Wolf-Rayet Stars
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Shaping the outflows of Wolf-Rayet stars

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Wolf-Rayet (WR) stars lose copious amounts of mass and momentum through dense stellar winds. The interaction of these outflows with their surroundings results in highly structured and complex circumstellar environments, often featuring knots, arcs, shells and spirals. Recent improvements in computational power and techniques have led to the development of detailed, multi-dimensional simulations that have given new insight into the origin of these structures, and better understanding of the physical mechanisms driving their formation. We review three of the main mechanisms that shape the outflows of WR stars:

- interaction with the interstellar medium (ISM), i.e., wind-ISM interactions;
- interaction with a stellar wind, either from a previous phase of evolution or the wind from a companion star, i.e., wind-wind interactions;
- and interaction with a companion star that has a weak or insignificant outflow (e.g., a compact companion such as a neutron star or black hole), i.e., wind-companion interactions.

We also highlight the broader implications and impact of these circumstellar structures for related phenomena, e.g., for X-ray binaries and Gamma-ray bursts.

1 Introduction

Massive stars have dense, powerful stellar winds, particularly in the final stages of evolution during which mass-loss rates can be as large as $10^{-4}\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ and winds as fast $3\,000\,\mathrm{km\,s}^{-1}$ (Lamers & Cassinelli 1999). These outflows not only remove mass from the outer layers of the star, but also carry away angular momentum. Both these effects can dramatically change the subsequent evolution of the star, determining its lifetime, the type of supernova (SN), if any, it will produce, and whether it will leave behind a neutron star or a black hole (Langer 2012; Smith 2014). The outflows also have a tremendous impact on the circumstellar environment, injecting large amounts of kinetic energy, and gas that is enriched with nuclear processed material and dust grains. Consequently, understanding the mass-loss process is crucial for stellar evolution calculations and population estimates alike, and also has broader implications for other areas in astronomy, e.g., affecting feedback and star formation, or the dust content and chemical evolution of galaxies.

The mass-loss mechanism and the nature of the stellar outflows, however, changes significantly as the stars evolve (see e.g., Lamers & Cassinelli 1999, and references therein). Massive O stars have radiatively driven, fast winds before passing through a red supergiant (RSG) or Luminous Blue Variable (LBV) phase where the winds are an order of magnitude slower and the mechanism that drives the outflows is less well understood. For the former, a combination of convective motions, pulsations, and radiation pressure on dust are thought to play a role, whereas the mass loss from LBVs is thought to be more episodic, giant eruptions. Eventually the stars transition to the Wolf-Rayet (WR) phase where the winds are once again radiatively driven, fast and hot. Each of these evolutionary transitions coupled with both internal and external processes (e.g., stellar and ISM magnetic fields; background radiation fields (such as from clusters) or from a companion; outflows from the ISM or a companion; stellar rotation or merger with a companion) results in the formation of complex circumstellar structures. Advances in both the resolution and sensitivity of the observations have revealed these structures in unprecedented detail. Similarly, advances in computing power have now made it possible to include a large number of physical processes in multi-dimensional models, enabling a more direct comparison with the observations.

In this review, we discuss three of the above processes that shape the outflows of massive stars, namely wind-ISM interactions, i.e., interaction of stellar outflows with the ISM; wind-wind interactions where the stellar wind collides with material either from a previous phase of evolution or the wind of a companion star; and wind-companion interactions where the outflow is shaped by a companion star that has a weak or insignificant outflow (e.g., a compact companion such as a neutron star or black hole). In Sec. 2, we highlight the role wind-ISM and wind-wind interactions play in the formation of 'ring nebulae' and bow shock arcs. The formation of spirals and equatorial, disk-like outflows through interaction with a binary companion are discussed in Sec. 3. We conclude by highlighting areas for further development and exploration in Sec. 4.

