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On the mass-loss properties of the most massive stars

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Abstract: The most massive stars are believed to form Wolf-Rayet like emission line spectra already on the main sequence. One goal of the new VLT-FLAMES Tarantula Survey is to understand the nature of such 'O stars on steroids', and to investigate the transition from normal O star to WR-type mass loss. The Tarantula nebula (30 Dor) hosts the closest starburst-like region in our neighborhood, with a cluster of 30-50 extremely massive stars in its center. In this paper we present a multi-wavelength program that includes integral field K-band spectra of the central region of 30 Dor with VLT/SINFONI. We discuss the prospects of this program in the context of our theoretical work on Γ-dependent mass-loss rates in the O-WR transition phase.

1 Introduction

Wolf-Rayet (WR) type mass loss fundamentally affects the evolution, the final fate, and the chemical yields of massive stars. The precise amount of mass loss in the WR phase determines whether a star ends its life as neutron star, or black hole (Heger et al. 2003). The nature of WR-type mass loss is however still poorly understood. E.g., stellar evolution models rely on empirical mass-loss relations (e.g., Nugis & Lamers 2000; Hamann et al. 2006), with the WR phase identified on the basis of observed WR surface abundances in our neighborhood. Clearly, for the modeling of stellar populations that cannot be observed locally, a more physical approach would be desirable.

In the present work we discuss such an approach, namely a mass-loss relation for WR stars that chiefly depends on the Eddington factor Γ_{e}. Such a relation has been predicted by theoretical studies of radiatively driven winds close to the Eddington limit (Gräfener & Hamann 2005, 2008, Vink et al. in prep.). Notably, the proximity to the Eddington limit provides a natural explanation for the occurrence of WR mass loss. Large Eddington factors can be reached, on the one hand, by very young and massive stars on the main sequence because of their extremely high luminosities, and on the other hand, by less massive evolved (He-burning) stars due to the enhanced mean molecular weight in their cores. The occurrence of WR-type mass loss for young, luminous, hydrogen-rich stars (typically late WN subtypes), and evolved, hydrogen-free WR stars can thus be explained in the same way.

