Physics of Mass Loss in Massive Stars

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Abstract. We review potential mass-loss mechanisms in the various evolutionary stages of massive stars, from the well-known line-driven winds of O-stars and BA-supergiants to the less-understood winds from Red Supergiants. We discuss optically thick winds from Wolf-Rayet stars and Very Massive Stars, and the hypothesis of porosity-moderated, continuum-driven mass loss from stars formally exceeding the Eddington limit, which might explain the giant outbursts from Luminous Blue Variables. We finish this review with a glance on the impact of rapid rotation, magnetic fields and small-scale inhomogeneities in line-driven winds.

Keywords. stars: early-type, stars: mass loss, stars: winds, outflows

1. Introduction

Stellar winds from massive stars are fundamentally important, in providing energy and momentum input into the ISM, in creating wind-blown bubbles and circumstellar shells, and in triggering star formation. The presence and amount of mass loss decisively controls the evolution and fate of massive stars† (e.g., the type of final Supernova-explosion), by modifying evolutionary timescales, surface abundances, and stellar luminosities. Moreover, mass loss also affects the atmospheric structure, and only by a proper modeling of stellar winds it is possible to derive accurate stellar parameters by means of quantitative spectroscopy. In the following, we review the status quo of our knowledge about the physics of these winds.

2. Basic considerations

Since massive stars have a high luminosity, they are basically able to generate a large radiative acceleration in their atmospheres.

Global energy budget – The photon tiring limit. Thus, a first question regards the maximum mass-loss rate that can be radiatively accelerated. By equating the mechanical luminosity in the wind at infinity with the available photospheric luminosity L_* (in this case, all photons have used up their energy/momentum, $L(\infty) = 0$), one obtains

$$\dot{M}_{\text{max}} = \frac{2L_*}{v_\infty^2 + v_{\text{esc}}^2} = \frac{\dot{M}_{\text{tir}}}{1 + (v_\infty/v_{\text{esc}})^2} \approx \dot{M}_{\text{tir}} \dots \frac{\dot{M}_{\text{tir}}}{10}, \qquad (2.1)$$

where v_∞ is the terminal wind speed (typically on the order of one to three times the photospheric escape velocity, $v_{\text{esc}} = \sqrt{2GM/R}$), and $\dot{M}_{\text{tir}}$ the 'photon tiring mass-loss rate' (Owocki & Gayley 1997), i.e., the maximum mass-loss rate when the wind just

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† A change of only a factor of two in the mass-loss rates can have a dramatic effect (Meynet et al. 1994).

escapes the gravitational potential, with $v_\infty \to 0$. In convenient units,

$$\dot{M}_{\rm tir} = \frac{2L_*}{v_{\rm esc}^2} = 0.032 \frac{M_\odot}{yr} \frac{L_*}{10^6 L_\odot} \frac{R/R_\odot}{M/M_\odot}. \qquad (2.2)$$

This maximum mass-loss rate is much larger than the mass-loss rates of winds from OB-stars/A-supergiants/WR-stars/Red Supergiants(RSGs) (by a factor of 10^3 and larger), whereas it is on the order of the mass-loss rates estimated for the giant eruptions from Luminous Blue Variables (LBVs, see Sect. 6).

Global momentum budget – optically thick/thin winds. The dominating terms governing the equation of motion of a massive star wind are the inward directed gravitational pull and the outward directed radiative acceleration, $g_{\rm rad}$†. In spherical symmetry, the latter can be written as

$$g_{\rm rad}(r) = \int_0^\infty d\nu \frac{\kappa_\nu(r) F_\nu(r)}{c} = \kappa_{\rm F}(r) \frac{L_*}{4\pi r^2 c}, \qquad (2.3)$$

with frequential flux F_ν, mass absorption coefficient κ_ν, and flux-weighted mass absorption coefficient $\kappa_{\rm F}$. By integrating the equation of motion over $dm = 4\pi r^2 \rho dr$ between the sonic point, $r_{\rm s}$, and infinity (and neglecting pressure terms), one can express the wind-momentum rate, $\dot{M} v_\infty$, in terms of the total momentum rate of the radiation field, L_*/c, and flux mean optical depth of the wind, $\tau_{\rm F}$,

$$\eta = \frac{\dot{M} v_\infty}{L_*/c} \approx \tau_{\rm F}(r_{\rm s}) - \frac{\tau_{\rm e}(r_{\rm s})}{\Gamma_{\rm e}} \qquad (2.4)$$

(cf. Abbott 1980). The second term on the rhs is a typically small correction for overcoming the gravitational potential, consisting of the electron-scattering optical depth $\tau_{\rm e}$, and the conventional Eddington-Gamma, $\Gamma_{\rm e} \propto L/M$, evaluated for electron-scattering. Note that this relation is only valid for $\dot{M} \ll \dot{M}_{\rm tir}$.