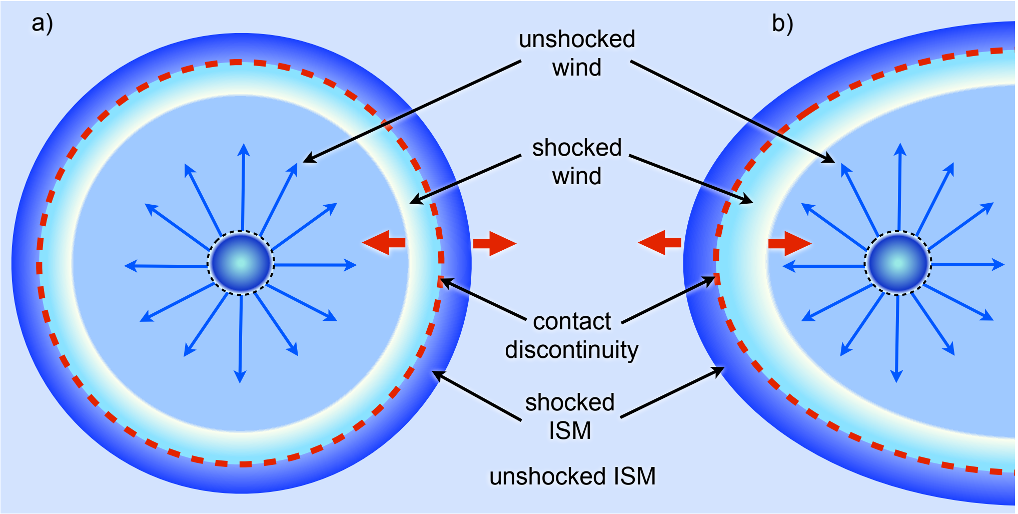

Fig. 1: The equilibrium morphology of the double shock structures that develop due to the supersonic interaction of a stellar outflow with its circumstellar environment. Four regions can be identified: the unshocked and shocked stellar wind separated from the shocked and unshocked surrounding medium (in this case the ISM) by a contact discontinuity. [a] If the star is stationary with respect to the surrounding medium, a ring-like shock structure forms, whereas, [b] if there is relative motion between the star and its environment, a cometary-shaped structure known as a bow shock results, with the apex pointing in the direction of motion. Note, the appearance of the latter depends on the viewing angle, e.g., if the relative motion is along the line-of-sight, the structure observed will look like [a] (see text for discussion). In both [a] and [b] the short, thick arrows in the direction of the ISM and unshocked stellar wind are the forward and reverse shocks, respectively.

2 The formation of ring and bow shock nebulae

When a stellar outflow encounters slower moving, dense circumstellar gas (either ISM or material ejected during an earlier phase of evolution), it sweeps up the material into a shell. As a result of the collision, the material in the interaction zone heats up and wants to expand, in the forward direction into the surrounding medium, driving a forward shock, and into the non-shocked wind material, resulting in a reverse shock. For a star that is non-stationary with respect to its surroundings, the shocks are distorted into a cometary arc-like structure known as a bow shock, pointing in the direction of motion (Weaver et al. 1977; Wilkin 1996; Lamers & Cassinelli 1999). The equilibrium, global morphology of ring and bow shock nebulae is shown in Fig. 1 (note that similar structures, planetary nebulae, are found around low/intermediate mass stars – see Guerrero et al., these proceedings).

The nebulae around WR stars are observed from radio to X-ray wavelengths (Gruendl et al. 2000; Arthur 2007; Toalá et al. 2015, and references therein). The detailed structure depends strongly on the properties (e.g., density, velocity, temperature, ionization degree etc.) of the material swept up by the WR wind, as demonstrated by, for example, models of WR-RSG versus WR-LBV wind interactions (e.g., García-Segura et al. 1996a,b; van Marle & Keppens 2012). The collision with slower, higher density RSG winds results in more highly radiative, unstable shocks than the faster, more ionized LBV winds. Similarly, wind-ISM interactions with fast winds are generally more stable than bow shocks with slow winds (Dgani et al. 1996). In addition to the Raleigh-Taylor instabilities that dominate wind-wind interactions, Kelvin-Helmholtz instabilities resulting from the shear induced by the stellar motion feature prominently in the bow shock models, as well as various thin shell instabilities (Brighenti & D'Ercole 1995; Blondin & Koerwer 1998). One of the most spectacular examples of a runaway WR star is WR 124, the star is moving at 180 $\mathrm{km\,s^{-1}}$ away from us (van der Sluys & Lamers 2003). Thus, the nebula around the star, M1-67, is a bow shock seen almost face-on (i.e. inclination close to 90°, cf. Fig. 2).

