Mass loss summary – a personal perspective

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**Abstract.** For the occasion of the official retirement of Henny Lamers, a meeting was held to celebrate Henny’s contribution to mass loss from stars and stellar clusters. Stellar mass loss is crucial for understanding the life and death of massive stars, as well as their environments. Henny has made important contributions to many aspects of our understanding of hot-star winds. Here, the most dominant aspects of the stellar part of the meeting: (i) O star wind clumping, (ii) mass loss near the Eddington limit, and (iii) and the driving of Wolf-Rayet winds, are highlighted.

1. Introduction

Andre Maeder opened the meeting with a comprehensive review describing the basic framework for massive star evolution models, emphasizing the importance of mass loss and rotation. Henny has played a crucial role in our appreciation for the role of mass loss in stellar evolution. Within the canonical framework, mass loss “peels off” the outer envelope, and O stars evolve into Luminous Blue Variable (LBV), and Wolf-Rayet (WR) stars, before they explode as supernovae (SNe).

Massive star winds became a hot research topic at the very start of Henny’s illustrious career. The field of stellar winds took off with the discovery of P Cygni profiles in the spectra of Orion’s O stars (Morton 1967), which initiated the construction of the first radiation-driven wind models by Lucy & Solomon (1970) and Castor, Abbott & Klein (1975; CAK, thoroughly reviewed by John Bjorkman during this meeting), but it also motivated Lamers & Morton (1976) to determine the first accurate empirical mass-loss rates. Intriguingly, the mass-loss rate for the prototypical O star ζ Pup (not Pub!) of \( \dot{M} = 7.2 \times 10^{-6} \, M_\odot\, \text{yr}^{-1} \) is very close to the current estimate.

This brings me to the main topic of this meeting: what are the real mass-loss rates of massive stars? After a discussion on the topic of wind clumping (Sect. 2), I will discuss the issues of mass loss in close proximity to the Eddington/Omega limit (Sect. 3), and the driving of Wolf-Rayet winds (in Sect. 4). I will focus on just a number of aspects of massive star mass loss and I hope I will be forgiven for not attempting the impossible task of highlighting all topics in the limited amount of time and space available.
2. What are the real mass-loss rates?

I borrow this title from Joachim Puls' contribution, as it was one of the main topics of this meeting. The background is the following: massive star evolutionary models either employ empirical or theoretical mass-loss formulae. But over the last couple of years, there has been a growing number of studies, based on both X-ray [in these proceedings see Oskinova; Albacete-Colombo] and UV [Massa] data which indicate that O star winds are significantly clumped, and canonical empirical mass-loss rates overestimated. Of course, no-one doubts that O star winds are clumped, but the question that needs to be addressed is by what factor empirical and theoretical rates – based on smooth line-driven wind models, might be in error. Even more fundamental is the question whether the effects of overestimating the mass-loss rate could significantly affect our understanding of massive star evolution.

As was comprehensively discussed by Alex de Koter, the UV mass-loss rates are the most sensitive diagnostic, but the drawback is that the wind ionization is very model dependent. Measuring the free-free radio or Hα emission leads to empirical mass-loss rates which are far less model dependent and probably more accurate (e.g. Lamers & Leitherer [1993]). These radio and Hα diagnostics however are both \( \rho^2 \) diagnostics and could be significantly affected by wind clumping. Progress can be made by investigating the radial dependence of the clumping factor (e.g. Runacres & Owocki [2002]).

Puls and co-workers studied the empirical clumping stratification in the radial direction and they found the inner part of the winds (where the Hα is formed) to be more strongly clumped than the outer wind regions (where the radio free-free emission is formed [Blomme]). If the outer wind is not significantly clumped, the evolutionary effects may be modest. If however, the outer winds are strongly clumped, the inner winds may be even more strongly clumped, and effects on our stellar models may be severe. In short, until we know the clumping factor of the outer wind, we will not be able to provide a clear-cut answer to the crucial question “what is the real mass-loss rate?”

To make progress, we need to put the pieces together. In addition to the X-ray, UV, Hα, infrared and radio diagnostics, probing the wind emission at different positions in the wind, polarimetry studies [Davies] may provide strong geometric constraints on wind structure. Polarimetry results for LBVs call for an onset of wind clumping very close to the stellar photosphere, as to be able to produce the observed levels of polarisation. Possibly, this situation may be the same for O stars.

In comparing observational aspects to our theoretical knowledge, I would like to take the opportunity to stress that a modest amount of wind clumping is actually required to match the theoretical line-driven wind models. Repolust et al. [2004] for the case of Galactic supergiants, and Mokiem et al. [2007] for Magellanic Cloud supergiants needed to down-revise the empirical Hα mass-loss rates by a factor 2-3, corresponding to a clump filling factor \( f \) of ~5, to match the theoretical wind-momentum luminosity relation.

Whether clumping would significantly effect the theoretical models is as yet an open issue. On the one hand, one might expect photons to be trapped in clumps, thereby potentially limiting the multi-scattering process, but on the other hand, the photons might escape more easily into inter-clump medium,
thereby travelling larger distances and depositing their momentum more efficiently. An additional effect might be that clumping may lead to the recombination of the dominant line-driving ions, and a similar effect as that of “bi-stability” (see below) may actually lead to an increase rather than a decrease of the predicted mass-loss rate. Only the future will tell.

3. Mass loss in close proximity to the Eddington/Omega Limit

Mass loss in close proximity to the Eddington limit for LBVs (e.g. Lamers & Fitzpatrick 1988) may be even more relevant for massive star evolution if the line-driven winds of O stars would turn out to be insufficient in removing most of the stellar mass. Continuum-driven winds were extensively reviewed by Stan Owocki and their implications for Eta Car [Smith; Hillier; Gull] and other LBVs led to some heated discussions during the meeting.

