
Eta Carinae and Nebulae Around Massive Stars: Similarities to Planetary Nebulae?

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Summary. I discuss some observational properties of aspherical nebulae around massive stars, and conclusions inferred for how they may have formed. Whether or not these ideas are applicable to the shaping of planetary nebulae is uncertain, but the observed similarities between some PNe and bipolar nebulae around massive stars is compelling. In the well-observed case of Eta Carinae, several lines of observational evidence point to a scenario where the shape of its bipolar nebula resulted from an intrinsically bipolar explosive ejection event rather than an interacting winds scenario occurring after ejection from the star. A similar conclusion has been inferred for some planetary nebulae. I also briefly mention bipolar nebulae around some other massive stars, such as the progenitor of SN 1987A and related blue supergiants.

Key words: bipolar nebulae, Eta Carinae, SN1987A, massive stars

1 Introduction: Massive Stars and PNe

Although this is a meeting on aspherical planetary nebulae (PNe), which are the descendants of intermediate/low-mass stars, I'd briefly like to shift gears and discuss massive stars. In the nebulae around massive stars, like PNe, we see a wide variety of non-spherical geometries with a common theme of bipolar shapes in the ejecta. For most of the more stunning examples of massive star nebulae, one can usually find a PN with nearly identical appearance, at least superficially. Some of the more familiar comparisons are η Car to Hb 5, Mz 3, or even the Red Rectangle (Soker 2007), as well as the similar multiple rings seen around SN 1987A, the luminous blue variable (LBV) star HD 168625 (Smith 2007), the Red Square (Tuthill & Lloyd 2007), and He 2-104 (Corradi et al. 2001), or the peculiar double rings around RY Scuti (Smith et al. 2002) and Abell 14, to name a few. Not surprisingly, discussions of the shaping mechanisms for massive stars and PNe share common themes: binaries/mergers vs. interacting winds vs. rotating ejections. For massive stars, though, magnetic fields still seem to be mostly taboo for the time-being.

Also, like lower mass stars during the AGB phase, it seems to be the case that massive stars shed most of their mass in a brief post-MS evolutionary phase, either as

a RSG or an LBV. This was not always thought to be the case: for very massive stars, the relative importance of LBV eruptions vs. steady winds has been appreciated fairly recently because of the revised lower mass-loss rates estimated for O stars on the main sequence, and because of the very high masses of LBV nebulae (see Smith & Owocki 2006).

Despite vastly different amounts of mass and energy, the compelling similarities between massive star nebulae and PNe make it worthwhile to ask if conclusions gleaned from massive stars can inform the shaping mechanisms of PNe, and vice versa. In the interest of being provocative, then, I'll mention some results for Eta Carinae and a few other massive stars that have been studied in detail, which challenge some familiar ideas developed from the study of PNe. But first, some general comments on winds.

2 Interacting Winds Scenarios?

A fast wind sweeping into a slower and denser wind is a natural avenue to pursue for shaping nebulae, and such models have had varying degrees of success in reproducing PNe shapes (there are dozens of potential references to cite here, including many in these proceedings). A similar process may occur in *some* massive stars if they pass through a very slow-wind phase as a RSG and then evolve through a faster wind phase as a BSG/LBV or a Wolf-Rayet (WR) star. This can and does produce a wind-blown bubble around the WR star in some cases.

A key point, though, is that in the case of massive stars we have some problems if we want interacting winds to account for most bipolar nebulae. First, the slower nebulae around RSGs and yellow hypergiants are generally not axisymmetric. They are often asymmetric or chaotic, but they almost never have clear signs of organized axisymmetry (see, e.g., VY CMa [Smith et al. 2001]; NML Cyg [Schuster et al. 2006]; IRC+10420 [Humphreys et al. 2002]). Second, the resulting wind-blown bubbles around WR stars are *NOT* bipolar!¹ This lack of axisymmetry occurs despite the apparent fact that massive stars have high binary fractions. What does that mean? If binary mergers and jets blown by binaries are dominant shaping mechanisms, shouldn't we see signs of axisymmetry at all stages? Why is it the case that the only bipolar/pinched-waist nebulae around massive stars are those seen around blue supergiants such as LBVs and B[e] supergiants?

