Winds From Massive Stars, And Implications for Supernovae and Gamma-Ray Bursts

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Abstract. We review the effects of winds from massive O and B stars on the surrounding medium over the various stages of stellar evolution. Furthermore we discuss some of the implications for SNe and GRB evolution within this wind-blown medium.

INTRODUCTION

Massive stars are stars $> 8M_\odot$ that don’t end their lives as white dwarfs. These stars lose mass during their evolution, with more massive stars losing a considerable amount of material [23] before they explode as supernovae. This material collects around the star, forming extended envelopes in some cases, and wind-blown 'bubbles' surrounded by a dense shell in other cases. Herein we review the development of the circumstellar material around massive stars during the various phases of evolution. We then explore the impact of this material on the subsequent evolution of the SN shockwave, and possibly GRB blast wave, upon the death of the star.

WINDS FROM MASSIVE STARS

The evolution of massive stars depends on several factors, the main ones being the initial mass of the star, its rotation velocity, the presence or absence of a binary companion(s), and the metallicity. A single, non-rotating massive star at solar metallicity starts its life as an early type main-sequence O/ B star. These stars lose mass via fast (few thousand km/s) and dense ($10^{-8} - 10^{-6} M_\odot \text{ yr}^{-1}$) radiatively driven winds [11]. The interaction of these winds with the surrounding medium gives rise to “wind-blown bubbles” (WBBs) surrounding the star, bordered by a dense shell. For a wind with fixed parameters (velocity, mass-loss rate), the density structure with radius shows 4 different regions (1) a freely expanding wind with density decreasing as $r^{-2}$, (2) a region of shocked wind (3) a region of shocked ambient material and (4) the unshocked ambient medium. Regions (1) and (2) are separated by an inwardly moving (in a Lagrangian sense) wind-termination shock, (2) and (3) by a contact discontinuity and (3) and (4) by an outwardly expanding shock wave. The presence of evolving winds with changing parameters, the growth of hydrodynamic instabilities and the onset of turbulence will all cause substantial changes in the structure and morphology of the bubble.

The radius of the outer shock of the bubble (the outer edge of the dense shell) is [22]:

$$
\text{Radius} = \frac{4}{3} \pi \rho_0 \Delta \frac{1}{r} \frac{1}{v_w}
$$
\[ R_{sh} = 0.76 \left( \frac{L}{\rho} \right)^{1/5} t^{3/5} \]  

(1)

where \( L = 0.5 \dot{M} v_w^2 \) is the mechanical luminosity of the wind, \( \dot{M} \) is the wind mass-loss rate and \( v_w \) is the wind velocity. In the case of a main-sequence (MS) star with \( \dot{M} = 10^{-7} M_\odot \text{ yr}^{-1} \), and velocity 2500 km s\(^{-1}\), \( L \) is about \( 1.984 \times 10^{35} \text{ ergs s}^{-1} \). If this lasts for about 10 million years, the total energy released will be about

\[ E_{\text{ms}} = 6.25 \times 10^{49} \dot{M}_{-7} v_{2500}^2 t_{10} \text{ ergs} \]  

(2)

where \( \dot{M}_{-7} \) is the mass-loss rate in terms of \( 10^{-7} M_\odot \text{ yr}^{-1} \), \( v_{2500} \) is the wind velocity in units of 2500 km s\(^{-1}\) and time is in units of 1 million years years \( (t_{10} = 10 \times 10^6 \text{ years}) \).

We assume that the main sequence star is formed in a medium with an average density of about \( 2.34 \times 10^{-23} \text{ g cm}^{-3} \) (a number density \( \sim 10 \) particles cm\(^{-3}\), appropriate for an ionized region). From equation \( \text{I} \) the radius of the swept-up shell will be

\[ R_{\text{ms}} = 48.8 \dot{M}_{-7}^{1/5} v_{2500}^{2/5} \rho_{10}^{1/5} t_{10}^{3/5} \text{ pc} \]  

(3)

