Wind Models for Very Massive Stars in the Local Universe

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Abstract. Some studies have claimed the existence of a stellar upper-mass limit of 150$M_\odot$. A factor that is often overlooked concerns the issue that there might be a significant difference between the present-day and the initial mass of the most massive stars – as a result of mass loss. The upper-mass limit may be substantially higher, possibly exceeding 200$M_\odot$. The issue of the upper mass-limit will however remain uncertain as long as there is only limited quantitative knowledge of mass loss in close proximity to the Eddington ($=\Gamma$) limit. For this reason, we present mass-loss predictions from Monte Carlo radiative transfer models for very massive stars up to 300$M_\odot$. Using our new dynamical approach, we find an upturn or “kink” in the mass-loss versus $\Gamma$ dependence, at the point where our model winds become optically thick. These are the first mass-loss predictions where the transition from optically thin O-star winds to optically thick Wolf-Rayet winds has been resolved.

1. Introduction

Stellar winds from massive O and Wolf-Rayet (WR) stars are ubiquitous and form an important aspect of both stellar and galaxy evolution. Despite recent reductions in O-star mass-loss rates by factors of $\sim 3$ in comparison to unclumped empirical rates, population synthesis models by Voss et al. (2009) – utilizing rotating stellar models such as those of Meynet & Maeder (2003) that employ theoretical Vink et al. (2000) rates that match the factors $\sim 3$ reduced rates – show that the role of stellar winds in massive-star feedback has increased over the last decade. The reason for this possibly counter-intuitive finding is that stellar rotation has increased luminosities, whilst the objects also enter the WR-phase sooner. Strong stellar winds may prevent the most massive stars from entering the eruptive Luminous Blue Variable (LBV) phase, at least at Galactic metallicity. It is these very massive stars (VMS) with their strong stellar winds that are thought to dominate the radiative and kinetic energy input in young ($< 10$ Myr) clusters, as well as the radio-active 26-Al input that gives rise to gamma-ray lines from Galactic star-forming regions like Orion and Carina (Voss et al. 2010, 2012).

Our understanding of stellar mass loss from the most massive stars is also crucial for the determination of their final fates, with respect to the formation of intermediate
mass-black holes (Belkus et al. 2007; Yungelson et al. 2008), the occurrence of pair-instability supernovae (Langer et al. 2007), and the mass distribution of neutron stars and black holes (Heger et al. 2003; Eldridge & Vink 2006).

A most relevant issue concerns the stellar upper mass limit. Until recently, many studies accepted the existence of an upper limit of 120-150$M_{\odot}$, but a recent study by Crowther et al. (2010) claimed much higher luminosities and masses for the central WN5h objects of the R136 cluster than previous estimates (de Koter et al. 1997). One of the potential problems with the Crowther et al. luminosities is that the stars are clustered, and whilst Crowther et al. took great care in the assessment of a potential binary nature of the objects, there is a non-negligible chance that the stars are “polluted” with the light from line-of-sight objects.

In the context of the VLT Flames Tarantula Survey, we have recently discovered and analysed a new WN5h object, VFTS 682, a near-identical twin of R136a3 (Evans et al. 2011, Bestenlehner et al. 2011). This object is in apparent isolation from the R136 cluster, some 30 pc away, which raises interesting questions about its origin (see Bestenlehner et al. for a discussion on the object having formed in isolation or being a slow runaway). It also allowed us to assess the reliability of the Crowther et al. luminosity claims for the WN5h stars in the central cluster. Our finding of log $L/L_{\odot} = 6.5 \pm 0.2$ for the “isolated” object VFTS 682 seems to support the claim for high luminosities of WN5h stars in the Tarantula region. As VFTS 682 is in relative isolation from the dense cluster, we argue that the chance of a line-of-sight coincidence is much lower than for the WN5h stars in the core of R136, and we thus have independent evidence that the “traditional” 120 or 150$M_{\odot}$ stellar upper-mass limit has been broken. The upshot is that mass-loss rates for stars with masses above 150$M_{\odot}$ are needed to establish the evolution and fate of the most massive stars. Here, we present predictions from 60 up to 300$M_{\odot}$.

In the VMS regime, stars are identified as late-type nitrogen-rich WNh stars. These objects are extremely close to the Eddington limit $\Gamma = g_{\text{rad}}/g_{\text{grav}} = \kappa L/(4\pi c GM)$.

2. Mass loss predictions using the Monte Carlo method

Stellar winds from massive stars are driven by radiation pressure as extensively described by e.g. Puls et al. (2008). Our Monte Carlo methodology is basically the same as the one used to predict mass-loss rates for standard OB stars (Vink et al. 2000). It is based on the energy extraction method of Abbott & Lucy (1985), and improved by de Koter et al. (1997) and Vink et al. (1999). The method underlying the mass-loss recipe however, was semi-empirical, in the sense that a $\beta$-type velocity law was assumed, that reached a certain terminal wind velocity $v_\infty$, which was consistent with empirical values (determined from blue edges of ultraviolet P Cygni profiles). As empirical $v_\infty$ values are quite accurate (to within $\sim 20\%$), this was the preferred approach in order to obtain reliable theoretical mass-loss rates, that could serve as input in stellar evolution calculations. Nevertheless, now that we wish to predict mass-loss rates for VMS, we advance our approach, aiming to derive mass-loss rates without the use of empirical constraints.

