RING NEBULAE AROUND PN NUCLEI AND MASSIVE STARS

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Abstract. Planetary nebulae (PNe) and ring nebulae around massive stars are not just superficially similar in morphologies. For massive stars that evolve through red supergiant phase, the final fast wind would sweep up the slow red supergiant wind and form a bubble of stellar material, reminiscing the two-wind formation of a PN. Sometimes it can be really difficult to determine whether the central star of a ring nebula is a PN nucleus or a Pop I massive star. Parallel studies of PNe and ring nebulae around massive stars can greatly benefit each other.

1. Introduction

Stars lose mass as they evolve. The outflowing stellar mass interacts with the ambient medium and often forms one or more circumstellar shells. Since optically visible shells attract attention more easily, extensive studies exist only for shells whose central stars heat up and emit ionizing radiation at late evolutionary stages. For stars with initial masses of 8 $M_\odot$ or less, their circumstellar shells are recognized as "planetary nebulae". For stars with initial masses $\gg$10 $M_\odot$, their shells are called "ring nebulae around massive stars" (Chu 1991). For stars with intermediate masses, the circumstellar shells may not be noticed until after the supernova explosion as in the case of SN1987A (Wampler *et al.* 1990).

"Planetary nebulae" and "ring nebulae around massive stars" share many similar physical properties and formation mechanisms. In fact, without knowing the distance it is often hard to distinguish whether the central star of a ring nebula is a massive star or a PN nucleus. In this paper I will discuss the similarities and differences between these two types of nebulae, examine the direct evidence of two-wind interaction for both nebulae, and plead the inclusion of ring nebulae in future PN conferences.

2. Mass Loss History and Shell Formation

The formation of a ring nebula, or a circumstellar shell, depends on the mass loss history of the central star. If the stellar evolution is known, the mass loss history of a star can be inferred from the observed mass loss of stars that represent earlier evolutionary stages. The formation and structure of circumstellar shells can then be hydrodynamically calculated.

2.1 Planetary Nebulae

The progenitor of a PN nucleus evolves off main sequence and starts to lose mass appreciably at red giant stage via slow wind then much more copiously at asymptotic giant branch (AGB) phase via "superwind". The superwind velocities range from a few to 80 km s^{-1} with the majority being 10–25 km s^{-1}, and the mass loss rates range from a few $\times 10^{-8}$ to $\geq 10^{-4}$ $M_\odot$ yr^{-1} with the majority being a few $\times 10^{-6}$ to 10^{-5} $M_\odot$ yr^{-1} (Knapp 1989). The superwind tapers off at the post-AGB phase. As the star heats up and ionizes the circumstellar shell into a visible planetary nebula, it also turns on a fast stellar wind, of which the velocity may be 600 to 3500 km s^{-1} and the mass loss rate may be 10^{-11} to 10^{-6} $M_\odot$ yr^{-1} (Patriarchi & Perinotto 1991).

This fast wind inevitably will catch up and interact with the previous slow wind

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(Kwok, Purton, & FitzGerald 1978). This wind-interaction mechanism was originally calculated for two spherically symmetric winds colliding inelastically (Kwok 1983). More sophisticated hydrodynamic calculation was later developed to include multiple and even non-spherical winds (Kahn 1989; Frank, Balick, & Riley 1990; Icke 1991). These models successfully explain many observed PN properties, especially the bipolar and butterfly PNe.

However, it ought be borne in mind that not every PN could be described by interacting fast wind and slow wind. 40% of PN nuclei do not show any evidence of fast stellar wind (Patriarchi & Perinotto 1991). Furthermore, many multiple shell PNe have density profiles and internal motions too complex to be explained by two- or three-wind models. For example, M2-2 has two shells with different expansion velocities and ellipticities and IC 3568 has an outer shell expanding faster than its inner shell (Chu 1989).

PN nuclei can lose mass more creatively than the aforementioned red giant wind, superwind, and fast stellar wind. Bipolar jets have been observed in NGC 2392 (Gieseking, Becker, & Solf 1985) and NGC 6543 (Miranda & Solf 1992). The spatiokinematic structure of the innermost, H-depleted nebulae in the born-again PNe A30 (Reay, Atherton, & Taylor 1983; Jacoby & Chu 1989) and A78 (Clegg *et al.* 1992) indicates a more violent ejection mechanism.

