Clumping in Hot Star Winds
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Advances in mass-loss predictions

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We present the results of Monte Carlo mass-loss predictions for massive stars covering a wide range of stellar parameters. We critically test our predictions against a range of observed mass-loss rates – in light of the recent discussions on wind clumping. We also present a model to compute the clumping-induced polarimetric variability of hot stars and we compare this with observations of Luminous Blue Variables, for which polarimetric variability is larger than for O and Wolf-Rayet stars. Luminous Blue Variables comprise an ideal testbed for studies of wind clumping and wind geometry, as well as for wind strength calculations, and we propose they may be direct supernova progenitors.

1 Introduction

This contribution consists of two complementary aspects of hot-star winds. We first describe the results of mass-loss predictions – widely used in current massive star models in the galaxy, and beyond. In particular, we test our predictions as a function of effective temperature against recent radio data, and we discuss the potential implications for the clumping properties of supergiants of various spectral types (Sect.2). We also discuss mass-loss predictions for the winds of Luminous Blue Variables (LBVs), and we present results of the clumping-induced polarimetric variability of hot-star winds (Sect. 3), before we conclude.

2 Monte Carlo mass-loss predictions

Our method to predict the mass-loss rates of massive stars is based on Monte Carlo radiative transfer calculations (see Vink et al. 1999, de Koter et al. 1997). In short, we compute non-LTE level populations for all relevant ions from hydrogen to zinc, before we follow the fate of a large number of photon packets through the wind. We predict the efficiency of the momentum transfer from the photons to the gas, generally assuming a pre-described velocity law (but see Vink et al. 1999, Müller & Vink, *in prep.*). We derive wind efficiencies, $\eta = (\dot{M} v_\infty)/(L/c)$, for a range of stellar parameters (including metallicities).

2.1 Results: successes

To gauge the success of our models and to be able to identify discrepancies, we test our predictions against a survey of radio mass-loss rates (Benaglia et al. 2007) from the free-free emission in hot-star winds.

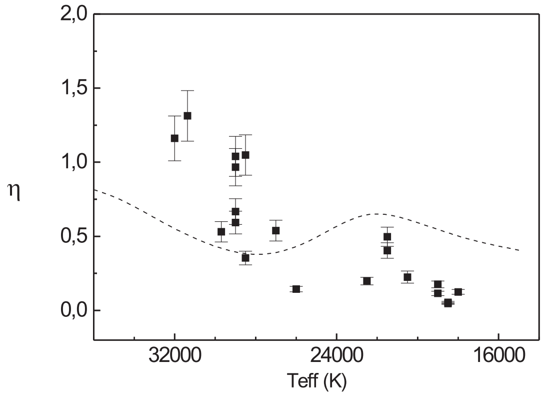

Figure 1: Radio wind efficiency vs. effective temperature (Benaglia et al. 2007). Overplotted are mass-loss predictions (Vink et al. 1999). Note the possible bi-stability jump at 21 000 K.

In Fig. 1, we plot the wind efficiency versus effective temperature in the regime of the wind bistability, where winds are predicted to change from lower $\dot{M}$, fast winds, on the hot side, to higher $\dot{M}$, slow winds on the cool side – a result of a change in the Fe ionisation that drives the wind. We overplot the mass-loss predictions around the bi-stability jump (dashed line) and focus on the general trends, before we continue our discussion on quantitative aspects, and their implications, in Sect 2.2.

The overall behaviour shows that η declines when the temperature drops. At the highest temperatures, the flux and the opacity show large overlap and the momentum transfer efficiency is maximal. At lower effective temperature, the flux is gradually emitted towards lower wavelengths, and there is a growing mismatch between the flux and the ultraviolet line opacity. Figure 1 shows that our predictions of this overall behaviour are confirmed by the radio survey. Our second prediction is that there should be an increase in the mass-loss rate due to the opacity increase when Fe recombines from Fe IV to Fe III. Our radio data appear to confirm the presence of a local maximum around 21 000 K, although data around this critical temperate is, as yet, sparse.

