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# STELLAR WINDS FROM MASSIVE STARS

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RESUMEN

Los vientos estelares de estrellas masivas son importantes para la retroalimentación de energía y momento, así como el enriquecimiento químico del medio interestelar. Observaciones a multifrecuencias de junto con simulaciones numéricas en 2 y 3 dimensiones han contribuido a nuestro entendimiento de la interacción de los vientos estelares con sus entornos. En este artículo, examino los advances recientes en los vientos de estrellas de la secuencia principal, choques de proa y vientos de etapas evolucionadas de estrellas masivas.

ABSTRACT

Stellar winds from massive stars are important for feedback of energy and momentum, as well as chemical enrichment of the interstellar medium. Multiwavelength observations together with numerical simulations in 2 and 3 dimensions have contributed to our understanding of the interaction of stellar winds with their environment. In this review, I examine recent progress on stellar winds from main-sequence stars, bow shocks and winds from evolved stages of massive stars.

*Key Words:* circumstellar matter — H II regions — ISM: bubbles — stars: mass loss — stars: winds, outflows

## 1. INTRODUCTION

For stars with initial masses above $15M_\odot$, mass loss through stellar winds is important at every stage of their evolution. On the main sequence, hot O or early B stars drive fast winds through momentum transfer from UV photons to metal ion lines in the stellar atmosphere. These stars also produce ionizing photons and so the stellar winds expand inside of H II regions. We might expect to see a spherical bubble filled with hot, shocked stellar wind material around every young massive star.

The GLIMPSE *Spitzer* Infrared Survey of the Galactic plane identified more than 500 partial and closed rings, interpreted as 2D projections of 3D bubbles (Churchwell et al. 2006, 2009). The survey covers between one and two degrees of latitude either side of the midplane and spans 65 degrees of longitude either side of the Galactic centre. The bubbles are rimmed with PAH emission at 3.6 and 8$\mu$m and the interiors reveal the presence of warm silicate dust at 24$\mu$m. These bubbles are primarily formed by hot young stars in massive star formation regions. About 25% of the bubbles coincide with known radio H II regions produced by O and early B stars, however, the majority are produced by non-ionizing FUV photons from B stars (Churchwell et al. 2009), which do not have important stellar winds. In addition, the presence of warm dust in the interior is an argument against the bubbles being formed by fast stellar winds, since dust is not produced in a wind and cannot survive in such an environment.

So, if these aren't the bubbles we're looking for, what does the interaction between a fast stellar wind and the environment look like? This review takes as inspiration a conference talk given by You-Hua Chu (Chu et al. 2004), where she posed the questions

- Why don't we see interstellar bubbles around every main sequence O star?
- How hot is the bubble interior?
- What is going on at the hot/cold interfaces in a bubble?

which are still relevant 20 years later. To this list I would add "What are the mass-loss rates?" since these have been revised (downwards) by an order of magnitude in the same time period.

## 2. INTERACTION OF A STELLAR WIND WITH THE ENVIRONMENT

The expansion of a stellar wind bubble in a uniform environment has been studied extensively in the literature, from analytical steady state solutions (Pikel'Ner 1968) and similarity solutions (Avedisova 1972; Dyson & de Vries 1972; Weaver et al. 1977) to numerical simulations (e.g., Falle 1975; Rozyczka 1985; Arthur 2007). Radiation-hydrodynamic simulations are particularly useful since they show that,

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although the hot shocked stellar wind can drive the dynamics of an internal bubble at early times, at late times the dynamics is governed by the photoionized gas in the external H II region, which dominates the pressure and confines the stellar wind bubble (Arthur 2007). Wind-blown bubbles around O stars in H II regions have been detected kinematically but not morphologically because there is no dense swept-up shell and the expansion speeds are low (Nazé et al. 2001). The temperature in the shocked wind bubble, $T_{\rm sh}$, depends on the stellar wind velocity, $V_{\rm w}$, through the relation $T_{\rm sh} = 3\mu m_{\rm u} V_{\rm w}^2/16k$, where $\mu$, $m_{\rm u}$ and $k$ are the mean particle mass, the atomic mass unit and the Boltzmann constant, respectively. For typical wind velocities of 1000 km s$^{-1}$, the temperature in the hot gas should be $> 10^8$ K.