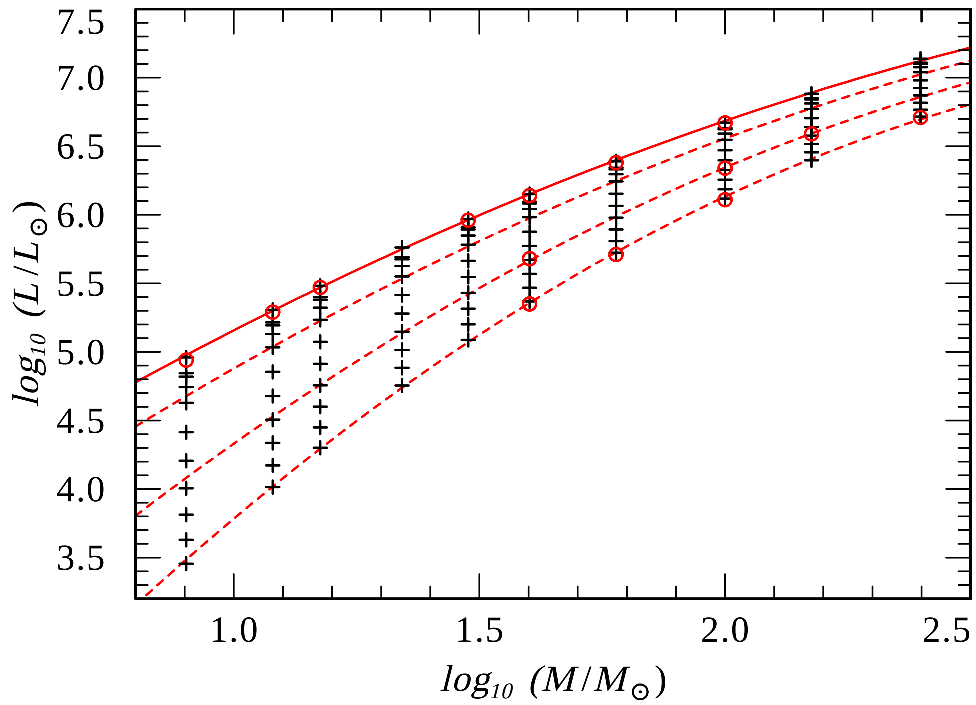

Figure 1: Homogenous stellar structure models for the mass range 8–250 $M_{\odot}$ (black symbols). The models are computed for hydrogen mass fractions $X_{\mathrm{H}} = 0.7$–0 (from bottom to top). Red lines indicate fitted M-L relations for H-burning models with $X_{\mathrm{H}} = 0.7$, 0.4, and 0.1 (dashed), and pure He-models (solid). For comparison, model computations from Ishii et al. (1999) are indicated by red symbols.

2 Mass loss predictions for very massive stars

Wind models for very massive stars close to the Eddington limit (Gräfener & Hamann 2008, Vink et al. in prep.) reveal a steep dependence on the Eddington factor Γ_{e} for the optically thick, WR-type winds of these objects. Moreover, Gräfener & Hamann (2008) find a very strong temperature dependence, with $\dot{M} \propto T_{\star}^{3.5}$. This strong sensitivity to stellar parameters offers the potential to provide very precise estimates of Γ_{e} for stars in this regime, based on the predicted mass loss relations. Using large stellar samples where parameters like $\dot{M}$, L, X_{H}, and Z are determined by spectral analyses, we can thus test the existence of such relations in an empirical way.

3 Mass–luminosity relations for very massive stars

To get a handle on the $\dot{M}$–Γ_{e} relation for observed stars we need to estimate the *expected* values of Γ_{e} for stars with observed stellar parameters L, and X_{H}. For this purpose we need to estimate the stellar mass M, and compute $\Gamma_{\mathrm{e}} = \chi_{\mathrm{e}} L/4\pi c G M = 10^{-4.813}(1 + X_{\mathrm{H}})L/M$. The important dependence on $(1 + X_{\mathrm{H}})$ enters this equation via the mass absorption coefficient χ_{e}, because, in a fully ionized gas, hydrogen provides one free electron per nucleon, in contrast to 0.5 for helium.

Because the internal structure of a single observed star is generally not known, we will concentrate here on the lowest and highest possible mass for a star with given parameters L, and X_{H}. The highest possible mass is given by the *chemically homogenous* case. Under this assumption, the star is characterized by one, constant hydrogen abundance X_{H}, which equals the observed surface abundance. The estimated stellar mass $M_{\mathrm{hom}}(L, X_{\mathrm{H}})$ is strongly dependent on the (observed) surface abundance X_{H}.

The lowest possible mass is given by the completely inhomogenous case, i.e., by a hydrogen-free stellar core. In this case the star is in the *core He-burning* phase. For the case of hot, massive stars with large convective cores the He-burning mass equals the mass of a pure He-star (Lauterborn et al. 1971), i.e., $M_{\rm Heb}(L) \equiv M_{\rm hom}(L, X_{\rm H} = 0)$. Note that, in contrast to the homogenous case, this mass estimate is completely independent of the observed surface abundance $X_{\rm H}$. In the following this difference will help to distinguish between samples of well-mixed, quasi chemically homogenous stars, and stars with a pronounced chemical profile. In Fig. 1 we illustrate the M–L relations as obtained from our own stellar structure computations for chemically homogenous stars.

