because these properties are usually a prerequisite for detectable ring nebulae around massive stars (Chu 1991), rings around B supergiants are expected to be different from the well-known ring nebulae around WR, LBV, and O stars. Indeed, the size and shape of the rings around SN 1987A are more in tune with those of planetary nebulae than with ring nebulae around massive stars.

Are the circumstellar rings around SN 1987A a rare event or a common phenomenon for B supergiants? Are there different morphological types for circumstellar rings around B supergiants? To answer these questions and to search for living counterparts of Sk$-69°$202, we made three pilot searches for ring nebulae around B supergiants. In this paper, we report the results of our searches and report on the circumstellar ring nebula around the B1.5 supergiant Sher 25, a serendipitously found object that is likely a Galactic counterpart of Sk$-69°$202.

2. Searches for Rings around B Supergiants

Depending on their evolutionary history, B supergiants may be surrounded by different types of ring nebulae, some interstellar and others circumstellar. A "first-time" B supergiant, having evolved off the main sequence, can be surrounded by a shell of interstellar material swept up by the fast stellar wind; this is an interstellar ring nebula. A "second-time" B supergiant, having looped back from the red supergiant phase, can be surrounded by a shell of swept-up red supergiant wind; this is a circumstellar ring nebula (Figure 1).

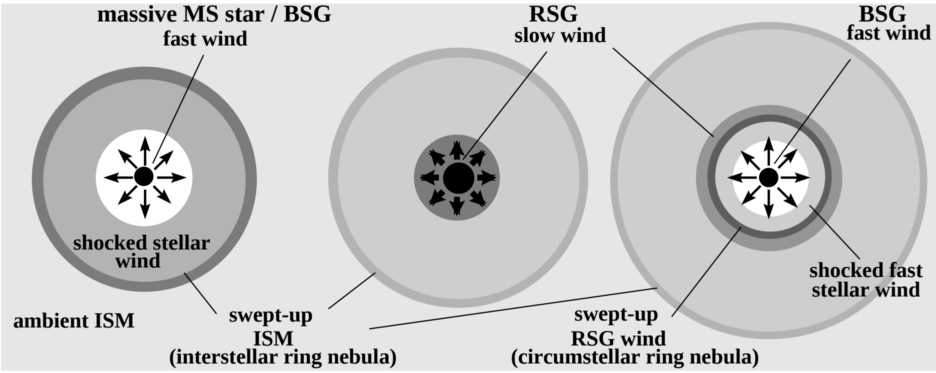

Figure 1. Schematic cartoon illustrating the formation of interstellar and circumstellar ring nebulae around B supergiants. As the star (its wind) evolves along the path MS (fast) $\rightarrow$ BSG (fast) $\rightarrow$ RSG (slow) $\rightarrow$ BSG (fast), a shell of interstellar gas surrounds the first-time BSG, and an additional shell of RSG wind surrounds the second-time BSG.

Interstellar and circumstellar nebulae can be distinguished using the information of size and of the [N II]/Hα line ratio. Interstellar ring nebulae have a wide range of sizes, up to a few tens or even hundreds of pc, while circumstellar ring nebulae are generally small, a few pc or a few tenths of a pc. Interstellar ring nebulae have similar [N II]/Hα ratios as their ambient medium, while circumstellar nebulae show higher [N II]/Hα ratios, because they contain CNO-processed material and hence an elevated nitrogen abundance.

Using both imaging or long-slit spectroscopy, we have made pilot searches for ring nebulae around B supergiants in the Galaxy, in 30 Doradus, and in the Small Magellanic Cloud. The methods and results are described below.

2.1. B Supergiants in the Galaxy

Direct Hα imaging is a traditional way to search for ring nebulae. We use Humphreys' (1978) list of Galactic B supergiants, which contains 166 stars with spectral types from B0 to B3. The list includes isolated stars and stars in loose associations or clusters. About half of them have southern declinations. Using the ESO/MPI 2.2m with EFOSC2 we imaged $\sim$30 B supergiants through an Hα filter. The field of view was $3\farcm5\times3\farcm5$, corresponding to 2pc $\times$ 2pc at a distance of 2 kpc. This field of view may be too small for interstellar ring nebulae, but perfectly adequate for circumstellar rings. None of the stars showed any sign of a ring nebula.