A different structure results if the massive star has supersonic motion relative to its environment. This can happen if the star itself is moving, for example, if it is a runaway star that has been ejected from a cluster, or if the star and its wind are embedded in a larger flow, such as a champagne flow or photoevaporated flow from an H II region. In these scenarios, a bow shock structure forms instead of a spherical bubble (van Buren & Mac Low 1992; Comeron & Kaper 1998). In the upstream direction, the stand-off distance, $d$, between the apex of the bow shock and the star is set by the balance between the ram pressure of material passing through the outer shock, $\rho_0 v_{\rm a}^2$, and the thermal pressure of the shocked stellar wind $\dot{M} V_{\rm w}/4\pi d^2$, where $v_{\rm a}$ is the relative velocity between the star and the environment and $\dot{M}$ is the mass-loss rate. These bow shock structures are most easily seen in the infrared because dust swept up from the environment absorbs UV photons from the massive star and reemits at longer wavelengths. Kobulnicky et al. (2016) catalogued over 700 arc-shaped mid-infrared nebulae in 24 $\mu$m *Spitzer* and 22 $\mu$m *WISE* surveys of the Galactic Plane as probable dusty interstellar bowshocks.

Observations of H II regions, such as the Eagle Nebula (M16) and the Orion Nebula (M42), reveal that their borders are not regular but instead consist of pillars and other concave and convex structures, clearly seen at optical and near-infrared wavelengths. These are the result of the interaction of the ionizing photons from the massive stars with a surrounding clumpy molecular cloud, and are readily reproduced in numerical simulations of H II regions (Mellema et al. 2006; Medina et al. 2014). The photoevaporation flows coming off the clumps and filaments can reach velocities up to two or three times the sound speed in the photoionized gas and interact in the interior of the H II region, producing a much higher internal velocity dispersion than in the standard expanding Strömgren sphere (Medina et al. 2014). Moreover, many H II regions are found at the edges of molecular clouds where there are strong density gradients. This produces champagne flows (Tenorio-Tagle 1979), in which the ionization front can break out in the direction of decreasing density and leads to a high-pressure outflow with velocities up to several times the sound speed in the ionized gas (Henney 2007). These are the complex environments in which stellar wind bubbles develop.

At first glance, the Bubble Nebula seems to fulfill the role of classical stellar wind bubble inside the photoionized region NGC 7635 which is illuminated by the single central O6.5III star BD+60°25 22. At optical wavelengths, it consists of an approximately circular parsec-scale wind-blown bubble. The stellar wind velocity of 2000 km s$^{-1}$ suggests that shocked wind temperatures should be $> 10^8$ K. However, no extended X-ray emission was detected by Toalá et al. (2020) with their XMM Newton EPIC observations, while optical spectroscopic observations reveal that the apparently simple bubble is really a series of nested shells and blisters. Additionally, the massive star has a peculiar velocity of $\sim$ 30 km s$^{-1}$, which led Green et al. (2019) to performed 2D hydrodynamical simulations of the Bubble Nebula as a bow shock due to the supersonic motion of the star relative to its environment. The best-matching simulation to the H$\alpha$ and infrared emission required an inclination angle of 60 degrees to the line of sight and the apparent sphericity of the bubble is a simply projection effect. This simulation predicts soft X-ray emission from the edges and wake of the bow shock due to mixing of dense cool gas into the hot shocked wind material, but this is not observed.

The Orion Nebula is a nearby blister H II region illuminated by the O6.5V star $\theta^1$ Orionis C. The ionizing photons from the hot star photoevaporate material from the surface of nearby protoplanetary discs around young low-mass stars, or proplyds (Henney et al. 1996). The photoevaporation flows are mildly supersonic and flow away from the proplyds until they reach pressure balance with the surrounding medium; for the proplyds closest to the central star this is the free-flowing stellar wind, while for more distant proplyds this could be the photoionized champagne flow (O'Dell et al. 2009). Bow shocks around proplyds are clearly visible in *Hubble Space Telescope* images of the inner Orion Nebula and these are evidence for the stellar wind from $\theta^1$ Orionis C, even though no closed stellar wind bubble forms due to the strong density gradient at the edge of the molecular cloud.

Of the 709 mid-infrared, bow-shaped nebulae catalogued by Kobulnicky et al. (2016), 286 objects have measured proper motions consistent with a runaway star scenario, 103 objects face giant H II regions and 58 objects face bright-rimmed clouds. An outstanding example of this latter class of object is the O7.5III star Menkib, which faces the California Nebula. Not only is the stellar wind from the hot star interacting with the photoevaporated flow from the face of the bright-rimmed cloud, but the star also has a peculiar motion of 64 $\mathrm{km\,s^{-1}}$ towards the nebula. At infrared wavelengths, the PAH near-infrared emission from the face of the nebula can be clearly distinguished from the bow-shaped arc of warm dust mid-infrared emission around the star. However, not all bow-shaped infrared arcs are bow shocks; a hydrodynamical wind-supported bow shock is the result only when radiation effects are unimportant. As the optical depth of the shocked shell increases, radiation pressure contributes a greater fraction of the total pressure to help support the shell structure (Henney & Arthur 2019). The limiting case, when the shell is completely opaque to the stellar radiation, is a radiation-supported bow shock, where it is the radiation pressure that completely balances the ram pressure of the external medium. For intermediate opacities and weak gas-grain coupling, the dust can decouple from the gas, leading to a dust wave outside of a wind-supported bow shock. Thus, the shell optical depth and the degree of coupling between the grains and the gas will determine what sort of bow shock is being observed. Bow shocks have the potential to allow stellar wind parameters, such as velocity and mass-loss rate, to be estimated in wind regimes where traditional diagnostic methods are difficult to apply, such as in the weak-wind regime and for stars with $T_{\mathrm{eff}} < 25000$ K (Kobulnicky et al. 2016; Mackey et al. 2016).