Because of its definition, η is called the wind performance number. For optically thin winds, defined by $\tau_{\rm F}(r_{\rm s}) < 1$, the performance number is lower than unity, $\eta < 1$, which is typical for OB-stars and A-supergiants, whilst for optically thick winds (e.g., WR-winds) with $\tau_{\rm F}(r_{\rm s}) > 1$ also $\eta > 1$. In a line-driven wind (see Sect. 3), η becomes roughly unity when each photon in the wind is scattered once. $\eta > 1$ then indicates that most photons have been scattered more than once (multi-line scattering).

3. (Optically thin) Line-driven winds

The winds from OB-stars and A-supergiants, with typical mass-loss rates $\dot{M} \approx 10^{-7} \ldots 10^{-5}$ $M_\odot$/yr, and terminal velocities, v_∞, ranging from 200 ... 3,500 km s^{-1}, are thought to be accelerated by radiative line-driving.

Photospheric light is scattered/absorbed in spectral lines, and momentum is transferred to the absorbing ions, predominantly into the radial direction. Note that there is no momentum loss or gain during the (re-)emission process, at least in a spherically symmetric configuration, since this process is fore-aft symmetric. Most of the momentum-transfer is accomplished via metallic resonance lines, and this momentum is then further transferred from the accelerated metal-ions (with a low mass-fraction) to the wind bulk plasma, H and He, via Coulomb collisions (e.g., Springmann & Pauldrach 1992).

Since the complete process requires a large number of photons (i.e., a high luminosity),

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† as long as pressure terms can be neglected, i.e., when $v(r) \gg v_{\rm sound}$ for the largest part of the wind.

such winds occur in the hottest stars, like O-type stars of all luminosity classes, but also in cooler BA-supergiants, because of their larger radii. Efficient line-driving further requires a large number of spectral lines close to the flux-maximum and a high interaction probability (i.e., a significant line optical depth). Since most spectral lines originate from various metals, a strong dependence of $\dot{M}$ on metallicity is thus to be expected, and such *line-driven* winds should play a minor role (if at all) in the early Universe (but see Sect. 6).

The theory of line-driven winds has been pioneered by Lucy & Solomon (1970) and particularly by Castor et al. (1975, 'CAK'), with essential improvements regarding a quantitative description and application provided by Friend & Abbott (1986) and Pauldrach et al. (1986). Line-driven winds have been reviewed by Kudritzki & Puls (2000) and more recently by Puls et al. (2008).

In the following, we will briefly consider some relevant aspects, mostly in terms of the 'standard model', assuming a steady-state, spherically symmetric, and homogeneous outflow (i.e., neglecting rotation, magnetic fields, and density inhomogeneities, considered later in Sect. 7).

Calculating the radiative acceleration by means of the Sobolev approximation (Sobolev 1960), assuming well-separated lines (justified for most optically thin winds, e.g., Puls 1987), and a distribution of line-strengths following a power-law with exponent $\alpha - 2$ (for details, see Puls et al. 2000), the *total* radiative line acceleration from all participating lines can be expressed by

$$g_{\rm rad}(\text{all lines}) \propto \Big(\frac{{\rm d}v/{\rm d}r}{\rho}\Big)^{\alpha}. \tag{3.1}$$

Particularly because of the dependence on ρ, this leads to a self-regulation of the mass-loss rate, and an analytic solution of the equation of motion is possible. In compact notation, and neglecting the (for O-stars typically weak) effects of an ionization stratification†, one finds the following scaling laws

$$\dot{M} \approx \frac{L_*}{c^2}\frac{\alpha}{1-\alpha}\Big(\frac{\bar{Q}\Gamma_{\rm e}}{1-\Gamma_{\rm e}}\Big)^{1/\alpha-1}\frac{1}{(1+\alpha)^{1/\alpha}} \tag{3.2}$$

