Massive Stars as Cosmic Engines
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Physical and Wind Properties of OB-Stars

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Abstract. In this review, the physical and wind properties of OB-stars are discussed, with particular emphasis on metallicity dependence and recent results from the FLAMES survey of massive stars. We summarize the relation between spectral type and $T_{\rm eff}$, discuss the status quo of the "mass-discrepancy", refer to the problem of "macro-turbulence" and comment on the distribution of rotational velocities. Observational constraints on the efficiency of rotational mixing are presented, and magnetic field measurements summarized. Wind properties are reviewed, and problems related to weak winds and wind-clumping highlighted.

Keywords. stars: early-type – stars: atmospheres – stars: fundamental parameters – stars: winds, outflows – stars: mass loss – stars: rotation – techniques: spectroscopic – surveys – magnetic fields

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1. Atmospheric models for hot stars

Most of our knowledge about the physical parameters of hot stars (effective temperatures, gravities, wind-properties, chemical composition of the outer layers) has (and will be) obtained by *quantitative spectroscopy*, i.e., the analysis of stellar *spectra* by means of atmospheric models. These have to be calculated in NLTE due to the intense radiation field and low densities in the line-forming regions. With respect to such models, the last IAU-symposium on massive stars in Lanzarote (2002) saw the begin of two important developments which are "standard" nowadays, namely the incorporation of metal-line blanketing and the inclusion and diagnostics of wind-clumping (see Sect. 7).

As a brief reminder, line blanketing summarizes the effects of the multitude of (E)UV metal lines which act as a "blanket", in such a way that the corresponding flux in the *outer* atmosphere is reduced, whilst both the mean radiation field and the electron temperature in the *inner* atmosphere increase due to backscattering and thermalization. Consequently, the degree of ionization increases as well (see Fig. 1), and diagnostic lines, such as from He, become weaker. Thus, in comparison to unblanketed models, *lower effective temperatures,* $T_{\rm eff}$ *(and gravities,* $\log g$*), are needed to fit the observations for a given spectral type.*

In Tab. 1, we have summarized the basic features and domains of applications of present state-of-the-art, NLTE, line-blanketed model atmosphere codes which have been/are used to analyze OB-stars (or are suitable to do so). There are two classes of codes: (i) those which refrain from (almost) any approximation within the model assumptions and thus need a substantial amount of computational time to calculate one model atmosphere (TLUSTY, CMFGEN, PoWR, PHOENIX); (ii) those which use certain approximations (mostly regarding the treatment of line-blanketing) such that the computational effort becomes considerably reduced (Detail/Surface, WM-basic, FASTWIND). Note that the applied approximations have been carefully tested within the corresponding domains of application, and that the agreement between most of the different codes is satisfactory, except for specific problems such as the strength of the He I singlet lines in later O-types (Najarro et al. 2006) or the ionizing fluxes below roughly 400 Å.

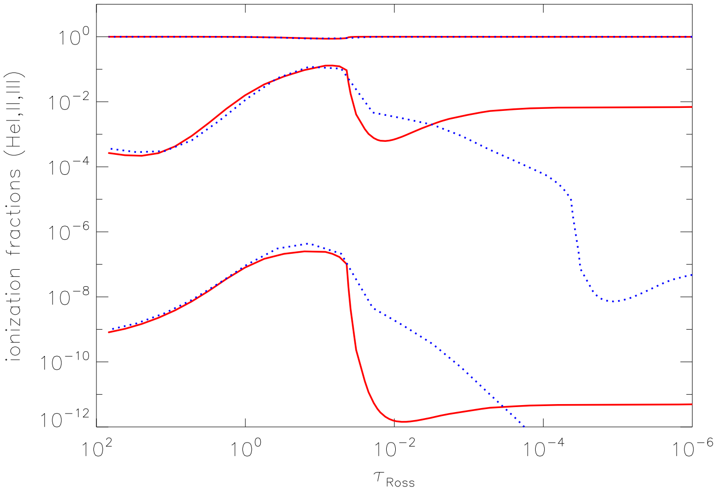

Figure 1. Ionization fractions of He I, He II and He III (from bottom to top) for an unblanketed model atmosphere at $T_{\rm eff}$=45kK and $\log g$=3.9 (dashed) and a blanketed one at $T_{\rm eff}$=40.5kK and $\log g$=3.7 (solid). In the region of photospheric line formation ($\tau_{\rm Ross} > 10^{-2}$), both models predict almost identical occupation numbers and synthetic line profiles, thus requiring a reduction of $T_{\rm eff}$= 4,500 K due to the effects of line-blanketing. Adapted from Repolust et al. (2004).

2. Effective temperatures of Galactic OB-stars

Since 2002, some 20 spectroscopic analyses of *Galactic* OB stars (excluding Galactic Centre objects, see Martins et al. this volume) of various luminosity classes have been

Table 1. Basic features and domains of applications of present state-of-the-art, NLTE, line-blanketed model atmosphere codes. Responsible authors in brackets.