## 3. STELLAR WINDS FROM MAIN-SEQUENCE MASSIVE STARS

The stellar winds of hot main-sequence stars are driven by the transfer of momentum from photons in the photosphere of very luminous stars to the gas in the stellar atmosphere through absorption by spectral lines (Kudritzki & Puls 2000). The hugely successful *International Ultraviolet Explorer* (IUE) telescope enabled hot star wind velocities to be determined with a high degree of accuracy ($\sim 10\%$) from P Cygni profiles of UV resonance lines of metal ions such as C IV, Si IV and N V. Wind velocities of 2000 to 3000 $\mathrm{km\,s^{-1}}$, or 2 to 3 times the escape speed, are found for main sequence O stars (Prinja et al. 1990). However, the same saturated line profiles cannot be used to determine the mass-loss rates.

The standard, empirical methods for obtaining mass-loss rates from OB stars use the H$\alpha$ recombination line and the radio or sub-mm continuum emission excess (Kudritzki & Puls 2000; Vink 2022). Both of these methods are density-squared dependent and so are sensitive to density inhomogeneities, shocks and clumping in the wind. Additionally, low-abundance unsaturated UV resonance lines like P V, which are linearly dependent on density, can be used to determine the mass-loss rate. Bow shocks can also be used to determine mass-loss rate if the stand-off distance, ambient medium density, relative velocity and wind velocity are known (Kobulnicky et al. 2019). Discrepancies between derived mass-loss rates from different methods of factors up to 2 or 3 are attributed to porosity, i.e. opacity effects from clumping, and vorosity, i.e. the effect of a velocity field on line processes (Owocki 2015).

A factor of only 2 or 3 difference in the main sequence mass-loss rate for a massive star can have huge repercussions for its evolution and final fate, even determining the type of supernova and compact remnant. The mass loss affects the main-sequence lifetime and impacts the core structure. In rotating stars it will affect the rate of angular momentum loss. Renzo et al. (2017) used the MESA stellar evolution code to explore outcomes for various initial mass stars using different mass-loss prescriptions and efficiency factors, and find that the initial mass to final mass ratio can vary by up to 50%, with the greatest uncertainty for stars more massive than $30\,M_{\odot}$. For a $60\,M_{\odot}$ star, this can be the difference between retaining most of its envelope right up to its death as a $25\,M_{\odot}$ black hole, or losing most of its mass through winds and ending its life as a $\sim 2\,M_{\odot}$ neutron star.

## 4. STELLAR WINDS FROM EVOLVED MASSIVE STARS

Massive stars do not spend much time on the main sequence. After less than 10 million years, core hydrogen burning stops, the stars expand and move to the right in the HRD. Stars with initial masses $< 30M_{\odot}$ become a cool, red supergiants (RSG) and will conserve part of the hydrogen envelope until ending their lives as Type II core-collapse supernovae. Derived mass-loss rates from RSG are much higher ($\sim 10^{-5}\,M_{\odot}\,\mathrm{yr^{-1}}$) than for main-sequence stars and determine the final evolution of a star. Mass loss from RSG is still not well understood: it probably requires the combined effects of radiation pressure on dust grains formed in the cool RSG atmosphere (Gehrz & Woolf 1971) together with pulsations to move sufficient mass to dust-forming regions (Yoon & Cantiello 2010), and empirically determined mass-loss rates differ by more than an order of magnitude (Decin 2021). Moreover, mass loss in RSG is highly anisotropic and episodic, as revealed by the recent "great dimming" of Betegeuse (Dupree et al. 2022).

For stars with initial masses above $30 M_{\odot}$, the single massive star scenario (Conti 1975) requires the complete loss of the hydrogen envelope before the Wolf-Rayet stage. Beasor & Smith (2022) have suggested that this route implies enhanced mass-loss rates ($> 10^{-4}\,M_{\odot}\,\mathrm{yr}^{-1}$) in the RSG stage, which are not observed. Instead, binary interaction has been proposed as a way of removing the stellar envelope, through mass transfer to a companion or through expulsion of a common envelope (Shenar 2022).