(Owocki 2004, and references therein),

$$v(r) = v_\infty\Big(1-\frac{R_*}{r}\Big)^{\beta} \qquad v_\infty \approx 2.25\frac{\alpha}{1-\alpha}v'_{\rm esc} \tag{3.3}$$

(Kudritzki et al. 1989), where $v'_{\rm esc} = v_{\rm esc}\sqrt{1-\Gamma_{\rm e}}$ is the effective escape velocity corrected for Thomson acceleration. For typical O-stars, Gayley's (1995) dimensionless line-strength parameter $\bar{Q} \approx 2000$, $\alpha \approx 0.6$, $\beta \approx 0.8$, and $\dot{M}$ is on the order of $10^{-6}\,M_\odot{\rm yr}^{-1} \ll \dot{M}_{\rm tir}$. Note that $\bar{Q}$ scales with metallicity, $\bar{Q} \propto Z/Z_\odot$, such that $\dot{M} \propto (Z/Z_\odot)^{0.7}$ for the above α.

For quantitative results, the most frequently used theoretical mass-loss rates are based on the wind models by Vink et al. (2000, 2001), calculated by means of approximate NLTE occupation numbers and a Monte Carlo transport (i.e., without invoking any line statistics). From interpolating the mass-loss rates derived in this way for a large model grid, the provided 'mass-loss recipe' becomes $\dot{M} = \dot{M}(L_*, M, T_{\rm eff}, v_\infty/v_{\rm esc}, Z)$, with a similar metallicity dependence as above. For alternative models and calculation methods, see, e.g., Krtička & Kubát (2000); Pauldrach et al. (2001); Kudritzki (2002).

The wind-momentum luminosity relation (WLR). By using the scaling relations for $\dot{M}$ and v_∞ (Eqs. 3.2, 3.3), and approximating $\alpha \approx 2/3$, one obtains the so-called

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† corresponding to a 'force-multiplier' parameter $\delta = 0$, see Abbott (1982)

wind-momentum luminosity relation – WLR – (Kudritzki et al. 1995),

$$\log D_{\mathrm{mom}} = \log\Big(\dot{M}v_\infty\big(\frac{R}{R_\odot}\big)^{\frac{1}{2}}\Big) \approx \frac{1}{\alpha}\log\Big(\frac{L_*}{L_\odot}\Big) + \mathrm{offset}(Z, \text{spectral type}), \qquad (3.4)$$

which relates the *modified* wind-momentum rate D_{mom} with only the stellar luminosity. The mass-dependence (due to Γ_{e}) becomes negligible as long as α is close to 2/3. The offset in Eq. 3.4 depends on metallicity and spectral type, mostly because the effective number of driving lines and thus $\bar{Q}$ depend on these quantities (e.g., Puls et al. 2000), via different opacities and contributing ions.

Though derived from simplified scaling relations, the WLR concept has also been confirmed by numerical model calculations, e.g., those from Vink et al. (2000, their Fig. 9). An impressive *observational* confirmation of this concept has been provided by Mokiem et al. (2007), compiling observed stellar and wind parameters from Galactic, LMC and SMC O-stars, and analyzing the corresponding WLRs. Accounting for wind-inhomogeneities (see Sect. 7.3) in an approximate way, they derive $\dot{M} \propto (Z/Z_\odot)^{0.72\pm0.15}$, in very good agreement with theoretical predictions.

4. (Optically thick) Winds from WR- and Very Massive Stars†

From early on, the mass-loss rates of Wolf-Rayet stars posed a serious problem for theoretical explanations, since they are considerably larger (by a factor of ten and more) compared to mass-loss rates from O-stars of similar luminosity. Though Lucy & Abbott (1993) showed that line-overlap effects, coupled with a significantly stratified ionization balance, can help a lot to increase the mass-loss, it were Gräfener & Hamann (2005, 2006, 2007, 2008) who were the first to calculate consistent WR-wind models with the observed large mass-loss rates in parallel with high terminal velocities (2000 - 3000 km s^{-1}). They showed that a high Eddington-Γ is necessary to provide a low effective gravity and to enable a deep-seated sonic point at high temperatures. Then, a high mass-loss rate leading to an *optically thick* wind can be initiated either by the 'hot' Fe-opacity bump (around 160 kK, for the case of WCs and WNEs) or the cooler one (around 40 to 70 kK, for the case of WNLs)‡. The high initiated mass-loss rates can then be further accelerated by efficient multi-line scattering in a stratified ionization balance (see above), at least if the outer wind is significantly clumped.