	Detail/Surf. (Butler)	TLUSTY (Hubeny)	CMFGEN (Hillier)	WM-basic (Pauldrach)	FASTWIND (Puls)	PoWR (Hamann)	PHOENIX (Hauschildt)
geometry	plane-parallel	plane-parallel	spherical	spherical	spherical	spherical	spherical/ pl.-parallel
blanketing	LTE	yes	yes	yes	approx.	yes	yes
line transfer	observer's frame	observer's frame	comoving frame (CMF)	Sobolev	CMF	CMF	CMF/ obs.frame
temperature structure	radiative equilibrium	radiative equilibrium	radiative equilibrium	e^- thermal balance	e^- thermal balance	radiative equilibrium	radiative equilibrium
photosphere	yes	yes	from TLUSTY	approx.	yes	yes	yes
diagnostic range	no limitations	no limitations	no limitations	UV	optical/IR	no limitations	no limitations
major application	hot stars with negl. winds	hot stars with negl. winds	OB(A)-stars, WRs, SNe	hot stars w. dense winds, ion. fluxes, SNe	OB-stars, early A-sgs	WRs	stars below 10 kK, SNe
comments	no wind	no wind	start model required	no clumping	explicit/ backgr. elements		molecules included, no clump.
execution time	few minutes	hours	hours	1 to 2 h	few min. to 0.5 h	hours	hours

Table 2. Spectroscopic NLTE analyses of Galactic (without Centre) OB-stars since 2002

from	reference	objects	code	$\dot{M}$
UV	Bianchi & Garcia (2002)	O-stars	WM-basic	yes
	Garcia & Bianchi (2004)	O-stars	”	yes
UV + optical	Bouret et al. (2005)	O-stars	CMFGEN	yes
	Martins et al. (2005)	O-dwarfs	”	yes
	Bianchi et al. (2006)	O-stars	WM-basic + CMFGEN	yes
optical	Herrero et al. (2002)	OB-stars (Cyg-OB2)	FASTWIND	yes
	Repolust et al. (2004)	O-stars	”	yes
	Mokiem et al. (2005)	O-stars (genetic algorithm)	”	yes
	Simon-Diaz et al. (2006)	OB-stars (Trapezium)	”	yes
	Urbaneja (2004)	B-supergiants	FASTWIND	yes
	Crowther et al. (2006)	B-supergiants	CMFGEN	yes
	Przybilla et al. (2006)	AB-supergiants	Detail/Surface	no
	Lefever et al. (2007)	B-supergiants (period. variable)	FASTWIND	yes
	Trundle et al. (2007)	B-stars (FLAMES: MW + MCs)	TLUSTY	no
	Hunter et al. (2007)	B-stars (FLAMES: MW + MCs)	”	no
	Markova & Puls (2008)	B-supergiants	FASTWIND	yes
NIR	Repolust et al. (2005)	O(B)-stars	FASTWIND	yes

performed, using different wavelength ranges and different atmosphere codes (see Tab. 2, ‘MW’ = Milky Way, ‘MC’ = Magellanic Clouds). Combining the results from several investigations, Martins et al. (2005), Trundle et al. (2007) and Markova & Puls (2008, see also Lefever et al. 2007) derived new spectral-type-$T_{\rm eff}$ calibrations for O and B stars, which are displayed in Fig. 2. Whereas for O-stars a linear relation provides a reasonable representation, for B-stars the relation can be described by a 3rd order polynomial, at least for supergiants. Compared to the previous scales by Vacca et al. (1996) and

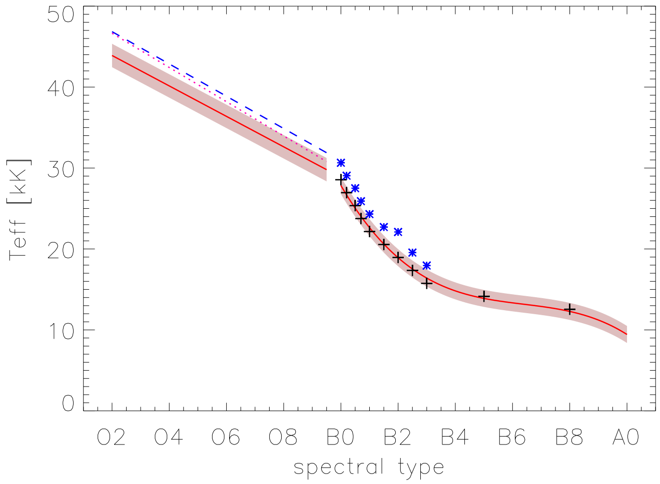

Figure 2. Spectral-type-$T_{\rm eff}$ calibrations for OB-stars. *O-star relations* from Martins et al. (2005) based on own data and data from Herrero et al. (2002); Repolust et al. (2004). Dashed, dotted and solid lines refer to dwarfs, giants and supergiants, respectively. *B-star relations* from Trundle et al. (2007): asterisks and plus-signs refer to dwarfs and supergiants. Overplotted is the corresponding relation (solid) as suggested by Markova & Puls (2008), using own data and data from Crowther et al. (2006); Lefever et al. (2007); Urbaneja (2004); Przybilla et al. (2006). The hatched area refers to the typical uncertainty of the calibrations.

Table 3. NLTE analyses of MC OB-stars since 2002 (without FLAMES). 'dw' = dwarfs, 'sg' = supergiants.

from	reference	objects	code	$\dot{M}$
UV	Martins et al. (2004)	SMC O-dw	CMFGEN	yes
UV + optical	Crowther et al. (2002)	MC O-sg	CMFGEN	yes
	Hillier et al. (2003)	SMC O-sg	”	yes
	Bouret et al. (2003)	SMC O-dw	”	yes
	Evans et al. (2004)	MC OB-sg	”	yes
	Heap et al. (2006)	SMC O-stars	TLUSTY	no
optical	Massey et al. (2004)	MC O-stars	FASTWIND	yes
	Massey et al. (2005)	”	”	yes
	Trundle et al. (2004)	SMC B-sg	FASTWIND	yes
	Trundle & Lennon (2005)	”	”	yes
	Dufton et al. (2006a)	SMC B-sg	TLUSTY	no

Table 4. Targets of the VLT-FLAMES survey of massive stars. Ages from publications as cited in Tab. 5.