In some cases the bubble may reach pressure equilibrium with the surrounding medium and stall before attaining this radius. Given the large radius and swept-up mass of the MS shell, the subsequent evolution is more or less confined to the MS cavity. The swept-up mass lies in a thin shell surrounding the cavity, which consists of an inner wind region followed by a region of almost constant density. The total wind mass ejected over time \( t \) is \( \dot{M} t \). The mass in the freely expanding wind is \( \dot{M} R_t / v_w \) (\( R_t \) = radius of wind termination shock). Since \( v_w t >> R_t \) by the end of the MS phase, a lower limit to the average cavity density is obtained by assuming that the wind material is uniformly distributed:

\[ \rho_{\text{bub}} = \frac{3 \dot{M} t}{4 \pi R_{sh}^3} = \frac{3}{4 \pi} 0.76^3 \left( \frac{2 \dot{M}^{2/3} \rho_a}{v_w^2} \right)^{3/5} t^{-4/5} \]  

(4)

which for the main sequence stage can be written as

\[ \rho_{\text{bubMS}} = 1.5 \times 10^{-28} \dot{M}_{-7}^{2/5} \rho_{10}^{3/5} v_{3000}^{-6/5} t_{10}^{-4/5} \text{ g cm}^{-3} \]  

(5)

Although this is a lower limit, especially if the bubble stalls early in the MS phase, it can be seen that the density in the interior of the bubble is on the order of \( 10^{-4} - 10^{-3} \) particles cm\(^{-3}\), orders of magnitude lower than that of the surrounding medium.

The main-sequence stage is followed by an intermediate stage. For stars with \( M \leq 50 M_\odot \) this is generally a red supergiant (RSG). These stars have large envelopes and slow winds (10-20 km s\(^{-1}\)) with a high mass loss rate of \( 10^{-5} \) to \( 10^{-4} M_\odot \text{ yr}^{-1} \). This creates a high density region around the star, confined by the pressure of the main-sequence bubble. For a RSG lifetime of about 200,000 years the total energy input is

\[ E_{\text{RSG}} = 8 \times 10^{46} \dot{M}_{-4} v_{20}^2 t_{0.2} \text{ ergs} \]  

(6)

where \( \dot{M}_{-4} \) is the mass loss rate in terms of \( 10^{-4} M_\odot \text{ yr}^{-1} \), \( v_{20} \) is the velocity in units of 20 km s\(^{-1}\), and \( t_{0.2} \) is the time in units of 200,000 years. The RSG wind, with its low velocity, should be able to expand a distance \( R_{\text{RSG}} \), with wind density \( \rho_{\text{RSG}} \).
\[ R_{RSG} = \kappa 4.2 \, v_{20} \, t_{0.2} \, \text{pc}; \quad \rho_{RSG} = 2.81 \times 10^{-23} \, \dot{M}_{-4} \, v_{-20}^{-1} \, r_{-2}^{-2} \]  
(7)

where we have added a factor \( \kappa \geq 1 \) to account for the fact that neither the transition, nor the change in velocity, from the MS to the RSG phase is instantaneous. Given the size of the MS bubble, it is clear that the RSG wind region will be confined to a small fraction of the main-sequence bubble. The total mass lost during the RSG phase is

\[ M_{RSG} = 20 \, \dot{M}_{-4} \, t_{0.2} \, M_\odot \]  
(8)

Thus although total energy of the outflow is small compared to the MS stage and the subsequent Wolf-Rayet stage, a large amount of stellar mass is lost in the RSG stage.

Stars less than about 35\( M_\odot \) will end their lives as red supergiants and explode to form Type II supernovae (SNe). Stars larger than this but less than about 50 \( M_\odot \) will lose their outer envelopes and form Wolf-Rayet (W-R) stars after the RSG phase. According to some models \[12\] stars > 40 \( M_\odot \) may become unstable for a short-period of time and pass through a Luminous Blue Variable (LBV) phase, in which they may lose much larger amounts of mass in a very short time. The extreme example is \( \eta \) Carinae, which is supposed to have lost 2-10 \( M_\odot \) of material in about 20 years. These may form LBV windblown nebulae within the main-sequence nebula. Many are known to be bipolar.