Furthermore, the effects of stellar rotation on the mass-loss rate [Owocki; Langer; Ceniga] were equally relevant. One of the most interesting discoveries was the broad Si IV line of the LBV AG Car [Groh], implying a projected rotational velocity of \( \sim 200 \text{ km sec}^{-1} \) – a significant fraction of the break-up speed. This may confirm that LBVs reside close to the Omega-Eddington limit.

Stellar rotation may lead to wind asymmetries [Maeder]. For most objects, the oblate distortion of the star and Von Zeipel gravity darkening for radiative envelopes may lead to a distribution of mass flux which is stronger towards the pole than to the equator [Owocki].

This configuration of a polar mass flux distribution may be the exact opposite for objects that find themselves at temperatures in close proximity of the so-called “bi-stability jump” (Pauldrach & Puls 1990, Lamers et al. 1995). At lower temperatures, the dominant line-driving ion of iron (Fe) recombines from IV to III, which is predicted to result in larger mass flux from the equator than at the pole. This “rotationally enhanced bi-stability” effect from Lamers & Pauldrach (1991) may be very relevant in explaining the B[e] phenomenon.

During this meeting, the first empirical evidence for the possible existence of a mass-loss bi-stability jump in the HRD was presented by Benaglia – through a radio survey over the bi-stability range. However, there remain a number of later type B supergiants for which the empirical and theoretical rates are discrepant [Crowther]. Future work should show whether these B-star discrepancies may be related to wind clumping – the main contender for the discordance of the UV mass-loss studies for O supergiants [Massa].

4. The driving of Wolf-Rayet winds

One of the most significant differences between Wolf-Rayet and O star winds is that WR stars invariably show very large “pseudo-photospheres”. This makes it particularly challenging to study the innermost regions of WR winds. Despite this disadvantage, a lot of progress to our understanding of the driving of WR winds has been made in the last couple of years.

This progress happened on the purely analytic front [Onifer], the semi-analytic front, as well as the quantitative modelling front. The postulation of
Nugis & Lamers (2002) that the continuum (OPAL) opacities play an instrumental role in starting the WR winds at deep layers helped the subsequent PoWR modellers [Gräfener, Hamann] to initiate and maintain the driving of a carbon-rich WC star from the photosphere into the regime where the wind reaches its terminal velocity.

This suggests that despite the differences with O star winds, both groups of winds are primarily driven by radiation pressure. As a result, we are now able to estimate mass-loss dependencies of WR stars as a function of metal content [Vink, de Koter], with important consequences for gamma-ray burst progenitors and early generations of massive stars.

Despite the successes, Gräfener warned that there are still many aspects of WR driving that remain poorly understood. One such aspect concerns the enigmatic WN8 stars, which are known to be highly variable. Observations with the MOST “humble space telescope” [Moffat] may tell us more about the role of WR pulsations. Another potentially most relevant physical ingredient involves the strength of the surface magnetic field. During her talk, Nicole St.-Louis set an upper limit of 25 Gauss on at least one WR star.

Finally, I wish to highlight the role of rotation for WR stars. In the case of WR1, Chené managed to derive a period of 16.7 days. Assuming a WR radius of 5 solar radii, the rotation speed at the stellar surface was estimated to be in the range 15-100 km sec$^{-1}$ [St. Louis]. Despite the necessary assumptions, this is clearly a unique constraint, as WR rotation rates cannot be determined from the more traditional method of measuring $v \sin i$ from stellar absorption line spectra, due to the broad lines in their spectra.

5. Final words

One of the fiercest discussions during the meeting was related to the possibility that giant LBV eruptions ($\eta$ Car type eruptions, not the typifying S Doradus variations) may be a dominant mechanism for the integrated mass loss during the life of a massive star, as severe clumping in O-star winds may imply negligible mass loss through line-driven winds.

Although the issue of the clumping factor in O star winds is very much an open one, if clumping factors would be significantly larger than $\sim$five, one might require extra mass loss during the LBV phase to produce the much lower masses of WR stars. An alternative could be an early SN explosion, as was discussed by several speakers [Smith; Vink]. Now that LBVs have been suggested as potential SNe progenitors, whilst e.g. Langer suggested the possibility of quasi-homogeneous evolution of GRB progenitors, it appears that the successful “standard scenario” for massive star evolution may need some revision.

Future mass-loss studies will play a major role in constructing a more complete picture of massive star evolution. These studies will no-doubt heavily rely on the insight of physical processes developed by Henny Lamers and his contemporaries.

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References

Castor, J.I., Abbott, D.C., Klein, R.I., 1975, ApJ 195, 157
Lamers, H.J.G.L.M., Morton, D.C., 1976, ApJS 32, 715
Lamers, H.J.G.L.M., Fitzpatrick, E.L., 1988, ApJ 324, 279
Lamers, H.J.G.L.M., & Pauldrach, A.W.A., 1991, A&A 244L, 5
Lamers, H.J.G.L.M., & Leitherer, C., 1993, ApJ 412, 771
Lamers, H.J.G.L.M., Snow, T.P., Lindholm, D.M., 1995, ApJ, 455, L269
Lucy, L.B., Solomon, P.M., 1970, ApJ 159, 879
Mokiem, M.R., de Koter, A., Vink, J.S., Puls, J., Evans, C.J., et al., A&A, to be submitted
Morton, D.C., 1967, ApJ 147, 1017
Nugis, T., Lamers, H.J.G.L.M., 2002, A&A 389, 162
Pauldrach, A.W.A. & Puls, J., 1990, A&A, 237, 409
Repolust, T., Puls, J., Herrero, A., 2004, A&A 415, 349
Runacres, M.C., & Owocki, S.P., 2002, A&A 381, 1015