Gal.	Cluster	Age	#O	#B
MW	NGC 3293	10-20 Myr	-	99
MW	NGC 4755	10-15 Myr	-	98
MW	NGC 6611	1-4 Myr	13	40
LMC	NGC 2004	10-25 Myr	4	107
LMC	LH9/10	1-5 Myr	44	76
SMC	NGC 330	10-25 Myr	6	109
SMC	NGC 346	1-3 Myr	19	85
total			86	615

McErlean et al. (1999) based on *unblanketed* and "wind-free" models, the new scale is cooler, by 6,000 K for the earliest O-dwarfs to 2,000 K for late O-/early B-supergiants, due to the inclusion of line-blanketing and wind effects.

3. OB-stars in the LMC/SMC and the FLAMES project

Similar investigations have been performed for OB-stars in the Magellanic Clouds, in particular to study metallicity effects on, e.g., effective temperatures and mass-loss rates (Z(LMC) $\approx 0.5 Z_{\odot}$, Z(SMC) $\approx 0.2 Z_{\odot}$, see Mokiem et al. 2007b and references therein). Tab. 3 summarizes important contributions since 2002, leaving aside the most recent results from the FLAMES survey (see below). Massey et al. (2004, 2005) investigated a large sample of MC O-stars by means of FASTWIND, and provided a spectral-type-$T_{\rm eff}$ calibration for the SMC. For the LMC, the situation remained unclear, since their sample was concentrated towards the hottest objects, O2-O4. Overall, it turned out that for a given spectral sub-type, $T_{\rm eff}$(SMC dw) $>$ $T_{\rm eff}$(MW dw) $\approx$ $T_{\rm eff}$(SMC sg) $>$ $T_{\rm eff}$(MW sg), where the $T_{\rm eff}$-scale for SMC O-stars differs much less from the unblanketed Vacca et al. (1996) calibration than the scale for their Galactic counterparts ('dw' = dwarfs, 'sg' = supergiants). This finding has been attributed to less blanketing and weaker winds due to the lower metallicity. For dwarfs (and also giants), the derived results are in good agreement with investigations of *different* samples performed with CMFGEN, whereas MC supergiants analyzed by means of CMFGEN turned out to be significantly cooler, even cooler than implied by the Galactic scale. Note, however, that a large number of these discrepant objects are somewhat extreme, thus implying significant mass-loss effects (lower $T_{\rm eff}$ due to strong *wind*-blanketing and wind-emission). Heap et al. (2006) analyzed a sample of SMC O dwarfs and giants, and compared their results (using TLUSTY) with other investigations. In summary, they found a fair agreement (though they stress the large scatter of $T_{\rm eff}$ within individual sub-types), except for data derived by WM-basic, which seem to suggest systematically cooler temperatures than all other studies.

One of the most important recent projects on OB-stars was the **VLT-FLAMES survey of massive stars** (FLAMES = Fibre Large Array Multi-Element Spectrograph). By means of this ESO *Large Programme* (PI: Stephen Smartt, Belfast), the massive stellar content of 8 Galactic/MC clusters (young and old, see Tab. 4) has been spectroscopically investigated, in order to answer urgent questions regarding (i) rotation and abundances (rotational mixing), (ii) stellar mass-loss as a function of metallicity and (iii) fraction and impact of

Table 5. FLAMES-related investigations

Evans et al. (2005)	overview Galactic clusters
Evans et al. (2006)	overview MC clusters
Mokiem et al. (2006)	SMC O-/early B-stars (parameters, rotation,. . .)
Mokiem et al. (2007a)	LMC O-/early B-stars (parameters, evolution,. . .)
Mokiem et al. (2007b)	empirical metallicity dependence of mass-loss rates/ WLR for O-/early B-stars
Dufton et al. (2006b)	Galactic OB stars (parameters, distribution of rotational velocities, cluster ages)
Hunter et al. (2007)	early B-stars in “young” clusters: surface chemical composition
Trundle et al. (2007)	early B-stars in “older” clusters: surface chemical composition, $T_{\rm eff}$-scale
Hunter et al. (2008a)	rotation and evolution of O/ early B-stars in the MCs
Hunter et al. (2008b)	rotation and N-enrichment: the role of rotation

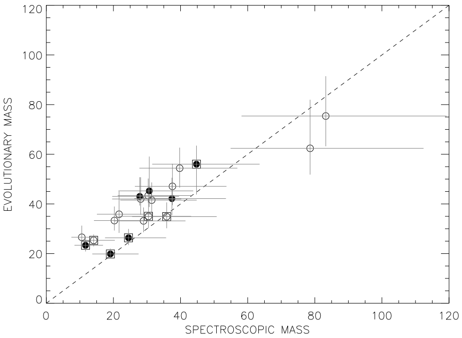

Figure 3. Spectroscopic and evolutionary masses for Galactic O-stars. Squares: rapid rotators; filled: objects with strongly enhanced He. A “real” discrepancy (accounting for errors) is present only for three low-mass stars, but a “mild” discrepancy can still be observed. From Repolust et al. (2004).

binarity. Tab. 5 gives an overview on the various publications which have appeared until now, and we will illuminate important findings in the remainder of this review.