4 The most massive stars in the Arches cluster

One of the biggest known samples of very massive stars is found in the Arches cluster, near the Galactic Center. Stellar parameters of these stars have been determined by Martins et al. (2008). In Figs. 2, and 3 we display semi-empirical mass loss relations, based on observed mass-loss rates, and mass estimates under the assumptions of homogeneity, and core He-burning. Only for the homogenous case (Fig. 3) we obtain a pronounced Γ-dependent mass-loss relation that compares well with theoretical predictions. Note that the qualitative difference between both plots arises from the dependence of $M_{\rm hom}(L, X_{\rm H})$ on the surface hydrogen abundance $X_{\rm H}$. For the homogenous case, this dependence puts the H-deficient WN stars on the same relation as the H-rich Of/WN stars. We interpret this as evidence 1) for the existence of a Γ-dependent mass-loss relation, and 2) for the H-burning nature of the Arches cluster stars.

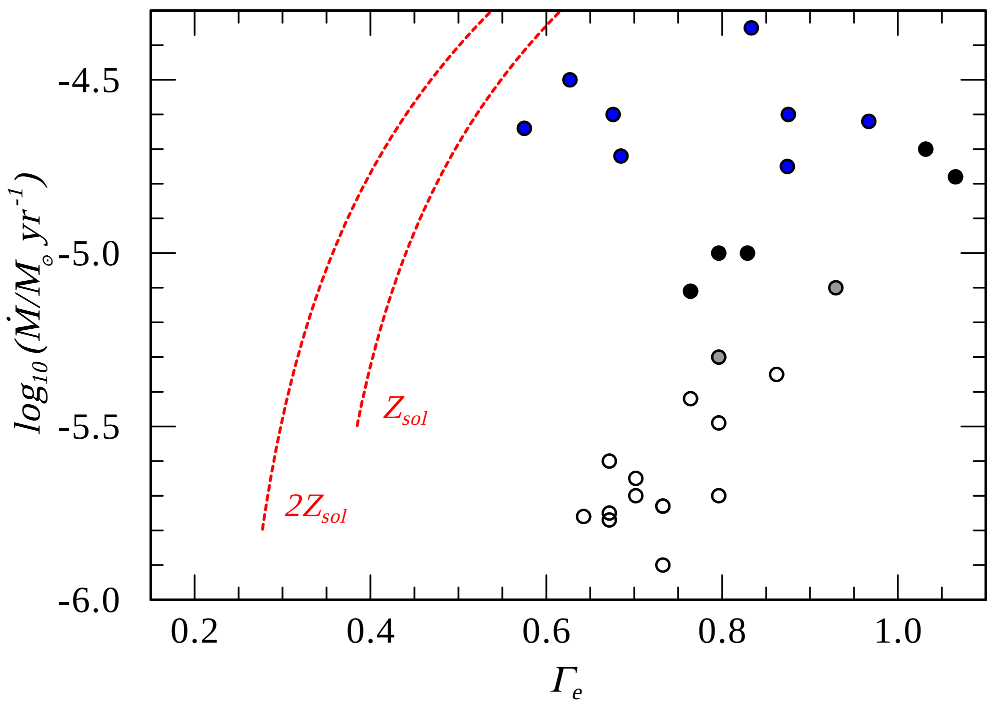

Figure 2: Under the assumption of central He-burning, the Arches cluster stars display no general Γ-dependence. Colored symbols indicate stars with spectral subtypes WNh (H-deficient blue, normal H abundance black), Of (grey), and O (white). We compare with mass loss relations by Gräfener & Hamann (2008) for $log(L) = 6.3$, $T_\star = 30\,$kK, and $X_{\rm H} = 0.7$ (dashed red lines).