2.2. B Supergiants in 30 Doradus

B supergiants have weak ionizing fluxes. SN 1987A's rings were ionized by the UV flash of the supernova, instead of the B3 supergiant progenitor Sk$-69°202$. It is conceivable that circumstellar nebulae around supergiants of B3 or later types will remain neutral and invisible, unless they are ionized externally by nearby early-type stars. By the same token, any circumstellar ring nebulae produced by mass outflows from interacting binary systems that have small ionizing fluxes will have to be illuminated externally to become visible.

The 30 Doradus giant H II region in the LMC contains a powerful ionizing source at its core, the R136 cluster. It is expected that circumstellar nebulae around later-type B supergiants or interacting binary systems in 30 Dor might be externally ionized and thus become visible in Hα. HST WFPC2 Hα images of two fields in 30 Dor are available, one field with the PC centered on the R 136 cluster (retrieved from the archive) and the other field with the PC centered on the Hodge 301 cluster (our proprietary data). The R136 cluster is too young to contain evolved, second-time B supergiants, but Hodge 301, being nearly 20 Myr old (Grebel & Chu 1997), contains one early B supergiant (R 132, B0.5 Ia) and three A0 to A5 supergiants (Melnick 1985; Walborn & Blades 1997). Unfortunately, R 132 is just outside our PC field; our field contains no known B supergiants, although it does contain two blue stragglers that are quite likely merged binaries (Grebel & Chu 1997). The 2$\times$700s-exposure PC image of Hodge 301 in the Hα line is shown in Figure 2. No ring nebulae around the two blue straggler or any other stars are detected in this image.

2.3. B Supergiants in the SMC

Circumstellar nebulae are expected to show enhanced [N II]/Hα ratios with respect to their background interstellar medium. Long-slit spectroscopy will thus be effective in searching for such nebulae. Using data from the ESO/NTT archive, we searched medium-dispersion long-slit spectra of 52 B Supergiants in the SMC for [N II] emission from the stars and their immediate surroundings. About half of the stars had spectral types between B0 and B3 and thus would provide enough ionizing flux to cause forbidden line emission in the circumstel-

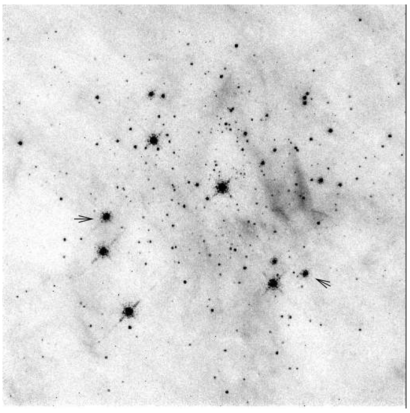

Figure 2. HST PC image of the cluster Hodge 301 in Hα. The field of view is $38'' \times 38''$. The two blue stragglers are marked.

lar nebulae. However, none of the spectra indicate the presence of any ionized circumstellar nebulae.

3. Ring Nebulae around B Supergiants Are Rarely Seen

Ring nebulae, interstellar or circumstellar, around B supergiants are apparently rare. The rareness of interstellar ring nebulae around B supergiants may be caused by the combination of a low-density interstellar environment and a weak stellar wind. An additional observational difficulty is demonstrated by the recently discovered interstellar bubble around the B2 supergiant Sk-69°271. An Hα arc around this star was detected by Weis et al. (1995); follow-up long-slit echelle spectroscopy shows clearly an interstellar bubble which is, however, more extended than the Hα arc and has no morphological counterpart (Weis et al. 1997). At present we do not have sufficient statistics to determine the real cause of the scarcity of visible interstellar ring nebulae around B supergiants.

The rarity of circumstellar ring nebulae around B supergiants may be caused by two factors. First, the ring nebula may have a short duration of visibility compared to the lifetime of the B supergiant phase. After all circumstellar material has been swept up, the further expansion will decrease the shell density and the shell will dissipate below the detection limit within $\sim 10^4$ yr. Second, circumstellar ring nebulae around supergiants of types B3 or later would remain largely neutral, as these stars have negligible ionizing power. The aspherical ring nebulae, such as the one around Sk-69°202, may need special conditions for their formation, for example, specific binary systems in the central star.