Using a genetic algorithm on top of FASTWIND model atmospheres to obtain the stellar/wind parameters from profile fitting in an objective way (for details, see Mokiem et al. 2005), Mokiem et al. (2006, 2007a) studied the O-/early B-star targets of the FLAMES survey in the SMC and LMC, respectively. Among other results, they confirmed the basic results from Massey et al. (2004, 2005), but refined the spectral-type-$T_{\rm eff}$ scale, particularly with respect to the LMC objects. They showed that at least for O-dwarfs (which are not “contaminated” by additional wind-effects), the effective temperatures for a given spectral sub-type decrease as a function of increasing metallicity, i.e., $T_{\rm eff}$(SMC) $>$ $T_{\rm eff}$(LMC) $>$ $T_{\rm eff}$(MW). A similar result was derived by Trundle et al. (2007) for the FLAMES B-type dwarfs, in this case based on TLUSTY model atmospheres. Interestingly, their $T_{\rm eff}$-scale for B-*supergiants* (which, for Galactic objects, coincides with the calibration provided by Markova & Puls 2008, see Fig. 2) seems to be independent on metallicity. This was interpreted by Markova & Puls (2008) as a consequence of applying, for SMC B-sgs, the (re-)classification scheme by Lennon (1997) which already accounts for the lower metallicity.

4. Masses – still a mass-discrepancy?

An important question concerns the present status of the so-called “mass-discrepancy”. Herrero et al. (1992) noted a large discrepancy between masses of *evolved* (Galactic) O-stars derived either spectroscopically (via $\log g$) or via evolutionary calculations, where the latter method resulted in systematically higher values, by roughly a factor of two. Since the spectroscopic analyses had been performed using plane-parallel, unblanketed H/He model-atmospheres (standard at that time), the question arises whether the discrepancy would still be present when the objects were analyzed with more “modern” tools. (Note that even though the inclusion of stellar rotation in recent calculations affects the evolutionary masses, this modification lies well below a factor of two, at least if rotation is not fast enough to result in chemically homogeneous evolution). Fig. 3 shows the outcome of such a re-investigation of the original sample, via blanketed spherical models with winds (Repolust et al. 2004). Indeed, the disagreement has decreased in all cases, and a "real" discrepancy, i.e., non-overlapping error bars, is present only for three low mass objects. However, a milder form seems to have survived, namely that a large fraction of the sample (mostly dwarfs) is located in parallel to the one-to-one relation, shifted by roughly 10 $M_\odot$ upwards in the vertical direction. Similar findings have been reported for LMC and SMC O-/early B-stars (see Massey et al. 2005; Mokiem et al. 2006, 2007a; Heap et al. 2006), and the common result is that the spectroscopic/evolutionary masses of O-*supergiants* seem to agree now, whereas discrepancies are found for dwarfs and giants.

A comprehensive illustration of the (present) problem has been provided by Mokiem et al. (2007a, their Fig. 10) who summarize the mass-discrepancy for Galactic, LMC and SMC O-stars *as a function of Helium content*, i.e, evolutionary status. This figure clearly shows no indication of any discrepancy for all supergiants and bright giants, independent of their Helium enrichment. Insofar, the improvements in atmospheric modeling, evolutionary calculations and spectral analysis techniques seem to have been successful, and the authors argue that the evolution of class I-II objects appears to be "well understood". (These objects are found in that region of the HR-diagram where they have evolved along relatively simple evolutionary tracks). On the other hand, Mokiem et al. find at least a trend that the mass-discrepancy seen for dwarfs and giants increases with increasing He-content, i.e., evolution. They argue that this might be an indication of efficient mixing in the main sequence phase, leading to (near-)chemically homogeneous evolution. Let us point out, however, that there is still a significant number of objects with a normal (or even depleted) He-content and a large discrepancy, which has to be explained in the near future.

5. Macro-turbulence, rotation and rotational mixing

Macro-turbulence. Investigating the efficiency of rotational mixing requires the knowledge of stellar rotational speeds, which can be obtained (at least statistically) from the projected rotational velocities, $v \sin i$, derived primarily from metal lines. For quite a while, however, there have been certain indications of significant broadening processes in addition to rotation (Conti & Ebbets 1977; Lennon et al. 1993; Howarth et al. 1997). Using high resolution, high S/N spectroscopy of early-type B-supergiants, Ryans et al. (2002) showed that this broadening can be described by a *Gaussian* (or similarly shaped) profile, with typical velocities of the order of 50 $\mathrm{km\,s^{-1}}$ for the considered objects. In analogy with solar terminology, this process has been denoted by "macro-turbulence", $v_{\rm mac}$.

Fig. 4 clearly shows the presence of such a process, though it turns out that the derivation of unique values for $v_{\rm mac}$ and $v \sin i$ *in parallel* is difficult using profile fitting methods alone. Fortunately, it is possible to derive an independent estimate of $v \sin i$ from the "first" minimum appearing in the *Fourier transform* of the spectrum. This method was firstly suggested by Carroll (1933), and recent implementations and applications to hot stars have been presented by Simon-Diaz et al. (2006) and Simon-Diaz & Herrero (2007). (For a rigorous discussion, see Gray 2005). Having derived $v \sin i$, the macro-turbulence can be obtained from profile fitting or from the *shape* of the Fourier transform.