A critical point, I think, is that *in these blue supergiants, their escape speeds, observed ejecta/wind speeds, and surface rotation speeds are all comparable*. They are around 100–200 km s⁻¹, as opposed to 10–20 km s⁻¹ for RSGs and 1000–2000 km s⁻¹ for WR stars. I suspect that this is an important clue that for many nebulae around massive stars, intrinsically aspherical ejection from the surface of a rotating star is a prime agent in shaping their nebulae (see Smith & Townsend 2007). In the context of interacting winds, then, I suspect that a very interesting avenue to pursue is an aspherical fast wind interacting with a slow spherical wind or thin shell. In

¹ Some WR nebulae are a little egg-shaped, but we don't see any with pinched waists. Also, I'm not including the "pinwheels" and related phenomena (see, e.g., Tuthill et al. 1999) around dust-producing WC stars, which represent a very different type of "interacting winds".

fact, due to the sporadic nature of episodic mass loss from massive stars, thin shells rather than steady winds is probably where most of the circumstellar mass resides.

Now, that discussion of interacting winds was for massive stars that go through a slow-wind RSG phase followed by a fast wind phase in their evolution...but that only occurs up to initial masses of about $40 M_{\odot}$. Stars with higher initial mass (like Eta Car and most LBVs) never pass through a RSG phase. So for these stars, *ejection as an LBV is the slowest the wind speeds ever get...but it is precisely those LBV nebulae that are observed to be bipolar*. How can this be? This means that they can't be shaped by interacting winds, because a slow dense wind blowing into a faster rarefied wind doesn't produce much interaction. Instead, the slow dense wind that follows the fast wind needs to be shaped on its own; this is discussed and amplified below. Despite the lack of interaction between the fast and slow wind, they produce shapes very similar to some PNe — a fact worth considering.

3 Eta Carinae

Eta Carinae is a key object for trying to understand the shaping of bipolar nebulae, partly because it is bright and so well-observed, and partly because we have caught it so soon (only 160 yr) after its violent mass ejection, before its shape has been corrupted by interaction with the ISM. Despite its status as the most luminous and most massive star known, there is considerable overlap with some topics in PNe research, as I will highlight here.

3.1 Energy and Momentum

Studies of the mass, kinematics, and detailed structure have led to the following basic results (summarized from Smith 2006; Smith et al. 2003):

1. The nebula follows a Hubble-like expansion law, with the same age for the equatorial and polar ejecta.
2. The walls of the nebula are very thin, indicating that the duration of mass ejection was less than 10% of the time elapsed since ejection.
3. Essentially all the mass is in the thin molecular shell, formed from material ejected by the star in the outburst, not in swept-up material.
4. The large mass, momentum, and kinetic energy came from a single explosive event, and could not have been driven by radiation pressure alone or by the stellar wind that has blown after the eruption.

All these clues point to a single violent bipolar explosion that ejected the nebula seen today. Interestingly, all these same basic conclusions were inferred by Alcolea et al. (2007) from a similar detailed study of the PN M 1-92.

In the case of Eta Carinae, though, the difficulties for an interacting winds scenario are compounded further. The mass as a function of latitude has been measured in the bipolar lobes around Eta Car, showing that most of the mass comes from high latitudes near the pole (Smith 2006). This rules-out the familiar type of interacting-wind scenario where a spherical wind plows into a disk or torus (e.g., Frank et al. 1995), because in that scenario, the pinched waist is essentially the result of mass loading at low latitudes (note that the bipolar nebula formed in a merger model is

a variation of this).² Similarly, a different type of interacting winds scenario where a fast aspherical wind³ plows into a slower wind doesn't work either (Frank et al. 1998; Gonzalez et al. 2004). This is because we can observe the stellar wind that has been blowing after the 19th century eruption, potentially inflating and shaping the nebula. However, it is about 1000 times too weak to shape the polar lobes (like a light breeze blowing on a brick wall), and besides, the post-outburst wind speed is almost the same as that of the nebula, so the winds are not interacting anyway! There seems to be little way to escape the conclusion that the bipolar shape of the Homunculus nebula around Eta Car resulted from an intrinsically bipolar ejection by the star itself, and not from any sort of interacting winds scenario. A possible avenue to pursue is discussed after the next section.

