

MASS LOSS OF MASSIVE STARS

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Abstract. In this contribution we review the properties of the winds of massive stars. We focus on OB stars, red supergiants, Luminous Blue Variables (LBVs) and Wolf-Rayet stars. For each type of star, we summarize the main wind properties and we give a brief description of the physical mechanism(s) responsible for mass loss.

Keywords: stars: massive; stars: winds, outflows; stars: mass loss

1 Introduction

Massive stars experience episodes of mass loss throughout their evolution. Either through continuous winds or bursts, large amounts of mass are ejected in the immediate surrounding. This deeply affects not only the star’s evolution, but also the structure of the interstellar medium, and thus the appearance of supernovae which occur in such environments.

Mass loss is one of the main drivers of massive stars evolution (Chiosi & Maeder 1986). During their lifetime, massive stars may lose up to 90% of their initial mass through stellar winds (Maeder & Meynet 1991). This strongly impacts on their internal structure and thus their evolution. Meynet et al. (2015) showed that changing the mass loss rate by a factor of ten only in the (short) red supergiant phase can affect the end point of stellar evolution: a star may become a supernova either as a red or as a blue supergiant depending on the mass loss history in the red supergiant phase.

The material ejected just before the explosion of a supernova also impacts on the appearance of the supernova itself. Depending on the density of the medium into which the supernova expands, its spectrum may be very different. For instance, type II_n supernovae are thought to have a spectrum dominated by nebular emission (Schlegel 1990; Chugai et al. 2004). In addition, different types of core-collapse supernovae are formed depending on the physical properties of the progenitor. As illustrated above, the progenitor’s appearance will strongly depend on the mass loss history of its parent star.

In this review, we describe the wind properties of massive stars in different evolutionary state (OB, red supergiant, LBV, Wolf-Rayet). We summarize the main properties and give a brief overview of the mechanism(s) driving the outflows.

2 OB stars

Massive stars are born as O or B stars. This phase is defined by effective temperatures higher than about 15000 K. It corresponds to the main sequence and slightly beyond when including “blue supergiants”, i.e. stars not on the main sequence any more but hot enough to have a spectral type O or B. Massive stars spend 85-90% of their lifetime on the main sequence. A 15 M_{\odot} star will stay 13 Myr on the main sequence for a lifetime of 15 Myr. For a 60 M_{\odot} star, the numbers are 3.5 Myr and 4 Myr respectively.

During this phase, massive stars eject material in the interstellar medium at a rate between 10^{-9} and $10^{-5} M_{\odot} \text{ yr}^{-1}$ depending on the initial mass and exact evolutionary state. The wind terminal velocities from 500 to 4000 km s^{-1} in the most extreme cases, with values usually between 1000 and 3000 km s^{-1} .

Winds of OB stars are explained by the radiatively driven wind theory. First developed by Lucy & Solomon (1970) and Castor et al. (1975) (see later developments by Pauldrach et al. 1986; Vink et al. 2001), it describes

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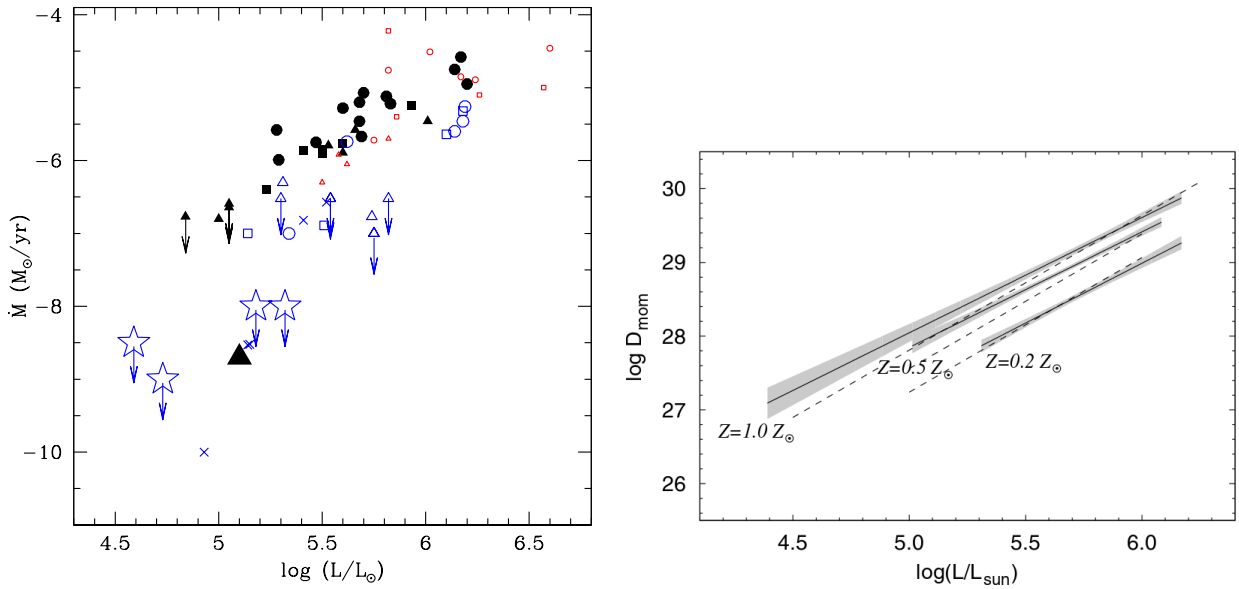