Several numerical studies of both wind-wind and wind-ISM interactions have used stellar evolution models as input for the time-evolution of the wind, from O star to WR phases (e.g., Dwarkadas 2007; Toalá & Arthur 2011, and review by Arthur et al., these proceedings). The result is the formation of multiple ring nebulae created with each successive slow-fast wind transition, a time-dependent trace of the mass lost over a star's life that could be used to constrain stellar evolution models. Simulated

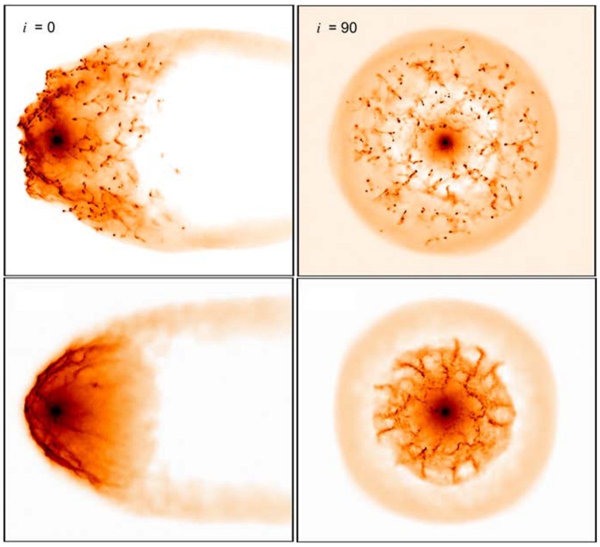

Fig. 2: 3D models of a RSG wind-ISM interaction: Hydrogen column densities (on a logarithmic scale) after 76 000 years seen at different inclination angles, i. The mass-loss rate ($3.1\times10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$) and RSG wind velocity ($17\,\mathrm{km\,s}^{-1}$) were kept constant, however, the ISM densities and stellar velocities, are $1.5\,\mathrm{cm}^{-3}$ and $32\,\mathrm{km\,s}^{-1}$[top], and $0.3\,\mathrm{cm}^{-3}$ and $73\,\mathrm{km\,s}^{-1}$ [bottom], respectively (see Mohamed et al. 2012a, for details).

elemental abundances or ionization levels compared to the observed nebulae can also be used to constrain the properties of the central source.

These circumstellar structures also have implications for supernovae explosions and Gamma-ray bursts (GRBs); the interaction with the rings and bow shocks creates radio, X-ray and optical brightening signatures in the light curves and narrow lines in the spectra (e.g., Brighenti & D'Ercole 1994; Eldridge et al. 2006, 2011; van Marle et al. 2006; Dwarkadas 2007; Mackey et al. 2014; Meyer et al. 2015). Comparing models to observations of SNe remnants and GRB afterglows can help constrain the nature of the progenitors of the explosions (e.g., van Veelen et al. 2009, found that the progenitor of Cas A is unlikely to have gone through a WR phase).

3 The formation of spirals and equatorial outflows

The above discussion focused primarily on single stars, however, the majority of massive stars are in binaries (Sana et al. 2012). Systems in which both components have dense, supersonic winds are known as colliding wind binaries (WR examples typically have an O star companion); the collision of their outflows results in a double shock structure separated by a contact discontinuity. The momentum flux ratio, $\eta = \dot{M}_1 v_1 / \dot{M}_2 v_2$, gives a good indication of the global morphology of the shocks; for $\eta = 1$ the location of the contact discontinuity is equi-distant between the two stars, whereas for $\eta \neq 1$, the contact discontinuity forms a cone-like structure that wraps around one of the stars and through orbital motion forms a larger-scale spiral structure around the system (e.g., Stevens et al. 1992).

As was the case for the rings and bow shocks, the detailed morphology of this wind-wind interaction region depends strongly on the excitation and growth of instabilities. In adiabatic simulations, Kelvin-Helmholtz instabilities result from the shear triggered by the orbital motion even when the stellar winds are identical (Lemaster et al. 2007; Lamberts et al. 2012). For very different stellar wind velocities, the instability becomes so violent that the spiral structure is completely destroyed (Lamberts et al. 2012). Adiabatic models are appropriate for wide binaries where the shock interaction is weak and the post-shock gas does not cool efficiently. However, if the dynamical timescale is short compared to the cooling timescale in one or both of the shock regions, then rapid cooling will give rise to thin shell instabilities (Stevens et al. 1992).

The compressed material in the inter-shock regions also radiates strongly from radio to X-rays; non-thermal emission is also detected in some cases indicating the presence of magnetic fields and particle acceleration (see Russell et al., Gosset et al., and Falceta-Goncalves et al., these proceedings for further details). A subset of these binaries also form dust, e.g., WR 104 and the other pinwheel nebulae in the Quintuplet cluster – infrared spiral structures found around carbon-rich WR (WC) stars (Tuthill 2006; Tuthill et al. 2008). While the radiation at X-ray wavelengths is not surprising since the shock temperatures are $\sim 1.2\,v_{\mathrm{wind}}^2$ keV (where v_{wind} is in units of $10^8\,\mathrm{cm\,s}^{-1}$, Stevens et al. 1992), infrared emission from dust grains in the harsh shock environment was unexpected.