3.2 Double-Shell Structure

I'd like to diverge for a moment to talk about the detailed ionization structure in the walls of the nebula around Eta Car, as opposed to its overall bipolar shape, where additional similarities to some PNe can be seen. Eta Car's nebula has a distinct double-shell structure, with a thin outer shell composed of molecular gas and cool dust, and a thicker inner shell of partially-ionized atomic gas and warmer dust (Smith 2006; Smith et al. 2003). In high-resolution spectra and images of H₂ 2.122 μm and [Fe II] 1.644 μm , this structure is almost identical to that seen in some PNe, most notably in M 2-9 (Hora & Latter 1994; Smith et al. 2005). These near-IR H₂ and [Fe II] emission lines are usually taken as signposts for shock excitation (Shull & Hollenbach 1978) because they are seen in supernova remnants, and the double-shell structure is reminiscent of a forward/reverse shock structure that one might expect for interacting winds (e.g., Chevalier 1982).

However, they can also arise from dense atomic and molecular gas that is heated radiatively in a dense PDR (e.g., Sternberg & Dalgarno 1989). Using CLOUDY simulations, Smith & Ferland (2007) demonstrated that the observed IR emission tracers, ionization structure, and the observed dust temperatures can arise naturally from radiative heating if the two shells contain roughly the amount of mass inferred from studies of the dust (Smith et al. 2003). In fact, in the case of Eta Car, radiative heating dominates the energy budget compared to shock heating. This is comforting, because as noted earlier, the post-eruption wind speed is very similar to that of the nebula ejected in the eruption, so there is little reason to expect a strong shock anyway. So, in Eta Car, it seems clear that the observed ionization structure arises from radiative excitation, not shocks. If this is not true for M 2-9, then the almost identical ionization structure is quite a coincidence, especially since the spectra of the central objects are so similar as well (Balick 1989).

² By the way, note as well that the disk seen in *HST* images of Eta Car is *not* the agent responsible for pinching the waist of the bipolar nebula, because it is the same age or younger.

³ The present-day wind appear to be bipolar on size scales smaller than the binary separation (see Smith et al. 2003; van Boekel et al. 2003).

3.3 How to Get Bipolar Lobes and a Disk

Observations of the bipolar nebula around Eta Car seem to dictate that it did not arise as a result of an interacting winds scenario, but instead, from an intrinsically bipolar wind or explosion. In other words, gas was launched from the surface of the star imprinted with the basic bipolar shape seen today.

The present-day, post-eruption wind of Eta Car is also bipolar in shape with a speed comparable to that of the nebula (Smith et al. 2003), although it is much weaker than the mass-loss rate during the 19th century eruption that made the nebula. Its almost as if the present-day bipolar wind density was simply “cranked-up” by a factor of 1000 during the outburst, maintaining the same basic speed and shape (e.g., Dwarkadas & Owocki 2002). If the bipolar nebula was created by some other external mechanism (such as jets blown by accretion onto a companion; see Soker, these proceedings) then it is a remarkable coincidence that the wind shape and speed so closely match the present-day properties of the primary star’s wind. On the other hand, if the primary star ejected that material, then it is not such a coincidence at all.

In the case of an intrinsically bipolar ejection, what determines the resulting shape of a nebula is not the *density* as a function of latitude, but the *speed* as a function of latitude. When mass is driven off the surface of a star, it is a general property that this material leaves at nearly the star’s surface escape speed. This is why RSGs with large radii have slow winds, and compact WR stars have very fast winds. Now, if a star is rotating fast enough to significantly modify the effective gravity at the equator (i.e. a non-negligible fraction of the critical rotation velocity), then the star’s escape speed will vary with latitude, being faster at the poles and slower at the equator. Because of this simple effect, the *default* shape we should expect for material driven from the surface of a rotating star is a bipolar nebula. Admittedly, for this effect to shape the wind, the rotation speeds should be comparable to the wind speed, but this is indeed the case for blue supergiants, as noted earlier. The degree to which the waist is pinched depends on how close the star is to critical rotation. In some cases, such models can also make an equatorial disk like that seen in Eta Car.

Smith & Townsend (2007) described this type of model in detail, with test particles launched from the surface of a rotating star, following simple ballistic trajectories thereafter. They showed that it could account for the shape and speed of the polar lobes of Eta Car, as well as the basic properties of its peculiar equatorial disk. Again, this is the simplest, default shape one should expect for ejection from a rotating object. Smith & Townsend (2007) noted that it may have application to some PNe as well. Please see that paper for further details. Matt & Balick (2004) present a somewhat different intrinsic shaping model for the present-day stellar wind and disk involving MHD effects; this type of mechanism might also be relevant if the magnetic field was strong enough during the outburst.