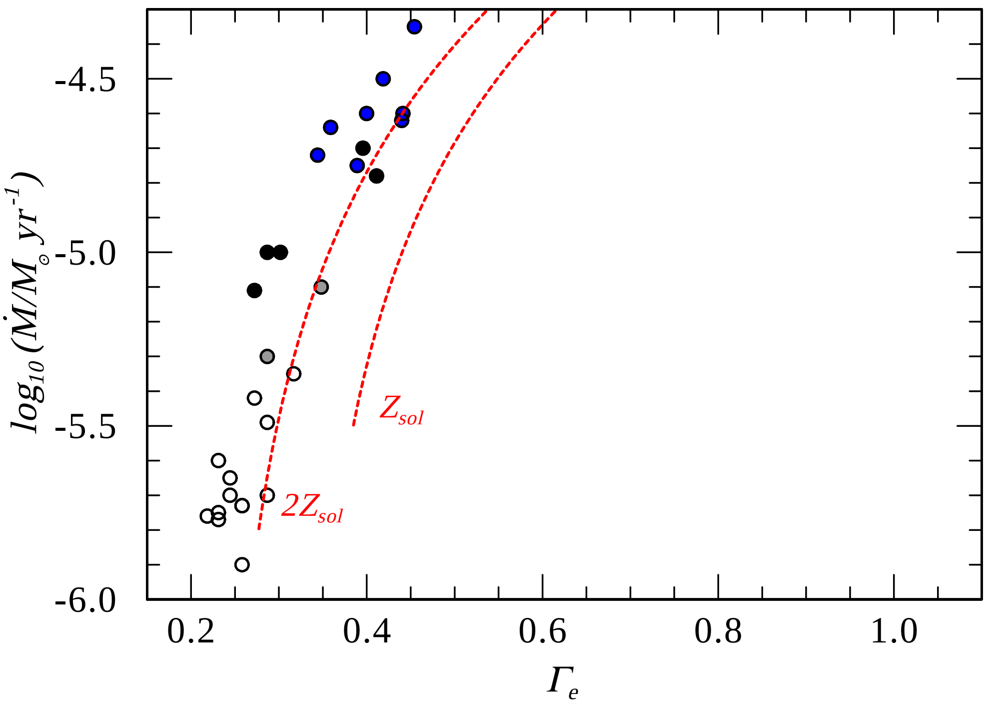

Figure 3: Under the assumption of chemical homogeneity, the Arches cluster stars display a pronounced Γ-dependent mass-loss relation. Symbols are the same as in Fig. 2.

5 The VLT-FLAMES Tarantula Survey

In the framework of the VLT-FLAMES Tarantula Survey we currently investigate the mass-loss properties of the most massive stars in the central part of 30 Dor in the LMC. This stellar sample will complement our previous investigation of the Arches cluster stars in an ideal way, as it represents very similar objects with different metallicity, and temperature. We will thus be able to investigate the important dependencies on these two parameters in an empirical way.

In Fig. 4 we illustrate the spatial coverage of the 30 Dor sample by different observational programmes. The FLAMES-MEDUSA fiber pointings are indicated in red. Due to crowding, the central part of the cluster is however largely omitted by this program. To obtain a homogenous dataset for the whole cluster we have secured SINFONI K-band spectra that cover the complete central cluster (yellow fields). These spectra provide the same mass-loss diagnostics as the previous IR studies, e.g., for the Arches cluster, and are augmented by existing HST data (blue).

6 Conclusions

In this work we have presented theoretical, as well as observational evidence for the existence of a Γ-dependent mass-loss relation for very massive stars.

For the most massive stars in the Arches cluster, we only find such a relation under the assumption of a chemically homogenous stellar structure. We interpret this as evidence for the H-burning nature of the WN stars in the Arches cluster. This is in line with the picture that WR-type mass loss is generally triggered by the proximity to the Eddington limit, for very massive stars as well as for 'classical' He-burning WR stars. Our ongoing work on the most massive stars in 30 Dor will help to investigate the stellar mass loss in this regime over a much broader range of temperatures and metallicities.