Solar metallicity stars above about 35 \( M_\odot \) end their lives as W-R stars. The mass-loss decreases somewhat to about \( 10^{-5} \) \( M_\odot \) yr\(^{-1} \), while the wind velocity increases to 2000 km s\(^{-1} \). For a lifetime of 100,000 years, the total energy input in the W-R phase is then

\[ E_{WR} = 4 \times 10^{49} \, \dot{M}_{-5} \, v_{2000}^2 \, t_{0.1} \, \text{ergs} \]  
(9)

Although the total mass is less, W-R winds may posses enough momentum to push out, and possibly break up, any dense shell surrounding the star from the previous intermediate wind stage, distributing its contents throughout the surrounding medium. Generally they will have enough momentum to collide with the MS shell, sending a reflected shock back. A W-R wind termination shock will be formed where the thermal pressure of the shocked wind bubble equals the ram pressure of the freely flowing wind.

The post-MS stages may add considerable mass to the bubble without increasing the volume much. However equations (4) and (5) imply that, even increasing the mass (\( \dot{M} t \)) by a factor of 30-40 results in number densities of order \( 10^{-3} - 10^{-2} \) cm\(^{-3} \). Therefore the density over the bubble interior is in general low for W-R bubbles.

Multidimensional calculation \[5, 6, 9, 10\] reveal the presence of hydrodynamic instabilities in many stages. In one calculation of a 35 \( M_\odot \) star, \[6\] found that both the RSG and subsequent W-R wind (expanding into the RSG wind) were Rayleigh-Taylor unstable (Fig 1a). These instabilities tend to break-up the RSG shell and distribute its material over the entire wind-blown bubble. They may lead to the formation of blobs, clumps and filaments in the WBB. Eventually, due to density fluctuations in various stages, the bubble interior becomes quite turbulent by the end of the simulation.

Other factors will considerably modify this simple picture. Rotation of the star can lead to enhanced mass-loss \[14\]. Also a star rotating close to its break-up velocity may emit a wind preferentially in the polar direction \[8\]. Mass-loss rates are also metallicity dependent, although rotation can lead to high rates even at low metallicity. And a binary companion can significantly alter the evolution.
FIGURE 1. (a) The evolution of the W-R wind into the RSG wind region in a 35 $M_{\odot}$ star. Both winds are R-T unstable. (b) The SN shock wave expanding within the turbulent interior of a wind-blown bubble can becomes wrinkled and loses its spherical shape. For further details see [6].

**IMPLICATIONS FOR SUPERNOVAE**

The star will end its life in a SN explosion, giving rise to a shock wave that expands outwards within this medium. Salient features of the expansion of the shock wave within the ambient medium have been revealed by numerical simulations [20, 7, 6]:

- Massive stars will generally be surrounded by low-density bubbles, whose size is set by the main sequence stage. If there is a RSG or LBV phase then the density may be much higher closer in to the star. However a subsequent W-R phase may destroy this high density medium and redistribute the material within the bubble.
- In either case, the medium near the star is a freely flowing wind, whose density varies as $r^{-2}$ if the wind parameters are constant. If the parameters are not constant then the density variation may be different. In SN 1993J there are several claims [19, 15, 17, 1] that the density of the medium immediately surrounding the star drops less steeply than $r^{-2}$, with some indications that the density exponent could be as low as $r^{-1.4}$.
- The energy deposited by the winds ($\sim 10^{49} - 10^{50}$ ergs, depending on the initial mass of the star) into the surrounding medium is a small but non-negligible fraction of the total SN kinetic energy ($\sim 10^{51}$ ergs).
- Supernovae arising from RSG stars will first expand within the high-density wind before expanding in the low-density cavity. SNe arising from W-R stars will expand in the freely expanding W-R wind before encountering the low-density bubble.
- Since the emission from the remnant after the first few months is mainly due to circumstellar interaction [4], and depends on the density, the low density implies that the emission will be considerably reduced in optical, X-rays and radio. Thus SNe in bubbles show much lower luminosities than their counterparts in the ISM.
- Since the mass is mainly contained in the dense shell bordering the bubble, the further evolution of the shock wave depends on the dense shell. Numerical calculation confirm
that the expansion depends basically on one parameter $\Lambda = \text{mass of shell/mass of ejecta}$. If $\Lambda \geq 1$ then the shell begins to have a significant effect. For low values of $\Lambda$ the shock wave forgets about the interaction over a period of a few doubling times. But as $\Lambda$ increases the kinetic energy of the ejecta is more rapidly converted to thermal energy within the shell, which may be radiated away. A transmitted shock enters the shell, while a reflected shock expands back into the ejecta towards the center.