Using such an approach, large values of $v_{\rm mac}$ (of the same order as $v \sin i$) have been derived for OB-supergiants (Dufton et al. 2006a; Lefever et al. 2007; Markova & Puls 2008). Simon-Diaz & Herrero (2007) showed that previous estimates of $v \sin i$ for O-supergiants have been overestimated, by roughly 20-40 $\mathrm{km\,s^{-1}}$. Regarding dwarfs, the present sit-

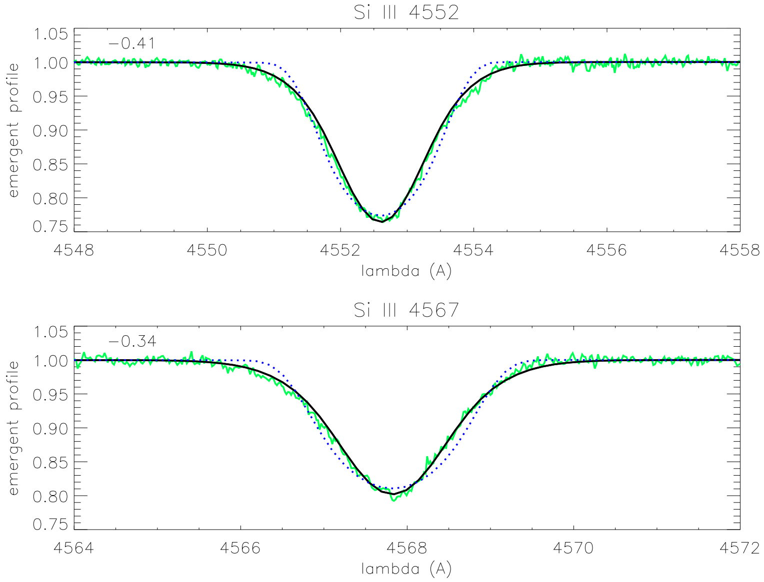

Figure 4. High resolution Si III spectra from HD 89767 (B0Ia), observed with CES@CAT (R = 70,000, S/N $\approx$ 250). Dotted: Best fitting profile with rotational broadening alone ($v \sin i = 80$ km s^{-1}). Large discrepancies are visible in the wings and cores. Solid: Perfect fit using $v \sin i = 47$ km s^{-1} and $v_{\rm mac} = 80$ km s^{-1} in parallel. Observations and data from Lefever et al. (2007).

uation remains unclear. Irrespectively, the presence of a Gaussian shaped broadening strongly points to the **presence of symmetrically distributed, deep seated and highly supersonic velocity fields**, in stark contrast to our present understanding of stellar photospheres. This finding needs urgent clarification, and one might speculate about a relation to stellar pulsations and/or winds.

Rotation. Having derived the observed distribution of $v \sin i$ for a large sample of stars, constraints on the intrinsic distribution of rotational speeds, $v_{\rm rot}$, can be drawn (for the methodology, see Chandrasekhar & Münch 1950), which, for typical sample sizes, is not unique though. Dufton et al. (2006b), Mokiem et al. (2006) and Hunter et al. (2008a) have analyzed the $v \sin i$ distribution of the Galactic, SMC and LMC/SMC FLAMES clusters, respectively. From the B-star sample, Hunter et al. (2008a) find a clear difference for LMC and SMC objects, namely that SMC objects (lower metallicity) rotate faster. Obvious reasons are weaker winds (less braking) and smaller stellar radii. Translated to the *intrinsic* $v_{\rm rot}$ distribution, this can be approximated by a Gaussian, with peaks at 100 km s^{-1} for the LMC and 175 km s^{-1} for the SMC (Hunter et al. 2008a). The latter value is consistent with the O-/early B-star results from Mokiem et al. (2006).

Comparison with evolutionary models: efficiency of rotational mixing. In addition to measuring $v \sin i$, Hunter et al. (2008b) have derived surface abundances, in particular those of nitrogen, which is a key-element for stellar evolution. Combining these data with similar data from slow rotators (Hunter et al. 2007; Trundle et al. 2007) obtained by identical methods/codes (i.e., the complete dataset is internally consistent), they were able to investigate the efficiency of rotational mixing for LMC B-stars, by plotting nitrogen abundance vs. $v \sin i$, and overplotting corresponding evolutionary tracks for different $v_{\rm rot}$ based on recent models from Yoon & Langer (2005). These models have been calibrated with respect to the efficiency of rotational mixing and overshooting parameter to reproduce the observed behaviour of the *bulk* of the objects in this

"Hunter-diagram" (at and slightly above the LMC nitrogen baseline abundance, with $v_{\rm rot}$ not larger than roughly 200 $\rm km\,s^{-1}$). In the following, we will concentrate on the results of this comparison for core-hydrogen burning objects alone, which have been found to be located at gravities $\log g \geqslant 3.2$, where objects with $\log g \geqslant 3.7$ are less evolved and the rest is evolved. By comparing the observed positions with the evolutionary tracks, two groups of problematic objects have become visible:

Group 1 consists of rapidly rotating, evolved objects with rather *weak* nitrogen enhancement, i.e., little mixing. According to theory, such objects should be much more enriched, at least if they were single stars. Though the observed low degree of N-enhancement might be the outcome of close binary evolution (Petrovic et al. 2005), no indication of binarity (from radial velocity variability) has been found at least for three objects.

Group 2 objects are slow rotators with significant N-enrichment. Since this group comprises a large number of objects, it is very unlikely to see all of them pole-on; consequently, these objects provide a real challenge for stellar evolution. Again, they might be the product of binary evolution, but Hunter et al. invoke also a possible correlation with magnetic fields.