4 SN 1987A, Rings, and Mergers

The triple ring system observed around SN 1987A inspired a great deal of theoretical work on interacting winds as a potential explanation for its equatorial ring and bipolar ejecta, as well as the formation of bipolar nebulae in general. The basic

avored picture is that the star had a blue loop, with a fast BSG wind pushing into a slower RSG wind. The bipolar shape and equatorial ring could arise if that RSG wind had denser material near the equator (Blondin & Lundqvist 1993; Martin & Arnett 1995), but in order for that to happen, the RSG needed to have an extra source of angular momentum, such as a binary merger event (Collins et al. 1999). This has evolved into a complex model that gives an impressive fit to the observed structure of the nebula (Morris & Podsiadlowski 2007) seen in *HST* images.

While this view is the result of considerable effort and thought, I wish to note a few flies in the ointment, which suggest that the merger model for SN 1987A might not be the final word, and may need to be revisited.

1. A merger model followed by a transition from a RSG to BSG requires that these two events be synchronized with the supernova event itself, requiring that the best observed supernova in history happens to be a rare event.

2. After the RSG swallowed a companion star and then contracted to become a BSG, it should have been rotating at its critical breakup velocity. Even though pre-explosion spectra (Walborn et al. 1989) do not have sufficient resolution to measure line profiles, Sk-69°202 showed no evidence of rapid rotation (e.g., like a B[e] star spectrum). Instead, Sk-69°202 had the spectrum of an entirely normal B3 supergiant.

3. Particularly troublesome is that this merger and RSG/BSG transition would need to occur twice. From an analysis of light echoes for up to 16 yr after the supernova, Sugerman et al. (2005) have identified a much larger bipolar nebula with the *same axis orientation* as the more famous inner triple ring nebula. If a merger and RSG/BSG transition are to blame for the bipolarity in the triple-ring nebula, then what caused it in the older one?

Now, these points may seem silly at first, they are hard to reconcile with the merger model. The last one, in particular, could even be considered to be a strong rebuke. Given that more luminous blue supergiants can eject intrinsically bipolar nebulae without resorting to RSG/BSG transitions or mergers, could SN 1987A's nebula be the result of a massive star ejection instead, like an LBV?

In addition to these problems with the specific case of SN 1987A itself, we also need to take into account the growing number of observed nebulae around massive stars with rings similar to SN 1987A. Is there any evidence that they also formed from mergers? The example most people are familiar with is Sher 25, in the massive cluster NGC 3603 in our Galaxy (see Brandner et al. 1997). It has an equatorial ring with the same physical radius as that of SN 1987A, and it also has bipolar lobes. Yet, studies of the central star in Sher 25 show that its abundances indicate that *it has not gone through a RSG phase* (Smartt et al. 2002). The newly discovered SBW1 in Carina also has a 0.2 pc radius identical to the equatorial ring around 87A; its central star has about the same luminosity as that of the progenitor of SN 1987A, but its ring has Solar N abundances, so it has also *not been through a RSG phase* (Smith et al. 2007). Finally, there's the triple-ring nebula around the LBV star HD 168625 (Smith 2007), which appears to be almost identical to that of SN 1987A. While this star could indeed be a post-RSG because it is mildly N-rich, it is an LBV – stars well known for their unstable bipolar mass ejections. Furthermore, Smith (2007) argued that if the triple ring nebula of HD 168625 is coeval (polar rings have the same age as the equator, as in SN1987A), then they could not have been ejected in a RSG phase because they would be far too fast.

So while the progenitor of SN 1987A may very well have passed through the RSG phase needed for the merger model, two of its twins did not, and a third is an LBV, where the shell was likely created in an LBV ejection. If a binary merger in the RSG phase really is required to make the ring around SN 1987A, how and why did at least three other objects make *nearly identical* nebulae in a different way? At the very least, this implies that a merger model is not the only viable option. Keep in mind that their central stars still exist and are easy to observe, yet there is currently no evidence that they are post-merger products. In fact, they appear as fairly normal blue supergiants; like the progenitor of SN 1987A, these other rings do not appear to be unusually rapid rotators as one would expect for a post-merger product (their inclinations are known from the equatorial ring nebulae). If further studies reveal that any of them survive today as close binaries (binaries that have not yet merged, so that the observed rings are obviously not from a merger event), it will critically wound the merger hypothesis for SN 1987A.

Acknowledgement. I would like to thank the conference organizers for the invitation to speak and for generous partial financial support that made my trip possible.

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