Alternative wind models for Very Massive Stars in the range of 40 $M_\odot$ < M < 300 $M_\odot$ (i.e., including models which should display WR spectral characteristics) have been constructed by Vink et al. (2011) (but see also Pauldrach et al. 2012), who argue that for $\Gamma_{\mathrm{e}} > 0.7$ these line-driven winds become optically thick already at the sonic point, which enables a high $\dot{M}$ with a steeper dependence on Γ_{e} than for optically thin winds¶. Recently, Bestenlehner et al. (2014) investigated the mass-loss properties of a sample of 62 O, Of, Of/WN, and WNh stars within the Tarantula nebula, observed within the VLT FLAMES Tarantula Survey (Evans et al. 2011) and other campaigns. Indeed, they found a change in the slope of $d\log\dot{M}/d\log\Gamma_{\mathrm{e}}$ towards higher values. However, this change occurs already at $\Gamma_{\mathrm{e}} = 0.25$, i.e., (much) earlier than predicted by Vink et al. (2011), and more consistent with the models by Gräfener & Hamann (2008). Moreover, at least for Of and Of/WN stars there is still the possibility that the conventional CAK theory (which

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† see also Gräfener, this Volume
‡ The importance of these opacity bumps had already been pointed out by Nugis & Lamers (2002).
¶ The actual origin of this behavior is still unclear, but the authors of this review speculate about a higher efficiency of multi-line effects.

already includes a tight dependence on Γ_e, cf. Eq. 3.2) remains applicable, though with a lower α (0.53 instead of 0.63) than for typical O-stars. Thus, a number of issues still need to be worked out before these optically thick winds are fully understood.

5. Winds from Red Supergiants

Typical mass-loss rates from RSGs† range from 10^{-5} to 10^{-4} $M_\odot \mathrm{yr}^{-1}$, with terminal velocities on the order of 20 to 30 $\mathrm{km\,s}^{-1}$ ($\approx v_{\mathrm{esc}}/3$). Note that the atmospheres of RSGs consist of giant convective cells, with diameters scaling with the vertical pressure scale height (Stein & Nordlund 1998; Nordlund et al. 2009). Though the physics of RSG winds is still unknown, a similarity to the dust-driven winds from (carbon-rich = C-type) AGB-stars is often hypothesized‡. In these stars, stellar (p-mode) pulsations or large scale convective motions lead to the formation of outward propagating shock waves, that lift the gas above the stellar surface, intermittently creating dense, cool layers where dust may form. Similar to line-driven winds, these dust grains are radiatively accelerated, and drag the gas via collisions (for a review, see Höfner 2009).

Josselin & Plez (2007) alluded to some problems of this scenario when applied to RSG-winds. Namely, RSGs have only irregular, small-amplitude variations, which makes lifting the gas difficult in the first place, and moreover the dust seems to form much further out than in AGB-stars. On the other hand, they also pointed out that turbulent pressure related to convection helps in lowering the *effective* gravity¶ and thus the effective escape velocity, $g_{\mathrm{eff}} \approx g/(1 + \mu v_{\mathrm{turb}}^2/(2k_{\mathrm{B}}T))$, with μ the mean molecular weight, and suggested that radiative acceleration provided by molecular lines might help lift the material to radii where dust can form, though without any quantitative estimate. To conclude, further investigations and simulations to explain RSG-winds are urgently needed.

6. Continuum-driven winds

As a prelude to the following scenario, let us check in how far a hot stellar wind can be also driven by pure continuum processes, with major opacities due to bound-free absorption and Thomson scattering.

The simple picture. Since these opacities (per volume) scale mostly with linear density, the corresponding mass absorption coefficients (frequential and flux-weighted, see Eq. 2.3) do not display any explicit density dependence. Consequently, the *total* Eddington-Gamma,

$$\Gamma_{\mathrm{tot}}(r) = \frac{g_{\mathrm{rad}}(r)}{g_{\mathrm{grav}}(r)} = \frac{\kappa_{\mathrm{F}}(r)L}{4\pi cGM} \to \Gamma_{\mathrm{cont}}(r) \tag{6.1}$$

is density-independent as well (contrasted, e.g., to the case of line-driving), and it seems that basically *any* $\dot{M}$ might be accelerated‖ as long as $\Gamma_{\mathrm{cont}}(r)$ increases through the sonic point, with $\Gamma_{\mathrm{cont}}(r_s) = 1$, and remains beyond unity above.