- The interaction of the shock with the high-density shell leads to a compression of the shell, increasing its density and therefore the optical and X-ray emission.
- 2D simulations show that the SN shock expanding in the turbulent interior may not remain spherically symmetric but acquires a corrugated shape (Fig 1b), due to its interaction with density fluctuations within the interior. The impact of the shock with the dense shell occurs in a piecewise fashion, with different parts of the shock colliding with the shell at different times. The emission from different regions of the shell increases in luminosity at different times. Correspondingly the reflected shock does not reach the center as one contiguous piece but as several smaller shocks at different times.

### SOME THOUGHTS ABOUT GAMMA-RAY BURSTS

Gamma-Ray Bursts (GRBs) are now widely thought to originate from Wolf-Rayet stars. The blast wave will then evolve in the wind-blown bubble surrounding the W-R star, as described above. It should therefore be possible to explain absorption line spectra seen in GRBs in the context of this model. The absorption line spectra indicate multiple absorption systems spanning (roughly) three velocity ranges (although not all GRBs show all velocity features) - high-velocity (1000-3000 km/s), intermediate velocity (few hundred km/s), and low velocity (tens of km/s). The first could arise in the freely expanding wind, the last slow velocity feature in the slowly-moving dense shell. The dense shell could also account for the high column density of neutral hydrogen (up to $N_H > 10^{22}$) seen in some GRBs [2]. The intermediate features are somewhat more problematic, because the temperature in the shocked wind is too high for much absorption to take place. They have been explained by [21] as due to fragmented W-R and RSG shells. In their analysis [21] did not consider the various individual ionization species, the detailed temperature structure, or the presence of an optical flash. These were taken into account by [13] to explain the high-velocity absorption line spectra of GRB 021004. Using a time-dependent photo-ionization code, these authors determined that, since most of the material within a few parsecs of the star is fully ionized, the wind-termination shock in GRB021004 must lie at a distance $> 100$ pc to explain the high-velocity absorption\(^1\), assuming it is local to the GRB. This implies a very large WBB stretching many hundreds of parsecs, which (see eq.3) therefore must have arisen in a medium with a very low number density of around $10^{-3} - 10^{-2}$ cm$^{-3}$.

\(^1\) A similarly large distance for the absorption feature in other GRBs was found by [18]
Several observations of GRB afterglows suggest that the burst is occurring in a constant density medium \[16\]. In the above picture, the only relatively constant density medium exists beyond the wind termination shock. Therefore it implies that the wind-termination shock is very close-in to the star \[3\], at a distance of perhaps 1000’s of AU rather than parsec scales. One way to obtain such a structure is if the density of the ambient medium is extremely high, in effect compressing the bubble outlined above to a very small size\[2\]. Our simulations show that densities \(> 10^4 \text{ particles cm}^{-3}\) would be required to achieve this. Thus some afterglow observations imply very high ambient densities, whereas absorption line spectra sometimes indicate very low densities, spanning a total ambient number density range of 7 orders of magnitude \((10^{-3} - 10^4)\). If this scenario is correct, then GRB progenitor stars are born (or at least spend a good fraction of their lives) in regions of both very high and very low density. It could indicate that more than one progenitor family is present. If the density range seems excessively large, then it could suggest that the absorbing material is not local but in the foreground, and/or our interpretation of GRB afterglows in a constant density medium is suspect.

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REFERENCES


\[2\] A high pressure without a high density may work, but requires unrealistically high temperatures