Fig. 1. Mass loss rates of OB stars and their relation to luminosity. **Left:** Mass loss rate as a function of luminosity for stars in the Galaxy (black symbols), the LMC (red) and the SMC (blue). Reproduced from Martins et al., 2004, A&A, 420, 1087. **Right:** Wind momentum - luminosity relation at different metallicities. The wind momentum is directly proportional to the mass loss rate. Reproduced from Mokiem et al., 2007, A&A, 473, 603

how a transfer of momentum from photons to matter occurs through radiation absorption by metallic lines in stellar atmospheres. Momentum is subsequently redistributed to the bulk atmospheric material through collisional coupling. This translates into the development of a steady-state stellar wind. Computations by Vink et al. (2001) show quantitatively that absorption through iron atoms is responsible for about 50% of the wind acceleration at solar metallicity, CNO ions being the next main contributors. At lower metallicity, CNO ions become the dominant wind drivers.

The radiation driven wind theory predicts that the resulting mass loss should scale with a power of the luminosity. Fig. 1 reveals that this is confirmed observationally: more luminous stars have on average higher mass loss rates. Since acceleration is due to metallic lines, stars in low-metallicity environments should have lower mass loss rates. This is confirmed empirically by the work of Mokiem et al. (2007) (see right panel of Fig. 1). A scaling relation $\dot{M} \propto Z^{0.83}$ is obtained when studying the winds of OB stars in the Galaxy and the Magellanic Clouds.

In the context of the radiation driven wind theory, terminal velocities are expected to scale with the escape velocity. Garcia et al. (2014) show that this is true, although the scatter is large. Leitherer et al. (1992) found a weak metallicity dependence of the wind terminal velocity: $v_{\infty} \propto Z^{0.13}$.

Even though radiatively driven winds are continuous, they are not homogeneous. This is due to the intrinsic instability of the driving mechanism. The radiative acceleration being proportional to the velocity gradient, any change in the later will lead to a runaway change in the former. Consequently, regions of higher-than-average velocities follow regions of lower-than-average velocities. Due to mass conservation, this translates into inhomogeneities in the density distribution. A clumping factor is defined as the ratio of the density of the densest regions to the average density. Most studies indicate a value of ~ 3 , although larger values can be found (Bouret et al. 2005).

3 Red supergiants

After the main sequence, at solar metallicity, stars with masses between ~ 8 and $\sim 25 M_{\odot}$ quickly (i.e. within 0.2-0.5 Myr) cross the HR diagram to become red supergiants (RSG). The RSG phase lasts 5 to 10% of the stellar lifetime (2.5 Myr for a $9 M_{\odot}$ star with a lifetime of 30 Myr; 0.3 Myr for a $25 M_{\odot}$ star with a lifetime of 7 Myr).