As pointed out by Owocki & Gayley (1997), however, photon tiring (Sect. 2) decreases the available luminosity, $L(r) < L_*$, and thus the mass-loss rate is still restricted by

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† for structure and stellar parameters, see Wittkowski, this Volume

‡ According to Höfner (2008), dust-driving might be also possible in oxygen-rich (M-type) AGB-atmospheres, if prevailing conditions allow forsterite grains (Fe-free olivine-type, Mg_2SiO_4) to grow to sizes in the micro-meter range.

¶ As a side note, we might ask whether the well-known mass-discrepancy for O-type dwarfs might be related to the neglect of a potentially large turbulent pressure in present atmospheric models (see Markova & Puls, this Volume).

‖ since the equation of motion does no longer depend on ρ

$\dot{M} \leqslant \dot{M}_{\mathrm{tir}}$. Moreover, the complete process requires a substantial fine-tuning to reach and *maintain* $\Gamma_{\mathrm{cont}} \geqslant 1$ in (super-) sonic regions, and such a 'simple' continuum-driving is rather difficult to realize.

Super-Eddington winds moderated by porosity. Whilst, during 'quiet' phases, LBVs lose mass most likely via ordinary line-driving (cf. Sect. 3), they are also subject to one or more phases of much stronger mass loss. E.g., the giant eruption of η Car with a cumulative loss of $\sim 10\ M_\odot$ between 1840 and 1860 (Smith et al. 2003) corresponds to $\dot{M} \approx 0.1\text{-}0.5\ M_\odot \mathrm{yr}^{-1}$, which is a factor of 1000 larger than that expected from a line-driven wind at that luminosity. Such strong mass loss has been frequently attributed to a star approaching or even exceeding the Eddington limit.

Building upon pioneering work by Shaviv (1998, 2000, 2001b), Owocki et al. (2004) developed a theory of "porosity-moderated" continuum driving in such stars, where the dominating acceleration is still due to continuum-driving, mostly due to electron scattering, i.e., $\Gamma_{\mathrm{tot}} \to \Gamma_{\mathrm{cont}} \approx \Gamma_{\mathrm{e}} > 1$.

For stars near or (formally) above the Eddington limit, non-radial instabilities will inevitably arise and make their atmospheres inhomogeneous (clumpy), see, e.g., Shaviv (2001a). As noted by Shaviv (1998), the *porosity* of such a structured medium can reduce the radiation acceleration significantly (photons 'avoid' regions of enhanced density), by lowering the *effective* opacity in deeper layers, $\Gamma_{\mathrm{cont}}^{\mathrm{eff}} < 1$ for $r < r_{\mathrm{s}}$, thus enabling a quasi-hydrostatic photosphere, but allowing for a transition to a supersonic outflow when the over-dense regions become optically thin due to expansion, $\Gamma_{\mathrm{cont}}^{\mathrm{eff}} \to \Gamma_{\mathrm{cont}} > 1$ for $r > r_{\mathrm{s}}$.

The effective opacity in a porous medium consisting of an ensemble of clumps can be derived from rather simple arguments (Owocki et al. 2004), but here it is sufficient to note that for *optically thick clumps* and ρ-dependent opacities

$$\kappa_{\mathrm{F}}^{\mathrm{eff}}(r) = \frac{1}{h \langle \rho \rangle (r)} \ll \kappa_{\mathrm{F}}(r), \tag{6.2}$$

the *effective* opacity (here: the effective mass absorption coefficient) becomes grey and much smaller than the original one. In this equation, $\langle \rho \rangle (r)$ is the *mean* density of the medium, and h the so-called porosity length, which is the photon's mean free path for a medium consisting of optically thick clumps. Thus, $\kappa_{\mathrm{F}}^{\mathrm{eff}}(r)$ and consequently $\Gamma_{\mathrm{cont}}^{\mathrm{eff}}(r)$ have a specific density dependence around the sonic point ($\propto \langle \rho \rangle^{-1}$), and there is a corresponding, well-defined $\dot{M}$ which can be initiated and accelerated.