2.2 Ring Nebulae around Massive Stars

Massive stars lose mass via fast stellar wind even at the main sequence stage (Garmany *et al.* 1981). They evolve off main sequence toward later spectral types at roughly constant luminosity, then loop back toward the left of H-R diagram at turning points that depend on the initial stellar mass (Maeder 1983; Maeder & Maynet 1988). The most massive stars never reach red supergiant stage.

Stars with initial masses $\geq 50\ M_\odot$ evolve into luminous blue variables (LBVs) near the turning points, eject H-rich envelopes and become Wolf-Rayet (WR) stars later (Humphreys 1991). LBVs are known to go through eruptions during which the mass loss rate reaches a maximum of a few $\times 10^{-4}\ M_\odot\ yr^{-1}$ and lasts $\sim$20 yr (Lamers 1989; Humphreys 1989). WR stars have the most powerful stellar winds with typical wind terminal velocities of 2000–3000 km s^{-1} and mass loss rates of 10^{-5}–$10^{-4}\ M_\odot\ yr^{-1}$ (Barlow, Smith, & Willis 1981; Willis 1982; Abbott *et al.* 1986; Prinja, Barlow, & Howarth 1991).

Stars with initial masses $<50\ M_\odot$ may evolve off main sequence and reach red supergiant phase (Maeder 1983), at which stage copious mass loss occurs at rates of a few $\times 10^{-5}\ M_\odot\ yr^{-1}$ with wind terminal velocities of 20–30 km s^{-1} (Jura & Kleinmann 1990). As red supergiants evolve toward the left of H-R diagram, only stars with initial masses $\sim 40\ M_\odot$ may lose enough H-rich surface material and become WR stars; the less massive ones evolve into blue superginats before exploding as supernovae.

Simplistically, a massive star starts to blow a bubble of interstellar material at the main sequence stage, ejects stellar material near the turning point of evolutionary track via LBV outbursts or red supergiant wind, and finally uses the hot fast stellar wind to sweep up the circumstellar material into a shell after it evolves into a WR star or a blue supergiant. In principle, an evolved massive star would be surrounded by multiple shells, *e.g.*, NGC 6164-5 (Bruhweiler *et al.* 1981; Leitherer

& Chavarria-K. 1987). However, multiple shells are not usually observed because of the following reasons. The interstellar bubble blown at main sequence stage may be too tenuous, especially if the star belongs to an OB association inside a superbubble. The final bubble of stellar material may fade below detection limit in a few $\times 10^4$ yr (Miller & Chu 1993). Evolved stars may not be hot enough to ionize the circumstellar shells, if the spectral type is later than B0-1. The final stellar wind may not be powerful enough to sweep the circumstellar material into a shell that is dense enough to be easily observable and large enough to be easily resolvable from the stellar image, *e.g.*, the circumstellar nebula around P Cyg (Johnson *et al.* 1992).

The reality is inevitably more complex than this simple scenario. As Dyson (1992) reviewed in this symposium, the motion of stars, the time intervals between different episodes of mass loss, the instabilities in shells, *etc.* all influence the physical structures of the final ring nebulae. It is not surprising that no two ring nebulae look exactly alike (Chu, Treffers, & Kwitter 1983; Miller & Chu 1993). Massive stars, too, can lose mass bipolarly, *e.g.*, AG Car (Paresce & Nota 1989), HD 148937 (NGC 6164-5; Pismis 1974; Leitherer & Chavarría-K. 1987), and Sk -69°202 (SN1987A; Wampler *et al.* 1990).

3. Similarities and Differences between PNe and Ring Nebulae

Figure 1 demonstrates some obvious similarities and differences bewteen PNe and ring nebulae. NGC 6720 (the Ring Nebula) and NGC 7094 are galactic PNe, and DEM 39 and DEM 231 are ring nebulae around WR stars in the Large Magellanic Cloud (LMC). Note the striking similarity in morphology between NGC 6720 and DEM 231, and between NGC 7094 and DEM 39. However, this morphological similarity between LMC nebulae (50 kpc away) and galactic nebulae at a similar angular resolution also implies that WR rings are at least 50–100 times larger than PNe. Most ring nebulae around massive stars are a few pc in diameter; some may be as large as 100-200 pc across. It can also be seen that WR rings are often in gas-rich environments while PNe are not.