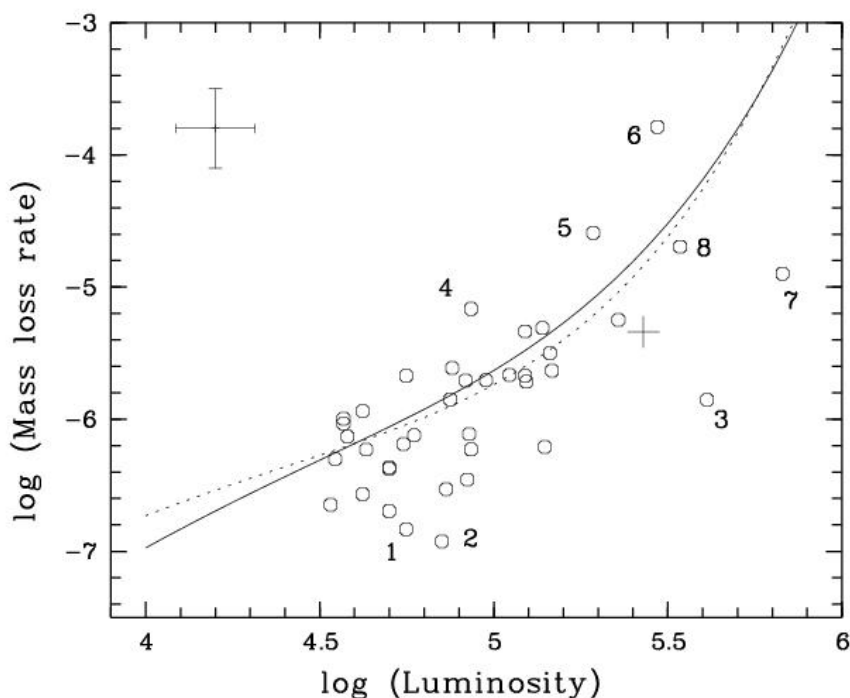


Fig. 2. Mass loss rate as a function of luminosity for red supergiants. The solid and dotted lines are the De Jager rates for different temperatures. Reproduced from Mauron & Josselin, 2011, *A&A*, 526, A56.

Although short, the RSG phase strongly impacts on the neighbouring environment. In that phase, mass loss rates range from 10^{-7} to $10^{-4} M_{\odot}$ and the wind velocities are typically of 10 to 40 km s^{-1} . Hence, the wind density is about a thousand times larger than in the OB phase. Fig. 2 shows mass loss rate as a function of luminosity for a sample of red supergiant studied by Mauron & Josselin (2011). Two key features are seen. First, there seems to be a trend of higher mass loss rates for higher luminosities. Second, at a given luminosity, the dispersion in mass loss rates is about a factor of ten. Mauron & Josselin (2011) also show that measurements for the same star but with different diagnostics lead to variation in mass loss rates of the same order (factor of ten). Consequently, the mass loss rates of red supergiants remain poorly constrained empirically.

The mechanism responsible for the ejection of matter in RSGs is not understood. By analogy with lower mass AGB stars, acceleration of photospheric material by stellar pulsations followed by radiation pressure on dust grains formed above the photosphere may trigger stellar winds. However, for red supergiants, there are no pulsations on the stellar surface. An alternative mechanism may be convection since recent high-resolution images indicate the presence of very large spots on the photosphere (Haubois et al. 2009). Such spots may be convection patterns. Magnetic loops at the surface (Aurière et al. 2010) may be an alternative possibility to trigger large scale motions. Another problem for red supergiant is the formation of dust. The seeds of such grains are not identified, and the conditions above the photosphere imply that dust formation can occur only a few stellar radii above the photosphere. The action of radiation pressure thus takes over at large distances from the surface, which may not be sufficient to trigger the stellar wind.

Whatever the mechanism at the origin of RSGs' stellar winds, a typical feature is inhomogeneity in the ejecta. Infrared observations of the closest objects reveal the presence of filaments and regions of overdensity (see e.g. Fig. 6 of Kervella et al. 2011).