Wolf-Rayet stars are hot and produce ionizing photons and fast, radiation-driven winds, with mass-loss rates $\dot{M} > 10^{-5} M_{\odot}\,\mathrm{yr}^{-1}$, at least an order of magnitude higher than those of O stars. This is because multiple scattering of the UV photons in the stellar atmosphere enhances the wind driving efficiency. The fast wind interacts with the circumstellar medium, which is composed of material expelled from the star in a previous stage of evolution or due to a binary interaction. Outside of cluster environments, this interaction can form Wolf-Rayet nebulae, which were first classified by Chu (1981). The most striking nebulae are found around runaway, nitrogen-rich WN stars. For example, the $\sim 17$ parsec diameter nebula S308 around the WN4 star WR 6 is a classical example of a wind-blown bubble (Chu 1981) and is one of only a handful of single massive star bubbles with detectable diffuse X-ray emission (Chu et al. 2003; Toalá et al. 2012). The other bubbles are NGC 2359 around WR 7 (Zhekov 2014), NGC 6888 around WR 136 (Toalá et al. 2016), and NGC 3199 around WR 18 (Toalá et al. 2017). However, despite the high stellar wind velocity ($V_{\mathrm{w}} = 1700\,\mathrm{km\,s^{-1}}$), the main X-ray component has a derived temperature of only $1.1 \times 10^{6}$ K, with a secondary component at $13 \times 10^{6}$ K (Toalá et al. 2012). In fact, all of the WR bubbles detected in diffuse X-rays have derived temperatures in the range $1$–$2 \times 10^{6}$ K (similar to those found for planetary nebulae).

The difference between wind-blown bubbles around Wolf-Rayet stars and those around main sequence O stars is the medium into which they are expanding and the timescales for the interaction. In Wolf-Rayet bubbles, the fast wind sweeps up the circumstellar medium, which is composed of material previously lost from the stellar envelope. The resulting thin shell is subject to hydrodynamic and radiation-hydrodynamic instabilities and the contact discontinuity between the hot, shocked stellar wind and the cooling swept-up material becomes distorted and very complex (Garcia-Segura et al. 1996; Toalá & Arthur 2011). Mixing at the interface can lead to gas with temperatures intermediate between the $\sim 10^{8}$ K shocked wind and the $\sim 10^{4}$ K photoionized shell. Thermal conduction can also play a role, evaporating shell material into the hot bubble, where it will have intermediate temperatures. Evidence for conduction fronts in stellar wind bubbles has proved inconclusive, since it requires spectroscopic observations at ultraviolet wavelengths (Chu et al. 2016). Toalá & Arthur (2018) suggest that turbulent mixing layers, together with the filtering effect of the sharply peaked emission coefficient, $\epsilon(T)$, are responsible for the narrow range of derived temperatures, even though the actual temperature distribution in the shocked stellar wind is much broader.

For Wolf-Rayet nebulae classified as "ejecta-type" (Chu 1981), such as M1-67 and WR 40, the interaction between the fast stellar wind and the circumstellar medium is less clear. If the clumps seen in the nebulae are pre-existing, i.e. come from a clumpy RSG wind or expelled common envelope, numerical simulations of the interaction of a shock with a clumpy medium show that a complex turbulent post-shock flow strips material from the clumps and destroys them, resulting in a thick, dense shell of mixed wind and circumstellar material (Alūzas et al. 2012). Alternatively, the clumps could be formed when a swept-up thin shell becomes dynamically unstable. Studies of Wolf-Rayet nebulae can tell us about the previous mass-loss stages of massive stars and discriminate between possible scenarios.

## 5. CONCLUSIONS

The interaction of stellar winds from massive stars with their environment is important for energy and momentum feedback as well as chemical enrichment of the interstellar medium. Multiwavelength observations, and their interpretation using 2D and 3D numerical simulations, provide insight into physical processes at interfaces and the interaction of stellar winds from stars that are moving with respect to the ambient medium. Bow shocks and dust waves are detected as mid-infrared arcs and are found both inside and outside of the H II regions where massive stars are normally found. Bow shocks can be used to find model-independent estimates of the stellar wind mass-loss rates. The mass-loss rates continue to be the most uncertain parameter, which has repercussions for the final evolutionary state of massive stars. New X-ray telescopes will help to determine the temperature distributions in the hot shocked gas in wind-blown bubbles but the lack of UV facilities means that it remains difficult to explore the intermediate temperature range predicted for interface regions by numerical simulations.

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