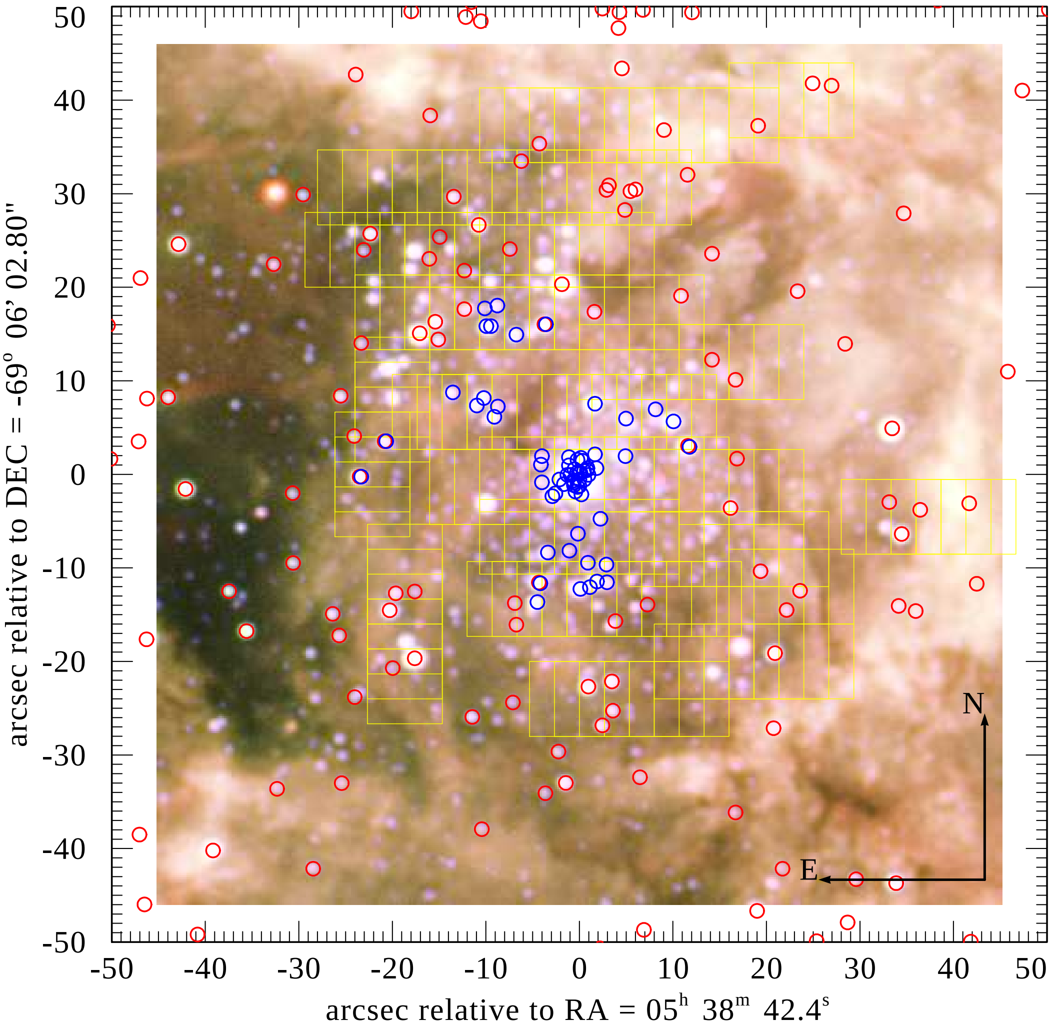

Figure 4: The VLT-FLAMES Tarantula Survey. The picture illustrates the central part of 30 Dor with pointings of the FLAMES-MEDUSA fiber spectrograph (red), existing HST spectra (blue), and SINFONI integral-field K-band spectroscopy.

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Discussion

I. Brott: You compare your mass-loss rates to homogeneous stars of $2\times$ solar metallicity. Usually, homogeneity does not appear in evolutionary models of solar or higher metallicity.
G. Gräfener: We use homogeneous structure models to constrain Γ. This method is independent from evolutionary models.
Comment: In a later discussion it turned out that also high-Z evolution models evolve homogeneously. They only do not evolve to the blue because of an envelope inflation.