4 Luminous Blue Variables

Stars more massive than about $25 M_{\odot}$ do not go through a RSG phase. For more massive stars, the redward evolution at high luminosity implies that the star reaches the Eddington limit above which it is not bound anymore. Observationally, this limit is seen as the 'Humphreys-Davidson' limit (Humphreys & Davidson 1979): no stars are observed rightward of this limit in the HR diagram. Stars reaching this part of the HR diagram are

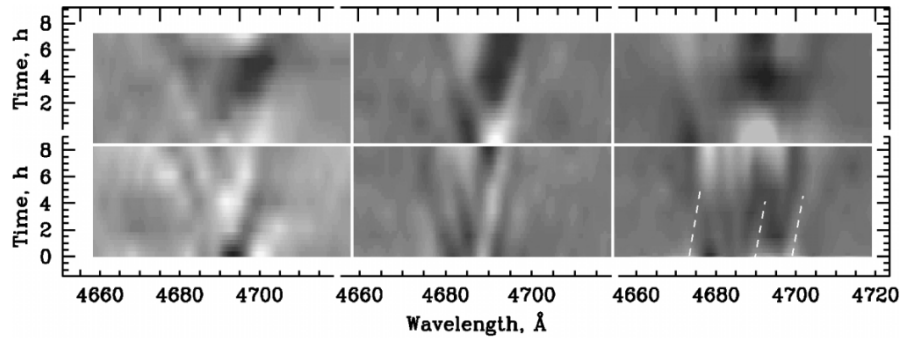


Fig. 3. Interpolated time series of the difference between individual and average line profiles around HeII 4686 for three WR stars in the SMC. Reproduced from Marchenko et al., 2007, ApJ, 656, L77.

usually classified as Luminous Blue Variables (LBV). As stems from their name, such objects show a variety of variable patterns, both photometrically and spectroscopically.

There are two main groups of LBVs. The first one is made of stars showing photometric modulation of the order 1 to 2 magnitudes at most. In the HR diagram, these stars are seen to evolve horizontally on short timescales. The rapid changes in effective temperature associated to a constant luminosity imply expansion/contraction of the stars (Clark et al. 2005). In that phase, where stars are also known as S-Dor variables, mass loss rates range from a few 10^{-6} to $10^{-4} M_{\odot}$. The wind velocities are between 100 and 500 km s^{-1} . Mass loss rates vary with changes in T_{eff} and radius (they are higher when the star is cooler/bigger) - see Stahl et al. (2001); Vink & de Koter (2002).

The second group is made of only two objects: η Car and P-Cygni. These are the true LBVs. They experience huge photometric variability and massive ejections. η Car became a LBV in the 1840's, when it brightened from a V magnitude of 2 to -1. It then faded down to a magnitude of 8 at the beginning of the XXth century, and kept becoming brighter from then, reaching $m_V = 4.5$ nowadays. At the same time, it experienced a short but intense eruptive phase during which it expelled about $10 M_{\odot}$ in 10 years, creating the so-called Homunculus nebula. LBVs are thus characterized by very strong mass loss rates of the order of a few tens of $M_{\odot} \text{ yr}^{-1}$. The ejections are not homogeneous, as the structure of the Homunculus reveals: filaments, spikes, debris, knots are observed (Morse et al. 2001).

The origin of stellar winds in LBVs is poorly understood. Radiative driving remains the best theoretical ground. In the S-Dor phase, changes in the effective temperature imply modification of the ionization structure, which in turn change the number of ions absorbing photons and thus accelerating the upper layers. This may explain the increase of mass loss rates at cooler temperatures since more atomic transitions from less ionized iron atoms are available (Vink & de Koter 2002). For the giant eruptions of LBVs, continuum driving (and not line-driving) may be the key factor (Owocki et al. 2004). This requires the presence of a clumped medium to be efficient.

5 Wolf-Rayet stars

Stars more massive than $25 M_{\odot}$ (at solar metallicity) end their lives as Wolf-Rayet stars (WR). The WR phase takes up to 5% of the star's lifetime. Typically, a $40 M_{\odot}$ star will spend 0.2 Myr as a WR for a total lifetime of 5 Myr. During that phase, Wolf-Rayet stars have strong stellar winds characterized by mass loss rates of 10^{-6} to $10^{-4} M_{\odot} \text{ yr}^{-1}$ and velocities of 800 to 2500 km s^{-1} . The wind density is thus ~ 10 times higher than in an OB star.