If one now considers clumps with a range of optical depths, distributed according to an exponentially truncated power-law with index α_{p} (Owocki et al. 2004), one obtains for sound speed a and pressure scale height H,

$$\dot{M}(\alpha_{\mathrm{p}} = 2) = \left(1 - \frac{1}{\Gamma_{\mathrm{cont}}}\right) \frac{H}{h} \frac{L_*}{ac} = \frac{\dot{M}(\alpha_{\mathrm{p}} = 1/2)}{4\Gamma_{\mathrm{cont}}}, \tag{6.3}$$

where the mass-loss rate for a canonical $\alpha_{\mathrm{p}} = 2$ model (obtained from a clump-ensemble that follows Markovian statistics, Sundqvist et al. 2012a; Owocki 2014) saturates for very high Γ_{cont}, but where the alternative $\alpha_{\mathrm{p}} = 1/2$ model can give an even higher mass loss for such cases, approaching the tiring limit under certain circumstances, and being on order the mass loss implied by the ejecta of η Car for an assumed $h \approx H$ (Owocki et al. 2004; Owocki 2014). Detailed simulations are needed here to further constrain the clump-distribution function and the porosity length in these models.

Nonetheless, together with quite fast outflow speeds, $v_\infty \approx \mathcal{O}(v_{\mathrm{esc}})$, and a velocity law corresponding to $\beta = 1$, the derived wind structure in such a porosity-moderated wind model may actually explain the observational constraints of giant outbursts in η Car and other LBVs. Moreover, the porosity model retains the essential scalings with gravity and

radiative flux (the von Zeipel theorem, cf. Sect. 7.1) that would give a rapidly rotating, gravity-darkened star an enhanced polar mass loss and flow speed, similar to the bipolar Homunculus nebula. Note that continuum driving (if mostly due to Thomson scattering) does *not* require the presence of metals in the stellar atmosphere. *Thus, it is well-suited as a driving agent in the winds of low-metallicity and First Stars, and may play a crucial role in their evolution.*

7. Additional physics in line-driven winds

In this last section we now return to line-driven winds, and discuss specific conditions and effects which might influence their appearance.

7.1. *Rapid rotation*

When stars rotate rapidly, their photospheres become oblate (because of the centrifugal forces, see Collins 1963; Collins & Harrington 1966), the effective temperature decreases from pole towards equator ('gravity darkening', von Zeipel 1924; Maeder 1999), and the winds from typical O-stars are predicted to become *prolate* (because of the larger illuminating polar fluxes), with a fast and dense polar outflow, and a slow and thinner equatorial one (Cranmer & Owocki 1995)†.

Whilst the basic effects of stellar oblateness and gravity darkening have been confirmed by means of interferometry (Domiciano de Souza et al. 2003; Monnier et al. 2007, see also van Belle, Meilland, Faes, this Volume), the predictions on the wind-structure of rapidly rotating stars have *not* been verified by observations so far (Puls et al. 2011 and references therein): first, only few stars in phases with extreme rotation are known (but they exist, e.g., Dufton et al. 2011), and second, the tools to analyze the atmospheres and winds (multi-D models!) of such stars are rare. Even though Vink et al. (2009) (see also Vink, this Volume) reported, analyzing data obtained by means of linear H_α spectro-polarimetry, that most winds from rapidly rotating O-stars are spherically symmetric (actually, they looked for disks), the asymmetry predicted for the winds of this specific sample should be rather low anyway.

Besides the polar-angle dependence of $\dot{M}$ induced by rotation, also the global mass-loss rate becomes modified; a significant increase, however, is only found for rapid rotation *and* a large Γ_e, with a *formal* divergence of $\dot{M}$ – which at least needs to be corrected for photon tiring effects – at the so-called $\Omega\Gamma$-limit. For details, see Maeder & Meynet (2000).

Finally, for near-critically rotating stars, mass loss might also occur via decretion disks (Krtička et al. 2011). The corresponding $\dot{M}$ from such decretion disks can be significantly *less* than the spherical, wind-like mass loss (aka 'mechanical winds') previously assumed in evolutionary calculations.

7.2. *Magnetic fields*

Recent spectropolarimetric surveys (mostly performed by the international Magnetism in Massive Stars, MiMeS, collaboration, e.g., Wade et al. 2012, and work done by S. Hubrig and collaborators, e.g., Hubrig et al. 2013; see also Grunhut, Morrell, this Volume) have revealed that roughly 10% of all massive stars have a large-scale, organized magnetic field in their outer stellar layers, on the order of a couple of hundred to several thousand Gauss.