The formation of dust grains requires sufficient densities and temperatures to form precursor molecules and small clusters which then coagulate to create larger grains. Strong cooling, instabilities and clumps in the intershock region may provide the required density and shielding from the harsh radiation field. Furthermore, mixing between H-rich material from a companion and the carbon-rich WR wind may be necessary for the chemical paths to form the precursors. As the mixing due to instabilities occurs on a macroscopic rather than microscopic scale, one possible solution is the destruction of clumps in the intershock region (Pittard 2007, Cherchneff et al., Williams et al., Hendrix et al., these proceedings).

Highly eccentric binaries show strong variations in their light curves and line profiles with orbital phase, e.g., WR 140. The system forms dust periodically at periastron passage (when the shock interaction, hence density increase is greatest), while the radio and X-ray emission also vary as the extinction along the line-of-sight changes (e.g., Williams et al. 2009). The strength of the shock interaction can also be affected by a close companion with a strong radiation field; e.g., radiative inhibition reduces the pre-shock wind velocity, hence the collision and the subsequent X-ray emission are weaker, e.g., in V444 Cyg (Stevens & Pollock 1994; Gayley et al. 1997).

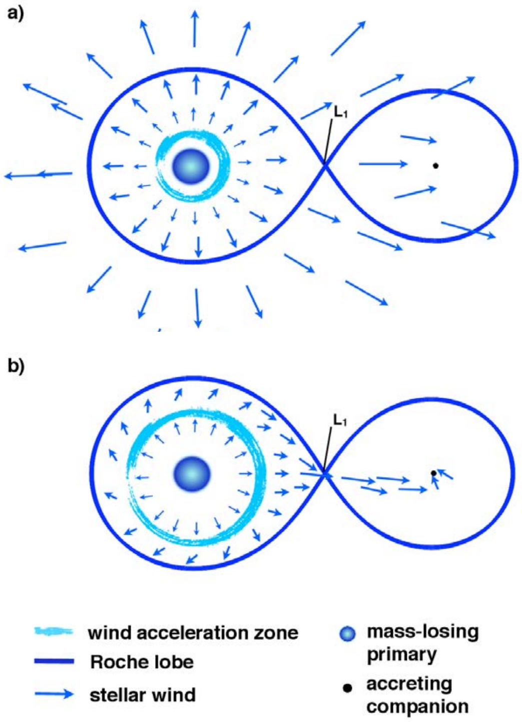

Fig. 3: Schematic diagram of mass transfer in detached binary systems where one of the stars is losing mass via a stellar wind. [a] Standard BHL wind accretion: if the wind acceleration radius is small compared to the RL radius (a wide binary), the wind will reach terminal velocity well before reaching the RL surface and escape, forming a largely spherically symmetric outflow. [b] WRLOF: if the radius of the wind acceleration zone is a significant fraction of the RL radius (e.g., binary separation is small), the dense stellar wind fills the RL and flows towards the companion through the inner Lagrangian point, L1, producing a highly aspherical outflow.

In massive binaries, mass and angular momentum transfer may occur via Roche-Lobe OverFlow (RLOF). If one of the stars fills its Roche lobe (RL) material is transferred to the companion through the inner Lagrangian point, L1. This is likely for short period systems in which the radiation and momentum of the companion's wind does not significantly affect the RL stream, however in wider systems, where the density of the accretion stream is comparable to that in the companion's stellar wind, transfer is inhibited (Dessart et al. 2003). Such binary interactions may play an important role in the formation of some WR stars (Petrovic et al. 2005).

Wind accretion occurs in wide systems when the companion star does not have a strong stellar wind of its own, instead it moves through the WR wind and accretes a small fraction, typically ~few percent. This mechanism powers systems such as high-mass X-ray binaries where the companion is usually a neutron star or a black hole. Although WR stars have fast, $\gtrsim 1000\,\mathrm{km\,s^{-1}}$, winds, results from self-consistent hydrodynamic models of WC stars showed that to drive the wind, two radiative acceleration zones, and a sufficiently high stellar temperature are necessary (Gräfener & Hamann 2005). This extended acceleration process means that an alternative mass transfer mode, Wind RLOF (WRLOF) (Mohamed 2010, PhD thesis; Mohamed & Podsiadlowski 2012b), may be possible for WR binaries, see Fig. 3. This mode occurs for wind interacting systems where the wind velocity at the RL surface is below the escape speed at that radius; in this case, the dense stellar wind, rather than the star itself, fills the RL and is channelled into the potential well of the companion through L1. Thus, for WR binaries where the acceleration zone is a significant fraction of the RL radius, WRLOF will result in high mass-transfer rates and aspherical outflow geometries.