The current understanding of WR winds is based on the radiation driven wind theory (Castor et al. 1975). To reach mass loss rates about one order of magnitude higher than in OB stars, it is necessary to invoke multiple scattering of photons, contrary to OB stars where photons are usually absorbed and re-emitted only once (on average). A correlation between mass loss rate and luminosity seems to exist (e.g. Fig. 7 of Crowther 2007). In addition, mass loss rates scale with metallicity (Crowther et al. 2002). These facts are consistent with the expectation of radiative driving through metallic lines.

Another characteristics shared by WR and OB stars' winds is the presence of inhomogeneities. Due to the higher density of WR stars' winds, such clumps can be directly observed. Fig. 3 shows time series of spectra

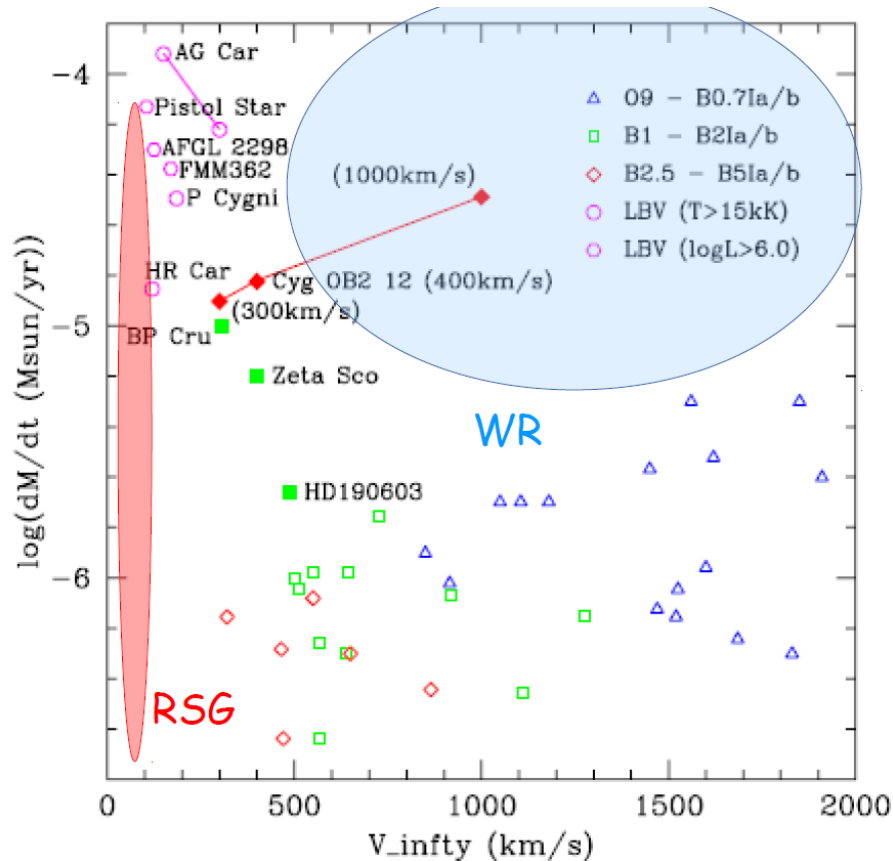


Fig. 4. Mass loss rate as a function of wind velocity for various types of stars. Circles (triangles/squares/diamonds) stand for LBVs (OB stars). The position of red supergiants (WR stars) is shown by the left (right) ellipse. Adapted from Clark et al., 2012, *A&A*, 541, A145.

centered on HeII 4686 for three WR stars. The presence of overdensities moving from the line center to the wings is clearly seen. This is interpreted as the presence of clumps originating close to the surface and following the wind motion up to high velocities, and thus up to the outer atmosphere.

6 Conclusions

In this short review we have summarized the main characteristics of the winds of massive stars in four different evolutionary phases: OB, red supergiant, LBV and WR. Fig. 4 gathers the mass loss rates and wind velocities of stars in these different phases. Wind densities can be extracted from this figure, considering that they are proportional to the mass loss rate divided by the wind velocity.

We also highlighted the timescales of the different phases. Most of the time is spent in the OB phase. The latest phases (RSG, LBV, WR) are much shorter, but immediately precede the supernova explosion, and thus affect the appearance of the SN. The nature of the progenitor depends on the entire history of mass loss over the star's lifetime.

FM thanks the organizers for the invitation to give this review and for a fruitful meeting.

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