The known ring nebulae around massive stars have a variety of physical properties, representing different stages in the simple scenario described in §2. For example, NGC 2359 and NGC 3199 contain mostly interstellar material, thus representing the main sequence bubble; NGC 6888 and RCW58 contain mostly stellar material, thus representing the final bubble of stellar material; RCW104 conatins a mixture of stellar and interstellar material, thus representing an intermediate case in which the final stellar bubble has merged with the remnant main sequence interstellar bubble (Esteban *et al* 1992; Miller & Chu 1993). The largest ring nebulae, the 100-200 pc rings in the LMC (Chu & Lasker 1980), were probably remnant main sequence bubbles in tenuous medium or superbubbles blown by a group of massive stars.

PNe on the other hand contain almost exclusively stellar material. The only interstellar matter contamination in a PN occurs at the outer edge of red giant wind, which sweeps up the ambient interstellar matter and produces limb-brightening in the faint halo of a PN.

One type of ring nebula formation is physically similar to PN formation. For a massive star that evolves through red supergiant into WR or blue supergiant, its circumstellar material lost via red supergiant wind will be swept up by the final fast stellar wind into a shell. This is identical to the popular two-wind formation of PNe. Only recently are ring nebulae around massive stars modeled as interacting asymmetrical slow wind and spherical fast wind (NGC 6888: Garcia-Segura & Mac Low 1992; ring around SN1987A: Martin & Arnett 1992).

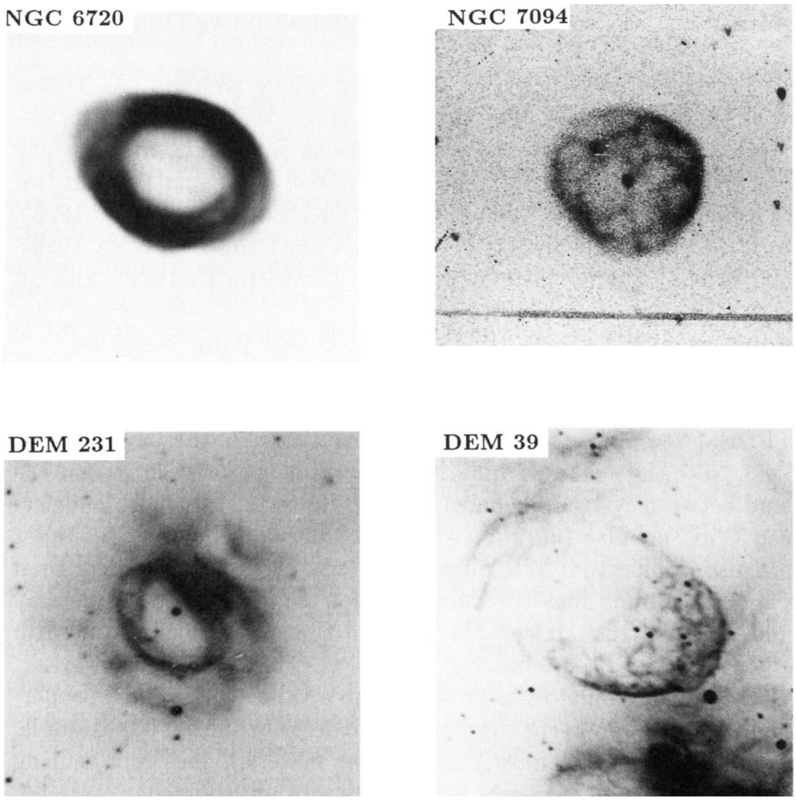

Figure 1. Images of two galactic PNe - NGC 6720 and NGC 7094, and two ring nebulae around WR stars in the Large Magellanic Cloud - DEM231 and DEM39. Note the morphological similarity between NGC 6720 and DEM231, and between NGC 7094 and DEM39.

4. Direct Evidence of Two-Wind Interaction

Around massive stars, the action of fast stellar winds is clearly manifested by the acceleration of ambient interstellar matter and the diffuse X-ray emission from bubbles. For example, the diffuse X-rays in NGC 6888 indicate the existence of 3-9$\times 10^6$ K plasma (Bochkarev 1988), and the observed X-ray luminosity as well as the nebular morphology can be better modeled by fast stellar wind sweeping up the previous asymmetric slow wind (Garcia-Segura & Mac Low 1992), just like the conditions for elliptical PNe (Kahn 1983).