The reason for doing so is based on the analysis of slowly rotating Galactic β Cep stars by Morel et al. (2006), who found significant nitrogen-enhancement in four out of their ten sample objects, i.e., a similar situation as for the *Group 2* objects. The authors argue that an origin due to pulsations is unlikely. Interestingly now, three of these four objects have strong magnetic fields, of order of several hundred Gauss (see Tab. 6). For the non-enhanced objects, on the other hand, no indication for B-fields has been found.

Thus, Hunter et al. (2008b) conclude that rotational mixing seems to be not the only mixing process, since (i) it is not efficient at low $v_{\rm rot}$ and (ii) it is unclear if it is the main mixing process at high $v_{\rm rot}$, due to the presence of *Group 1* objects. Binarity and/or magnetic fields might help to explain the observed distribution of nitrogen abundances. Finally, note that Mokiem et al. (2006) in their SMC O-star analysis found three slowly rotating OVz stars with strongly enhanced Helium content, which might originate from the same process as present in the *Group 2*-stars.

6. Magnetic fields

So, what is the probability to find a sufficient number of massive stars with strong magnetic fields? Until 2006, only *eight* magnetic massive stars (including the nitrogen enriched β Cep stars from Morel et al. 2006) were known, excluding Ap/Bp stars (see Tab. 6, where B_p is the magnetic field strength in Gauss at the magnetic pole of the approximately dipolar field). Interestingly, all of these stars display certain peculiarities in their spectra. The listed field strengths have been derived by means of Stokes-V spectropolarimetry, collected with the MuSICoS polarimeter (Donati et al. 1999) mounted at the Telescope Bernard Lyot(TLB), Pic du Midi and the AAT, with ESPaDOnS@CHFT and with FORS1@VLT.

Recently, the number of analyzed objects considerably increased due to the thesis work by Schnerr (2007) and co-workers. This team has surveyed 25 OB-stars at various phases with MuSiCoS@TBL, and additional 11 O-stars at three different phases with FORS1@VLT. No evidence for magnetic fields has been found in any target, with 1-σ upper limits of $\sim$40-100 Gauss for the longitudinal field averaged over the stellar disk. A similar result has been obtained for 12 A-supergiants by Verdugo et al. (2003).

In conclusion, for non-peculiar hot stars, B is either weak and/or acts only on small

Table 6. Compilation of magnetic massive stars known until 2006, from Schnerr (2007). For references, see same work.

Star	Sp. Type	B_p
θ^1 Ori C	O4-6V	1100 ± 100
HD 191612	O6-8	~ 1500
τ Sco	B0.2V	~ 500
ξ^1 CMa †	B1III	~ 500
β Cep †	B1IV	360 ± 40
V2052 Oph †	B1V	250 ± 190
ζ Cas	B2IV	340 ± 90
ω Ori	B2IVe	530 ± 200

† nitrogen enriched β Cep stars from Morel et al. (2006)

Table 7. Mass-loss rates from H_α alone.

reference	objects	method
Lamers & Leitherer (1993)	Gal. O-stars	approx.
Puls et al. (1996)	Gal./MC O-stars	approx.
Kudritzki et al. (1999)	Gal. BA-sg	unblanketed model atm.
Markova et al. (2004)	Gal. O-stars	approx.

scales (spots). To cite Donati et al. (2006), "magnetic fields (at least those of moderate to high intensity) are not a common feature of most hot stars, but rather a rare occurrence."

Nevertheless, even weak fields can have some impact, at least on the stellar winds from massive stars. As outlined by ud-Doula & Owocki (2002), the decisive quantity is the so-called confinement parameter, η_*, which measures the ratio of the magnetic to the wind energy at the magnetic equator,

$$\eta_* = \frac{E_B}{E_{\rm wind}}\,(\text{magn. equator}) \approx 0.19 \frac{B_{100}^2(\text{polar}) R_{10}^2}{\dot{M}_{-6} v_8},$$

when B_p is measured in units of 100 Gauss, the stellar radius, R, in units of 10 $R_\odot$, the mass-loss rate, $\dot{M}$, in units of $10^{-6}\,\mathrm{M}_\odot$/yr and the terminal velocity, v, in units of 1000 km s^{-1}. If $\eta_* \geqslant 1$, magnetic fields have a significant or strong effect on the wind, leading to the formation of a disk and strong shocks. But even if $\eta_* \approx 0.1$, B still has some impact, leading to density enhancements at the magnetic equator. Two examples: to reach $\eta_* = 1$ for the strong wind of ζ Pup ($R_{10} \approx 2, \dot{M}_{-6} \approx 4, v_8 \approx 2$), a considerable field strength of $B_p \approx 320$ Gauss is required. For a rather weak wind with $\dot{M} = 10^{-8}\,\mathrm{M}_\odot$/yr and $v_\infty = 2000$ km s^{-1}, on the other hand, $\eta_* = 1$ is already reached for $B_p \approx 32$ Gauss, i.e., well beyond present detection capabilities!