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† All these effects become significant if the rotational speed exceeds roughly 70% of the critical one. Note also that cooler winds might retain an oblate structure, if the ionization balance decreases strongly from pole to equator, and the effective number of driving line increases in parallel.

The origin of these fields is still unknown, though most evidence points to quite stable fossil fields formed sometimes during early phases of stellar formation (Alecian et al. 2013). The interaction of these fields with a line-driven stellar wind has been investigated by ud-Doula, Owocki and co-workers in a series of publications (summarized in ud-Doula 2013, see also ud-Doula, this Volume). In the following, we concentrate on *slowly* rotating magnetic O-stars (spectroscopically classified as O f?p, Walborn 1972), which give rise to so-called 'dynamic magnetospheres' (Sundqvist et al. 2012b).

The most important quantity to estimate the influence of a magnetic field on the wind is the ratio of magnetic to wind energy,

$$\eta = \frac{B^2/8\pi}{\rho v^2/2} = \frac{B_*^2 R_*^2}{\dot{M} v_\infty^2} f(r) := \eta_* f(r), \tag{7.1}$$

with η_* the so-called confinement parameter. E.g., for a typical O-supergiant a B-field of 300 Gauss is required to reach $\eta_* = 1$ (for $\eta_* < 1$, the wind is not much disturbed). In the case of an η_* significantly greater than unity, to a good approximation the corresponding Alvén radius (which is the maximum radius for closed loops, and determines whether the wind is confined in such loops), can be expressed by $R_A \approx R_* \eta_*^{1/4}$.

An instructive example for a strongly confined wind can be found in, e.g., Sundqvist et al. (2012b), who performed hydro-dynamical simulations and Hα radiative transfer calculations for the prototypical Of?p star HD 191612, with a B-field of $\approx 2{,}500$ Gauss corresponding to $\eta_* = 50$. In this model, the field loops are closed near the equatorial plane ($R_A \approx 2.7 R_*$), and the confined wind is accelerated and channeled upwards from foot-points of opposite polarity. The flows collide near the loop tops, forming strong shocks with hard X-ray emission (Gagné et al. 2005). The shocked, very dense material then cools and becomes accelerated *inwards* by the gravitational pull, emitting strongly in, e.g., the optical H$_\alpha$ line. Whilst there are complex infall patterns along the loop lines, the field lines in polar regions are still open and the polar wind remains almost undisturbed. The *infalling* material of dynamical magnetospheres reduces the global mass-loss rates, for large η_* by a factor ~ 5 compared to non-magnetic winds (ud-Doula et al. 2008, analytic scaling relations available). Note also that the non-spherical structures require well-suited diagnostic methods.

7.3. Inhomogeneous winds – a few comments

We finish this review with few comments about the presence and impact of small-scale wind inhomogeneities (for a detailed discussion and references, also regarding large-scale inhomogeneities, see, e.g., Puls et al. 2008).

Over the last two decades, a multitude of direct and indirect indications has been accumulated that hot star winds are inhomogeneous on small scales, i.e., consist of over-dense (compared to the mean-density) clumps and an inter-clump material which is frequently assumed to be void (but see Šurlan et al. 2013; Sundqvist et al. 2014).

The most likely origin is the line-driven (or line-deshadowing) instability, which, for short-wavelength perturbations, can be summarized by $\delta g_{\rm rad}^{\rm lines} \propto \delta v$, giving rise to strong, outward propagating reverse shocks emitting in the X-ray regime, and a wind-structure consisting of fast and thin material (inter-clump matter), and dense, spatially narrow clumps moving roughly at the speed of smooth-wind models.

In dependence of the considered absorption process and wavelength, clumps can be optically thin ('micro-clumping') or optically thick ('macro-clumping'/ porosity, see Sect. 6). Moreover, line processes are prone to porosity in velocity space. To account for the effects of wind-inhomogeneities, a simplified treatment is typically employed (both within radiative transfer and when calculating the occupation numbers), based on a one- or two-

component description, with parameterized clumping properties such as volume-filling factors, over-densities, etc.