It is more difficult to observationally verify two-wind interaction in PNe, because the pre-shocked gas is already expanding outward and the fast stellar wind is weak. X-ray emission from PNe has been detected by EXOSAT and Einstein Observatory, but only point sources are found (Tarafdar & Apparao 1988; Apparao & Tarafdar 1989). Extended X-ray emission from PNe is first reported in this syposium by Kreysing *et al.* (1992) using ROSAT PSPC observations; among the 6 PNe reported, NGC 6543 and NGC 6853 provide the most convincing cases of extended emission. Future theoretical models need to explain the X-ray shell morphology of NGC 6543 and the very low plasma temperature implied by the X-ray spectrum of NGC 6853.

The shocked fast stellar wind is so hot that high ionization absorption lines should be present against the stellar spectra. Unfortunately, O VI $\lambda\lambda$1031.9, 1037.6 lines are not accessible by IUE or HST, and the N V, C IV, and Si IV lines are dominated by the photoionized dense PN shells. Kaler, Feibelman, & Henrichs (1988) reported absorption components blue-shifted by up to 250 km s^{-1} in high ionization lines in the UV spectrum of the nucleus of A78, and suggested it as direct evidence of fast stellar wind interacting with the PN shell. It ought to be noted that the H-depleted nebula in A78 has a very high expansion velocity (Clegg *et al.* 1992), and it is possible that the observed high-velocity absorption comes from the H-depleted nebula in front of the nucleus. High-velocity absorption in high ionization lines should be searched for in other PNe to verify its origin of interacting winds.

5. Real Confusion between PNe and Ring Nebulae

Many ring nebulae around massive stars were once cataloged as PNe, *e.g.*, AG Car (PK 289-0°1) and NGC 6164-5 (PK 336-0°1). There are also nebulae classified alternately between PNe and ring nebulae, *e.g.*, M1-67 and We21.

M1-67 was discovered by Minkowski (1946), and classified as a PN by Bertola (1964) because the radial velocity of the central star 209 BAC was very high ($\sim$200 km s^{-1}). However, no other PNe have WN8 nuclei, and the extinction of A_V=4.1 mag may require a distance larger than the 0.9 kpc adopted by Bertola (1964). Using the absolute magnitude calibration for Pop I WR stars (Smith 1973), Cohen & Barlow (1975) estimated a distance of 4.3 kpc, and proposed that M1-67 was a ring nebula around a Pop I WN8 star. Van der Hucht *et al.* (1985) compared the IR emission of M1-67 to that of the central region of RCW58 (an ejecta-type ring nebula around a Pop I WN8 star) and claimed that the color temperature of M1-67 was warmer than that of RCW58 but similar to those of PNe, hence concluded that M1-67 was a PN. Esteban *et al.* (1991) examined IRAS color temperature for more ring nebulae around massive stars and found that IRAS color temperature could not discriminate between PNe and ring nebulae around massive stars. Finally, Crawford & Barlow (1991a) used the interstellar Na I absorption velocity profile and the galactic rotation to derive a distance of 4–5 kpc for 209 BAC, making M1-67 a ring nebula around a Pop I WN8 star again.

We21 (Weaver 1974) is a less well-known WN8 star in a small ring nebula (Duerbeck & Reipurth 1990). It was assumed to be a PN at discovery; however, the velocity profile of the interstellar Na I absorption suggested a distance of 11.5 kpc (Crawford & Barlow 1991b). This large distance requires We21 to be a luminous Pop I WN8 star.

At present the massive, Pop I WN8 nature of We21 and 209 BAC is favored. Nevertheless it is possible that unexpected new evidence would change the nebular nature back to PN.

6. Epilogue

According to the original definition, "planetary nebulae" should have included all ring nebulae around massive stars, too. The segregation of PNe and ring nebulae is, to some extent, artificially made by stellar astronomers. These two types of nebulae represent circumstellar shells produced by mass loss from low-mass and high-mass stars, respectively. The apparent gap at the intermediate stellar mass is owing to the invisibility of circumstellar shells around evolved B supergiants. From the nebular point of view, PNe and ring nebulae would be best studied comparatively. Future conferences about PNe may consider including ring nebulae around massive stars, especially the ones consisting of mostly stellar material.

Finally, I would like to point out the fact that circumstellar shells have been systematically searched only around galactic and Magellanic Cloud WR stars and galactic Of stars. More effort should be devoted to surveys of circumstelalr shells around other evolved massive stars.

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