7. Wind properties of OB stars at different metallicities

Overview. Wind-properties of Galactic/MC OB-stars (primarily mass-loss rates, $\dot{M}$, and velocity field parameters, β) have been determined by numerous investigations, from H_α alone (Tab. 7) and other spectral ranges (Tab. 2 and 3). In most cases, terminal velocities, v_∞, have been adopted from UV-measurements and/or calibrations (see Kudritzki & Puls 2000 and references therein). Wind-momentum luminosity relations (WLR) have been inferred and compared with theoretical predictions, mostly from Vink et al. (2000, 2001). Remember that radiation driven wind theory predicts a power-law relation between modified wind-momentum rate, $D_{\rm mom}$, and stellar luminosity,

$$\log D_{\rm mom} = \log(\dot{M} v_\infty R_\star^{1/2}) \approx x \log(L/L_\odot) + D(\text{metallicity, spectral type})$$

(see Kudritzki & Puls 2000 and references therein). The most important results of these studies can be summarized as follows: (i) for given luminosity, mass-loss rates of SMC-stars are lower than for their Galactic counterparts, consistent with theory. (ii) For O-/early B-stars, the theoretical WLR is met, except for O-sgs with rather dense winds, where the "observed" wind-momenta appear as "too large" (explained by wind-clumping, see below), and for low luminosity O-dwarfs, where the "observed" wind-momenta are considerably lower than predicted (denoted as the "weak wind problem"). (iii) B-sgs located *below* the so-called bi-stability jump (i.e., with $T_{\rm eff} < 22$ kK, Vink et al. 2000) show lower wind-momenta than predicted (Crowther et al. 2006; Markova & Puls 2008).

The **metallicity dependence** of the winds from O-/early B-stars could be quantified due to the large sample provided by the FLAMES survey. From the analysis of the SMC/LMC objects by Mokiem et al. (2006) and Mokiem et al. (2007a), respectively, and in combination with data from previous investigations, Mokiem et al. (2007b) derived the WLRs for Galactic, LMC and SMC objects, with rather small 1-σ confidence intervals, and showed that the wind-momenta strictly increase with metallicity Z (i.e., the WLR of the LMC lies in between the corresponding relations for the MW and the SMC). Using $Z(\mathrm{LMC}) \approx 0.5 Z_\odot$, $Z(\mathrm{SMC}) \approx 0.2 Z_\odot$, and allowing for a "clumping correction", they obtained $\dot{M} \propto Z^{0.72 \pm 0.15}$, which is in very good agreement with theory. Further details can be found in de Koter et al., this volume.

The weak wind problem (see also Hillier, this volume). Bouret et al. (2003) were the first to note a significant discrepancy between observed and predicted mass-loss rates for late-type O-dwarfs (the observed ones being lower), in their sample of SMC/NGC346 objects. Martins et al. (2004) observed a similar disagreement, in this case for extremely young O-dwarfs in SMC/N81, where the differences turned out to be larger than a factor of 10. Though investigating various reasons for this failure of theory, none turned out to be conclusive. The same problem was found by Martins et al. (2005) for Galactic O-dwarfs with $\log L/L_\odot < 5.2$. To date, this discrepancy still lacks any explanation, but one might speculate about a relation to magnetic fields, since only low field strengths are necessary to induce significant effects on the wind topology (see above). Note also that τ Sco (B0.2V) with a very large B-field (Tab. 6) is probably affected by the weak wind problem.

Clumping in hot star winds was the objective of an international workshop held in Potsdam 2007. The following is only a *very* brief summary of the status quo. For details, the reader is referred to the corresponding proceedings (Hamann et al., eds., 2008).

During recent years, there have been various direct and indirect indications that hot star winds are not smooth, but clumpy, i.e., that there are small scale density inhomogeneities which redistribute the matter into over-dense clumps and an almost void inter-clump medium. Theoretically, such inhomogeneities have been expected from the first hydrodynamical wind simulations on (Owocki et al. 1988), due to the presence of a strong instability inherent to radiative line-driving. This can lead to the development of strong reverse shocks, separating over-dense clumps from fast, low-density wind material. Interestingly, however, the column-depth averaged densities and velocities remain very close to the predictions of stationary theory. (For more recent results, see Runacres & Owocki 2002, 2005 (1-D) and Dessart & Owocki 2003, 2005 (2-D)).

In order to treat wind-clumping in present atmospheric codes, the standard assumption (so far) relates to the presence of optically *thin* clumps and a void inter-clump medium. A consistent treatment of the disturbed velocity field is still missing. The over-density (w.r.t. average density) inside the clumps is described by a "clumping factor", $f_{\rm cl}$. The most important consequence of such a structure is that any $\dot{M}$ derived from ρ^2-diagnostics (H_α, radio) using *homogeneous models* needs to be scaled down by a factor of $\sqrt{f_{\rm cl}}$.

Based on this approach, Crowther et al. (2002); Hillier et al. (2003); Bouret et al. (2003, 2005) derived clumping factors of the order of 10...50, with clumping starting at or close to the wind base. From these values, a reduction of (unclumped) mass-loss rates by factors 3...7 seems to be necessary. The *radial* stratification of the clumping factor has been studied by Puls et al. (2006), from a simultaneous modeling of H_α, IR, mm and radio observations. They found that, at least in dense winds, clumping is stronger in the lower wind than in the outer part, by factors of 4…6, and that unclumped mass-loss rates need to be reduced *at least* by factors 2…3.

Even worse, the analysis of the FUV P V-lines by Fullerton et al. (2006) seems to imply factors of 10 or larger, which would have an enormous impact on massive star evolution. However, as suggested by Oskinova et al. (2007), the analyses of such optically *thick* lines might require the consideration of wind "porosity", which reduces the effective opacity at optically thick frequencies (Owocki et al. 2004, Cohen, this volume). Consequently, the reduction of $\dot{M}$ as implied by the work from Fullerton et al. might be overestimated, and factors similar to those cited above (around three) are more likely.