A spiral structure (of non-accreted material) would also form in this case, however, it would be focused toward the orbital plane resulting in an equatorial outflow. This is one mechanism proposed for the focused outflow in systems such as Cyg X-3 (WR+compact companion) or the formation of the unusual N-rich outflow around WR 122, NaSt1 (Mauerhan et al. 2015). The NaSt1 disk-like outflow shows hints of spiral arms; this substructure and central infrared emission may indicate that the system is a binary (rotation and/or magnetic fields may also play a role). The high mass-transfer rates could lead to spin-up of the accretor which in turn would affect the accretion process and could halt it altogether. The interplay of these complex processes is significant for several related systems, such as SNe, GRBs and bipolar LBVs (e.g., the equatorial outflows may help collimate the ejecta during outbursts).

4 Summary

Models of stellar wind interactions with the ISM, material lost in previous phases of evolution or a nearby companion can broadly explain the formation of rings, bow shock arcs, spirals and equatorial outflows observed around massive stars. These circumstellar structures hold clues both to their mass-loss history and to their final fate.

There are still, however, a large number of complications and uncertainties with both the numerical approaches and physical processes. For example, the enhancement or suppression of instabilities can be influenced by the numerical methods used, e.g., the number of dimensions (2D vs 3D, e.g., Blondin & Koerwer 1998), resolution or type of solver (e.g., Lamberts et al. (2012) found that the Lax-Friedrichs Riemann solver suppresses instabilities in van Marle et al. (2011) while the shocks in their 2D calculations align with the grid, artificially enhancing them). Physical processes such as radiative cooling, thermal conduction, and the stellar radiation field will also affect the shape of the outflow (e.g., Raga et al. 1997; Toalá & Arthur 2011; Meyer et al. 2015). Another example, already highlighted above, is the highly uncertain process of dust formation.

Further complications result as the winds themselves will be shaped by other processes resulting in strong deviations from a smooth, homogeneous, spherical continuous outflow, e.g., the radiation and stellar magnetic fields, pulsations, and rotation produce latitude dependent winds such as disk-like outflows, co-rotating interaction regions, other wind inhomogeneities such as internal shocks, clumping, porosity, and time-dependent episodic ejections (Cranmer & Owocki 1996; Townsend 1997; Feldmeier & Owocki 1998; Ud-Doula et al. 2008, Küker et al., these proceedings). Environmental inhomogeneities will also play a role including density/velocity gradients in the surroundings as well as ISM radiation and magnetic fields. Finally, binary interactions remain uncertain, as a companion can have a marked effect on the stellar outflow depending on the mass, separation, phase of evolution and luminosity, e.g., interactions may lead to mergers, or spin-up which have important implications for understanding, e.g., GRBs and SN 1987A.

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Michael Corcoran: How would the bow shock structure be altered if the moving WR system is a binary?

Shazrene Mohamed: A lot would depend on the orbital parameters; if they were such that the circumbinary outflow is not spherically symmetric but rather more equatorial, it could change the global morphology of the bow shock considerably. Other effects of binarity include the additional mass, velocity structure and luminosity from the companion, the possible presence of dust or magnetic fields, which may change the size of the bow shock, and the cooling/heating rates of the material and therefore affect the growth of instabilities.

Andy Pollock: In low density collisonless plasmas, it is presumably difficult to maintain a contact discontinuity. Would this change the instability properties of the interface?

Shazrene Mohamed: I imagine that you may get similar types of instabilities but the physical processes leading to the favourable conditions for their excitation and growth may be quite different, e.g., ram pressure and thin shell instabilities.

Paul Crowther: NaSt1 is a very interesting system but the X-ray alone (cf. single WR 18) do not necessarily point to a (current) binary colliding wind origin.

Shazrene Mohamed: Yes, that is correct, the disk-like outflow could also be produced by other processes, e.g., rotation or magnetic fields. However, the core is dusty and the hints of "spiral arms" are suggestive of a binary interaction.