Müller & Vink (2008) suggested a new line force parametrization that explicitly depends on radius (rather than the velocity gradient as often assumed). Furthermore, a new iteration method was proposed, and utilized with respect to a 40$M_{\odot}$ “standard” O star. The results were encouraging in that the predicted $v_\infty$ was only slightly ($\sim 10\%$) larger than observed. More recently, Muijres et al. (2012) computed an extensive grid of mass-loss rates and terminal wind velocities, and tested the methodology of Müller
& Vink (2008) by comparison to hydrodynamical computations. Encouragingly, both methods give similar results for the supergiant regime, validating the Müller & Vink (2008) approach for VMS.

Nugis & Lamers (2002) highlighted the relevance of the iron-peak opacities in the deepest photospheric layers for the initiation of Wolf-Rayet winds, which was confirmed by the Gräfener & Hamann (2008) models for hydrogen-rich late WNH stars. According to these wind models, the presence of opacity peaks may cause $\Gamma$ to exceed unity in deep layers, leading to the formation of optically-thick winds. In the Monte Carlo approach, we trace the radiative driving of the entire wind, and as most of the energy is transferred in the supersonic regime, we are less susceptible to the details of the photospheric region. Our strategy has the advantage that it allows us to explore the transition from transparent to dense stellar winds, that occurs in models that do include the full $\Gamma$ in subsonic regions for $\Gamma$ close to one. As our Monte Carlo models capture the full physics in the layers around and above the sonic point, we argue that they correctly predict the qualitative behaviour of the transition from transparent to opaque winds (Vink et al. 2011 for further details).

3. Resulting VMS mass-loss rates

In Fig. 1 we present our new dynamically consistent mass-loss predictions for high $\Gamma$ values. In order to assess the $\Gamma$ dependence separately from an additional mass or luminosity dependence, we divided the new mass-loss rates by $M^{0.7}$. For the lower $\Gamma$ range, the slope of $M \propto \Gamma^{2.2}$ is in good agreement with previous O star results. We highlight the kink at $\Gamma \sim 0.7$. Above the kink, the winds are optically thick, and the
\[ \dot{M} \propto \Gamma^{4.7} \], in agreement with the earlier reported \[ \dot{M} \propto \Gamma^{5} \] for the semi-empirical (i.e., not necessarily locally dynamically consistent) calculations (Vink 2006). This steep slope in the high \( \Gamma \) regime agrees well with the empirically determined slope in the Arches cluster stars, as well as that determined using the PoWR models (see Gräfener et al. 2011 for further discussion).

In order to find out if radiation-driven mass-loss rates continue to rise with increasing \( \Gamma \), we consider the mass-independent wind efficiency parameter \( \eta = \dot{M}v_{\infty}/(L/c) \). At values of \( \Gamma \sim 0.5 \) we find \( \eta \) numbers of \( \sim 1 \), in accordance with standard Vink et al. (2000) models. However, when \( \Gamma \) approaches unity, \( \eta \) rises in a curved manner to values as high as \( \eta \sim 3 \). Such large \( \eta \) values are more commensurate with WR winds than those of common O stars, and these results thus confirm a natural extension from common O-type mass loss to more extreme WN behaviour. Additionally, we note that the kink in the predicted mass-loss rate is accompanied by a transition of the velocity-law parameter \( \beta \), with \( \beta \sim 1 \) around the kink, in accordance with models of Müller & Vink (2008) and Muijres et al. (2012), to values larger than unity when \( \Gamma \) exceeds 0.7. Large \( \beta \) values had already been suggested to be more commensurate in WR stars previously, but it is reassuring to find that our modelling naturally predicts a transition in \( \beta \) at the same point as where the kink in the mass-loss relations occurs.

4. Spectral morphology: the characteristic He 4686 Ångstrom line

We have presented evidence for a transition in the mass-loss-\( \Gamma \) exponent, as well as in the wind acceleration parameter \( \beta \) from the moderate \( \Gamma \) “optically thin wind” cases to “optically thick wind” cases for objects that find themselves above \( \Gamma \gtrsim 0.7 \), forming
pseudo-photospheres. We might expect that the transition \( \Gamma = 0.7 \) is the point where the spectral morphology of standard O-type stars changes from the common O and Of-types into a WN-type spectrum. The spectral sequence involving the Of/WN stars has a long history (e.g. Walborn et al. 1992) but it had yet to be placed into a proper theoretical context. Figure 2 shows a sequence for the predicted He \( \text{ii} 4686\text{Å} \) lines for three gradually increasing values of \( \Gamma \). Although the first spectrum below the transition \( \Gamma \) already shows filled-in emission – characteristic for Of stars – the line-flux is rather modest compared to that found for the next two profiles with \( \Gamma \) values exceeding the critical \( \Gamma \) value. The stars show very strong He \( \text{ii} 4686\text{Å} \) emission lines, more characteristic for WR stars of the nitrogen sequence (WN).

5. Summary and conclusions

We presented mass-loss predictions from Monte Carlo radiative transfer models for VMS in the mass range 40-300\( M_\odot \) and with Eddington factors \( \Gamma \) in the range 0.4–1.0. Our models suggest that the spectral transition from O to WN corresponds to a transition from relatively low \( \Gamma \) to high \( \Gamma \) values (and larger velocity law parameter \( \beta \)) for WN stars. This assertion is not only based on the numerically larger mass-loss values, but more specifically on the finding of a “kink” at \( \Gamma = 0.7 \) where the mass-loss slope in function of \( \Gamma \) shows an upturn.

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