8. Summary

In this review, we have highlighted important findings and conclusions regarding the physical and wind properties of OB-stars, which have been obtained since the last massive star symposium in 2002:
1. The $T_{\rm eff}$-scale of OB-stars has become lower due to the effects of line- and wind-blanketing accounted for in present-day atmospheric models. **2.** Particularly for supergiants, there is a significant spread in $T_{\rm eff}$ for a given spectral sub-type, probably related to different degrees of mass-loss. **3.** For a given spectral sub-type, the effective temperatures of OB-dwarfs increase with decreasing metallicity. **4.** The "mass-discrepancy" has been solved for O-sgs, but there are still problems for dwarfs and giants. **5.** The physics (and consequences) of *supersonic* macro-turbulence detected in OB-sgs needs to be understood. **6.** The $v_{\rm rot}$-distribution of OB-stars peaks at higher values for samples with lower metallicities. **7.** Rotational mixing alone might not be able to explain the observed nitrogen-abundances in OB-stars. Binarity and/or magnetic fields might help. **8.** But: Magnetic fields of *significant* strength seem to be absent in *normal* OB stars, though weak fields can affect weak winds. **9.** Mass-loss rates scale with metallicity as $\dot{M} \propto Z^{0.72\pm0.15}$. **10.** The weak-wind problem needs to be clarified. **11.** Mass-loss rates derived from homogeneous models need to be scaled down, due to the presence of wind-clumping. Factors of three are rather likely.

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Discussion

MEYNET: Regarding the Hunter diagram. Two Remarks:
1. It would have been surprising that present rotating models would successfully reproduce all the observations in all details. My feeling is that rotating models can account for the general trends and the bulk of the observed data.
2. The Hunter diagram is not very easy to analyze. It contains stars of different initial mass, of different ages, the inclination makes the things also complicate to interpret. Thus I would be more careful in the conclusions about the difficulties of rotational mixing based on this diagram.

PULS: I've not established the diagram, I have only reported on this result which is, in my opinion, a very important one. I agree that regarding the stars with high vsini and low Nitrogen abundance, the conclusions are difficult, due to the low number of objects. Certainly, however, there *is* a problem with stars with low vsini which are strongly enriched. Note that due to the large number of stars showing this problem, the probability that all have been observed pole-on is very low, and that rotational mixing for slowly rotating stars cannot be efficient. Thus, I would conclude that indeed there is a class of objects with abundances which cannot be explained by rotational mixing alone.

KUDRITZKI: How do you explain the difference between the new T_{eff}-scales for O-stars derived from the He I/II equilibrium and the work by Garcia/Bianchi and Sally Heap and collaborators who use UV lines?

PULS: In my talk, I haven't outlined this problem. Note that also Sally Heap and coworkers state that the T_{eff}-scale by Garcia/Bianchi is significantly lower than "all" other results, including their own work. This discrepancy has not been solved yet and urgently requires further effort. But note also that the UV-temperature scale by Garcia/Bianchi results from analyses performed with Adi Pauldrach's code WM-basic, which has not been designed for the analysis of photospheric conditions (e.g., the photospheric line-acceleration is far from being perfect, due to the use of the mCAK formalism to calculate this quantity), so that such discrepancies might also result from the used approximations, at least in part.

STANEK: Why don't you compare the evolutionary masses and the spectroscopic masses with the actual masses derived from eclipsing binaries (EB's)? There are now samples of well observed EB's in the SMC, LMC and Milky Way.

Puls: Indeed, there have been attempts to do this, particularly for B-dwarfs where the present answer is not unique. The major problem is that there are very few EBs (particularly in the O-star range) which have been analyzed by spectroscopic tools, and for those few cases the EB results lie mostly in between the spectroscopic and evolutionary results. Certainly, a systematic comparison has to be performed in the near future. But note also that the "mass-discrepancy" paradigm has somewhat changed: Previously, before using line-/wind-blanketed models, the discrepancy was located in the supergiant range, whereas now (after improving on the models) the dwarfs are most affected.

Dopita: In turbulent atmospheres with multiple shocks the clumping distribution is more likely to be log-normal rather than the two-phase as assumed in the X-ray opacity models. Have more sophisticated clumping distributions such as log-normal been modelled yet?

Puls: Indeed, analyses of the mass-spectrum of the clumps in Wolf-Rayet winds by Moffat, St-Louis and co-workers point to the presence of a power-law distribution, consistent with the assumption of supersonic turbulence. These results, however, refer mostly to the structure in the outer wind (the inner one is optically thick). With respect to the analyses of the more thinner O-star winds, where the present working hypothesis on the origin of the clumps is related to the line-driven instability, we are just in the beginning of analyses and modeling. Note that for optically thin clumps (regarding, e.g., H_α) the actual distribution plays a minor role, and only the average, effective overdensity (or volume filling factor) is of importance. Here, "we" are just at the beginning to obtain results for the corresponding spatial distribution. For optically thick processes such as UV and X-ray line emission, there is the alternative "porosity" approach by Owocki and co-workers, which defines the porosity length (a combination of blob cross-section and separation) as the photons' mean free path in a porous medium. At least for such models, the distribution of the optical thickness of the clumps has been assumed by a power-law as well.

Nieva: Concerning the "Hunter-plot", you said something I don't agree very much: "This is a challenge to theory". It is also a challenge to the quantitative spectral analysis. Systematic errors up to 1 dex are not taken into account in most spectral analyses for abundance determinations. I would consider these results with caution.

Puls: Since I did not perform this work myself, I don't know about the individual errors. But note that the Hunter plot compares the derived abundances in a differential way, where the theoretical predictions have been gauged to match the "observed" bulk of the observations. Since the discrepancy (for the low vsini stars) is of the order of one dex and since many objects are affected (and there are many more with "normal" abundances), I think that the discrepancy is real.