The bi-stability limit is relevant for stellar evolution calculations when stars evolve off the main sequence towards the red part of the Hertzsprung-Russell diagram (HRD). It may also play a role for LBV winds, when LBVs such as AG Car, change their temperatures – and radii – on timescales of the S Dor variations (of the order of years to decades). This variable wind behaviour – predicted by Vink & de Koter (2002) – is anticipated to result in circumstellar media consisting of concentric shells with varying wind densities. Kotak & Vink (2006) recently suggested that the quasi-periodic modulations seen in the radio lightcurves of some supernovae may imply that LBVs could be *direct* supernova progenitors. At first this seems at odds with stellar evolution calculations, which do not predict LBVs to explode. However, there is a growing body of evidence hinting that LBVs may nonetheless explode (Pastorello et al. 2007, Smith 2007, Gal-Yam et al. 2007).

Despite the success of our models in explaining LBV mass-loss variability, the bi-stability jump, and the scaling of $\dot{M}$ with metallicity (see de Koter, this volume), we turn to discrepancies of our models against empirical mass-loss rates.

2.2 Results: discrepancies

Discrepancies have been noted between the Vink et al. (2000) predictions and empirical mass-loss rates in several areas of the HRD. One group of objects is that of low L ($\log L/L_{\odot} < 5.2$) O dwarfs, where the data of Martins et al. (2005) fall well below predictions, by factors of 10 or more. The reason for this discrepancy is as yet not understood. Another area of discrepancies is that of the B supergiants where empirical rates have been found to be much lower than predicted rates (Vink et al. 2000, Trundle & Lennon 2005).

The most worrisome however is the situation with garden-variety type O stars! Figure 1 shows that the Vink et al. (2000) predictions are *lower* than the observed rates. The radio rates are likely to be upper limits as the radio free-free emission is a ρ^2 process, and any form of clumping leads to a maximal $\dot{M}$. Mokiem et al. (2007) and Puls (this volume) noted that *if* this discrepancy is related to wind clumping – and theoretical rates are unaffected – the empirical ρ^2 mass-loss rates must be down-revised by a factor 2-3, suggesting a clumping factor f ~5. Recent massive star evolution models would not be effected by such modest clumping factors as these already use the theoretical Vink et al. (2000) rates.

If f ~5 were universal, one would expect the empirical $\dot{M}$ for B supergiants to be *lower* than indicated in Fig. 1 and the discrepancy would amount to an order of magnitude, or more. This implies there are some serious issues with our theoretical understanding of hot-star winds, and we need to reconsider even our most basic modelling assumptions, such as sphericity and homogeneity, which can be tested with linear polarimetry.

3 Linear polarisation variability

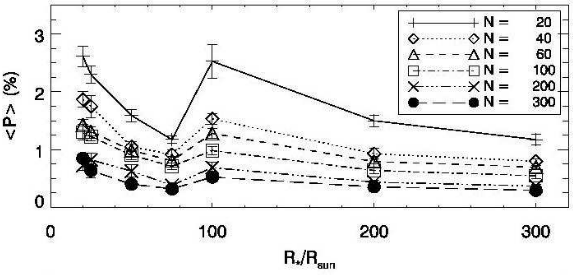

Figure 2: Polarisation variability vs. stellar radius – for different clump ejection rates. $N = \dot{N}\ t_{\rm fl}$, where $\dot{N}$ is the clump ejection rate (related to the mass-loss rate) and $t_{\rm fl} = R/v_{\infty}$ (see Davies et al. 2007).

Linear polarimetry is a tool to measure asymmetries. Davies et al. (2005) performed a polarimetric survey of LBVs and found asymmetries in a majority of them. When the position angle (PA) of the polarisation shows a straight line in the Stokes QU diagram this is generally attributed to a large-scale, axi-symmetry, e.g. a disk. Davies et al. (2005) found time-variable PAs for objects such as AG Car and attributed these to wind clumping. Subsequently, Davies et al. (2007) constructed an analytic clumping model, releasing clumps with a certain ejection rate per wind flow-time, N, from the wind base. The average polarisation of the clump ensemble was calculated; the results for LBVs with a range of temperatures and radii are shown in Fig. 2.