The major impact of these inhomogeneities regards the various mass-loss diagnostics. If clumps are optically thin for ρ^2-dependent opacities (e.g., H_α and IR diagnostics in O-stars), the actual rates turn out to be lower than derived from smooth-wind models. If clumps are optically thick and/or velocity porosity needs to be accounted for (e.g., UV-resonance lines), the final rates are larger than derived from models assuming optically thin clumps alone. On the other hand, mass-loss diagnostics based on bf-absorption (by the cool wind) of X-ray line emission from the above wind-embedded shocks is particularly robust, since it remains uncontaminated by inhomogeneities in typical O-star winds: first, there is no direct effect from micro-clumping, because the involved bf-opacities (per volume) scale with ρ, and second, porosity-effects are negligible or low (e.g., Cohen et al. 2010, 2013; Leutenegger et al. 2013; Hervé et al. 2013).

Comparing now 'observed' O-star mass-loss rates with theoretical ones (from Vink et al. 2000) used in stellar evolution, there is the following status quo†: These theoretical mass-loss rates are (i) a factor of 2-3 *lower* than those from standard H_α diagnostics assuming a smooth wind; (ii) roughly consistent with radio mass-loss rates assuming a smooth wind; (iii) a factor of 2-3 *larger* than recent diagnostics of Galactic O-stars accounting adequately for wind inhomogeneities (Najarro et al. 2011: mostly IR-lines; Cohen et al. 2014: absorbed X-ray line emission; Sundqvist et al. 2011, Šurlan et al. 2013, Sundqvist et al. 2014: UV-lines including velocity porosity+optical lines).

Of course, further investigations and larger samples are certainly required to prove this discrepancy, but particularly the X-ray results are a strong argument. Indeed, there are various possibilities for a potential overestimate of theoretical mass-loss rates, summarized by Sundqvist (2013). A rather promising explanation relates to (so far neglected) effects from velocity porosity when calculating the line force, which can lead to reduced theoretical mass-loss rates if already present in the lower wind (Sundqvist et al. 2014, see also Muijres et al. 2011).

In summary, there is still much to do, and the physics of massive star winds remains a fascinating topic!

Acknowledgements

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† to, e.g., clarify corresponding statements in the recent review by Smith (2014) that are somewhat simplified in this respect.

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Discussion

DE KOTER: We find that the line-driven winds of O stars at metallicities below that of the SMC do not seem to obey the theory of line driving: the mass-loss rates are higher (Tramper et al. 2011). What are your ideas on an explanation of this peculiar behaviour?

PULS: Actually, this is not completely clear. As will be shown in the next talk by M. García, there might be a bias on $\dot{M}$ due to variations in the ratio of $v_{\infty}/v_{\mathrm{esc}}$, and in this particular case the iron abundance (driving agent) might be higher than implied by the oxygen abundance.

DE KOTER: The winds of RSG are very difficult to understand, so currently we focus on understanding AGB winds. Though ideas have been put forward to explain the O-rich outflows, in my view there are still fundamental problems. These winds can only be driven through scattering on large $(0.3\,\mu\mathrm{m})$ grains and it is not clear at present how to grow such large grains in the warm molecular layer.

PULS: Completely agreed.

KHALAK: Can you explain the reasons for the excitation of atoms that increases line opacity and causes optically thick wind having $\Gamma_{\mathrm{e}} > 0.7$ in WR stars?

PULS: 1. Lines become more easily optically thick because of the higher density. Line overlap effects are particularly effective for optically thick lines. 2. Due to the higher wind density, the ionisation/excitation couples closer to the local electron temperature.

Thus there is an ionisation stratification (which again allows for efficient line overlap), and the occupation numbers of the excited levels increases as well (closer to Boltzmann).

WEIS: You showed how the giant eruption could be explained. Can that model also explain the bipolar structure?

PULS: Indeed, the radiative acceleration due to porosity-moderated continuum driving has a similar dependence on polar angle as in line-driven winds, for rapidly rotating stars/winds. Thus, also here a prolate structure is expected.

NOELS: Would it be possible to have a table with simple formulas of the mass-loss rates across the upper part of HR diagram, with the uncertainties (even large!)? This could appear "as of today" in this proceeding.

PULS: I will try my best, but only scaling relations can be provided in some cases (e.g., excluding RSGs). The absolute numbers of mass-loss rates are heavily debated, e.g. due to the impact of wind inhomogeneities. *Added after review has been finished:* Actally, such a table could not be provided, given the limited space and the state of our knowledge. Anyhow, all relevant references have been provided, but there is still strong disagreement on the uncertainties. And since factors of two *are* important, quoting disputed values with large error bars is not meaningful.

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