Imaging or long-slit spectroscopic searches for ring nebulae for at least a few hundred B supergiants are needed before we can draw any statistically significant conclusions. These surveys may be tedious and yielding mostly negative results; however, every positive detection of a circumstellar ring guarantees utmost excitement. An excellent example is Sher 25 as described in the next section.

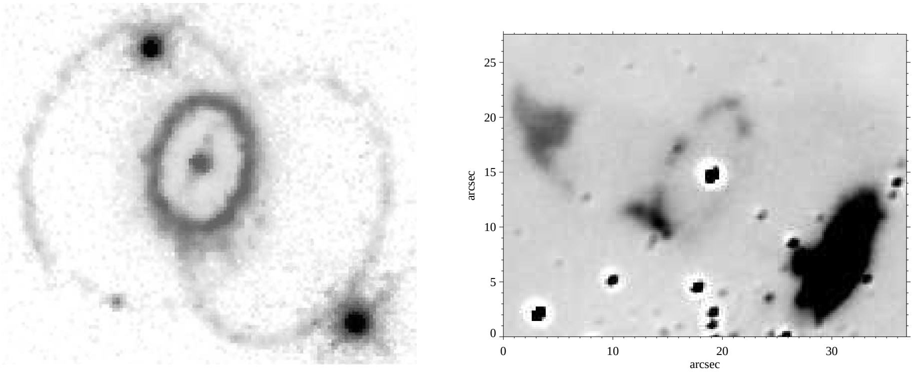

Figure 3. The ring nebulae around SN1987 A (left) and Sher 25 (right) plotted in the same physical scale. The ring diameter is 0.4 pc in both cases.

4. Sher 25: a Galactic Counterpart of Sk$-69°$202

We serendipitously discovered a ring-shaped emission-line nebula and a bipolar outflow centered on the B1.5 supergiant Sher 25 located in the Galactic giant H II region NGC 3603 (Brandner et al. 1997). The clumpy ring around Sher 25 appears to be tilted by 64° against the plane of the sky. Its semimajor axis is $6\farcs9$ long, which corresponds to a ring diameter of 0.4 pc – exactly the same diameter as observed for the inner ring around SN1987 A! The bipolar outflow filaments, presumably located above and below the ring plane on either side of Sher 25, have a separation of $\approx$ 0.5 pc from the central star. Table 1 gives a comparison between SN1987 A's progenitor Sk$-69°$202 and Sher 25, and Figure 3 shows Hα images of SN 1987A and Sher 25 at the same linear scale.

Sher 25's circumstellar nebula resembles that of SN 1987A (e.g. Burrows et al. 1995) in many aspects. Both objects have an equatorial ring and bipolar nebulae, and show high [N II]/Hα 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.

Yet, differences exist. As shown in the table above, the expansion velocities and [N II]/Hα ratios are different. The [N II]/Hα 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]/Hα 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 as the late progenitor of SN 1987A, Sk$-69°$202. However, the differences between the nebulae imply that the evolutionary history differs. This may be due to the abundance differences between the young population in the LMC and in the Milky Way, and to the mass difference between the two stars.

We have been awarded HST time in Cycle 7 to take WFPC2 images of Sher 25's nebula in Hα and [N II] lines, and we have mapped the velocity field

Table 1. Comparison between Sk$-69°202$ and Sher 25.

	Sk$-69°202$	Sher 25
Spectral type	B3 I[a]	B1.5 Iab[b]
Diameter	0.4 pc[c]	0.4 pc[d]
V_{exp}	10 km s^{-1}[e]	20 km s^{-1}[d]
$([N\,II]/H\alpha)_{ring}$	4.2[f]	0.9–1.2[d]
$([N\,II]/H\alpha)_{outer}$	2.5[e]	2.1[d]
$([N\,II]/H\alpha)_{H\,II}$	0.09[g]	0.15[d]
Distance	50 kpc	6–7 kpc

References: a – Rousseau et al. 1978, b – Moffat 1983, c – Panagia et al. 1991, Plait et al. 1995, d – Brandner et al. 1997, e – Jakobsen et al. 1991, f – Panagia et al. 1996, g – Chu, unpublished

of the nebula with the CTIO 4m echelle. These observations will allow us to spatio-kinematically model the nebular structure and determine its formation mechanism. Future observations to determine the binarity and surface abundances of Sher 25 would be extremely interesting.

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