When the LBVs decrease their radii, the clumps become smaller and denser, and produce more polarisation. This behaviour reverses at the temperature of the bi-stability jump where the wind becomes faster, and the clumps spend less time at the wind base. As a result the polarisation drops. Figure 2 also shows that when the ejection rate increases, the polarisation drops as the wind approaches that of a smooth outflow leading to zero polarisation.

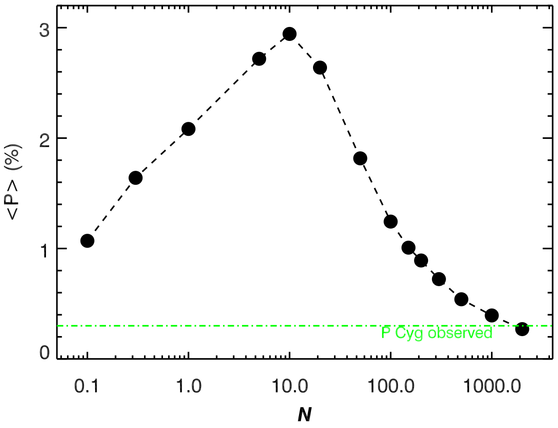

Figure 3: Polarisation variability vs. clump ejection rate. The presence of a maximum implies there are two solutions compared to the observed level of P Cyg.

We now consider the average polarisation as a function of ejection rate. The right-hand side of Fig. 3 shows the regime of many optically thin clumps. A maximum is reached at $N \sim 10$ where the clumps become optically thick and multiple scattering becomes important. The left-hand side represents the optically-thick clump regime. The observed level of polarisation of P Cyg is shown as a horizontal line that intercepts both branches. The data either point to a wind with low N, or to one with $N \sim 1000$. We distinguish between these two branches using timescale information of the polarimetric variations. Preliminary results from our recent monitoring campaign indicate that the high-N scenario is likely to be the correct one (Davies et al. *in prep*), which would suggest that LBV winds consist of thousands of optically thin clumps close to the photosphere.

4 Conclusion

Polarimetry is a tool to constrain the clumping properties of hot-star winds. This may become a powerful means by which to constrain non-LTE models and mass-loss predictions. We anticipate to witness an increased understanding of hot-star winds – an important endeavour because of the impact mass loss has on massive star evolution modelling.

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Puls: In how far do the results depend on model details (e.g. on the opening angle), and will you be able to derive clumping factors? In Lunteren, you quoted a clumping factor of two.

Vink: For optically thin clumps, the exact shape/opening angle of the clumps is not so important, as long as the clumps do not become too large. Deriving clumping factors is tricky, as we only constrain the polarization from the clumps and not from the interclump medium. Using a range of diagnostics, this may well be constrained (polarimetry will provide geometrical constraints).

Groh: When you compare your predictions with the observations for AG Car, should clumping and rotation not be taken into account in your models in order to obtain results?

Vink: We make assumptions when modelling the radiative acceleration (homogeneity and sphericity). We are working to improve these assumptions (e.g. by polarimetric modelling of LBV winds).

Cassinelli: The importance of the angular size of the clump is that it determines the fraction of the stellar light that is scattered.

Vink: Once the clump becomes very large, you need to look at the detailed shapes indeed. In our modelling, the clumps are small and the exact opening angle is less relevant to determine $\langle \rho \rangle$.

Ignace: Although the data do not appear to support the idea of optically thick clumps, in principle the polarization from thick clumps depend on their shape.

Vink: Yes, I agree. For thick clumps you need to do Monte Carlo simulations. Nonetheless, the point of our analysis is that the average polarization will drop once you go to low injection rates, the exact function how $\langle P \rangle$ falls of with low N (number of clumps) is less relevant for our arguments.

Smith: In order to see a net polarization, where you jump around randomly on the Q-U plot: does that require some large scale asymmetry in the wind, i.e. are there sporadic mass ejections in random directions?

Vink: First results from our recent polarimetric monitoring campaign seem to suggest that we are working in the "high-ejection rate" regime, resulting in a "stochastic" low level of average polarization (producing short timescale variability) rather than sporadic mass ejections.