New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
Proceedings IAU Symposium No. 307, 2014
G. Meynet, C. Georgy, J. H. Groh & Ph. Stee, eds.

doi:10.1017/S1743921314007078

Constraining general massive-star physics by exploring the unique properties of magnetic O-stars: Rotation, macroturbulence & sub-surface convection

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Abstract. A quite remarkable aspect of non-interacting O-stars with detected surface magnetic fields is that they all are very slow rotators. This paper uses this unique property to first demonstrate that the projected rotational speeds of massive, hot stars, as derived using current standard spectroscopic techniques, can be severely overestimated when significant "macroturbulent" line-broadening is present. This may, for example, have consequences for deriving the statistical distribution of rotation rates in massive-star populations. It is next shown how such macroturbulence (seemingly a universal feature of hot, massive stars) is present in all but one of the magnetic O-stars, namely NGC 1624-2. Assuming then a simple model in which NGC 1624-2's exceptionally strong, large-scale magnetic field suppresses atmospheric motions down to layers where the magnetic and gas pressures are comparable, first empirical constraints on the formation depth of this enigmatic hot-star macroturbulence is derived. The results suggest it originates in the thin sub-surface convection zone of massive stars, consistent with a physical origin due to, e.g., stellar pulsations excited by the convective motions.

Keywords. stars: early-type, stars: rotation, stars: magnetic fields, convection

1. Introduction

Over the past decade, new generations of spectropolarimeters and large survey programs have revealed that roughly ∼10 % of all massive main-sequence stars harbor large-scale, organized surface magnetic field, quite similar to intermediate-mass ApBp stars (see, e.g., Wade *et al.* 2012; Grunhut, this Volume). The fields are strong, typically on the order of kG, and their fundamental origin is basically unknown, although recent observations of Herbig pre-main sequence stars point toward surviving fossils from early phases of stellar formation (Alecian *et al.* 2013). A particularly neat property of these magnetic massive stars is that they are *oblique rotators* (meaning their magnetic and rotation axes are offset), so that their rotation periods can be readily measured from the observed variation of the line-of-sight field (e.g., Borra & Landstreet 1980) or from photometric/spectral variations caused by their circumstellar magnetospheres (e.g., Howarth *et al.* 2007). This paper focuses on (non-interacting) magnetic O-stars, which all have very long measured rotation periods (likely because they have been spun down through magnetic braking by their strong stellar winds, e.g. Petit *et al.* 2013). By means of high-quality spectra collected within the Magnetism in Massive Stars project (MiMeS, Wade *et al.* 2012), I use these unique properties to examine:

- The accuracy of standard methods for inferring rotation rates of massive stars.
- General origin (and magnetic inhibition of) "macroturbulence" in hot stars.

Table 1. Stellar and magnetic parameters for the sample O-stars, including $v \sin i$ as implied from the measured rotation periods and macroturbulent velocities θ (assuming here isotropic macroturbulence, θ_G, see text). Table adapted from Sundqvist *et al.* (2013a).

Star	**Spec. type**	T_{eff} [kK]	$\log g$ [cgs]	B_{pole} [kG]	P_{rot} [d]	$v \sin i$ [km s^{-1}]	θ_G [km s^{-1}]
NGC 1624-2	O6.5-O8 f?cp	35	4.0	20	158	0	$2.2 \pm^{0.9}_{2.2}$
HD 191612	O6 f?p-O8 f?cp	35	3.5	2.5	538	0	$62.0 \pm^{0.5}_{0.5}$
HD 57682	O9 V	34	4.0	1.7	64	0	$19.2 \pm^{0.3}_{0.3}$
CPD -28 2561	O6.5 f?p	35	4.0	1.7	70	0	$24.3 \pm^{1.0}_{0.9}$
HD 37022	O7 Vp	39	4.1	1.1	15	24	$42.9 \pm^{0.5}_{0.6}$
HD 148937	O6 f?p	41	4.0	1.0	7	45	$54.0 \pm^{0.9}_{0.9}$
HD 108	O8 f?p	35	3.5	0.5	1.8×10^4	0	$64.4 \pm^{0.4}_{0.4}$
HD 36861	O8 III((f))	35	3.7	0	–	45	$50.0 \pm^{0.3}_{0.3}$

2. Rotation and macroturbulence in massive, hot stars

For most stars, it is not possible to directly measure the rotation rate. Instead one typically infers the *projected* stellar rotation, $v \sin i$ (with inclination angle i), from observed, broadened line-spectra. However, it is since long known that rotation is not the only macroscopic broadening agent operating in hot star atmospheres. The additional broadening is of very large width, typically on order ~ 50 km/s (well in excess of the photospheric speed of sound, $\sim$20 km s^{-1}), and the occurrence of this "macroturbulence" seriously complicates deriving accurate $v \sin i$ rates for massive stars that are not too rapidly rotating (e.g., Howarth *et al.* 1997; Simón-Díaz & Herrero 2014). Moreover, since early-type stars lack surface convection associated with hydrogen recombination – which is responsible for such non-thermal broadening in late-type stellar atmospheres (Asplund *et al.* 2000) – the physical origin of macroturbulence in hot stars remains unclear (though see, e.g., Aerts *et al.* 2009). At the present, it is normally treated by simply introducing ad-hoc photospheric velocity fields with Gaussian distributions of speeds, assumed to be either *isotropic* or directed only *radially and/or tangentially* to the stellar surface.

Properties of the magnetic O-stars. Table. 1 summarizes relevant parameters for the sample of magnetic O-stars considered here, including a non-magnetic comparison star (HD 36861). The table includes derived values of characteristic (isotropic) macroturbulent velocities θ_G from Sundqvist *et al.* (2013a), obtained by using information about $v \sin i$ from the measured rotation periods. Note in particular two things from this table: i) The long rotation periods of the magnetic stars indeed imply $v \sin i \approx 0$ km s^{-1} for several of them, and ii) strong macroturbulent line-broadening is present in all but one of the magnetic O-stars, namely NGC 1624-2.

3. Does standard methods overestimate $v \sin i$?

I here follow Sundqvist *et al.* (2013b) and use HD 191612 and HD 108 as test-beds, the two stars in Table 1 with $v \sin i < 1$ km s^{-1} and characteristic macroturbulent velocities $\theta_G > 50$ km s^{-1}. Fig. 1 shows the results from deriving $v \sin i$ and macroturbulent velocities for HD 191612 and HD 108, using the standard Fourier Transform (FT) and Goodness-of-fit (GOF) techniques. As illustrated by the figure, the FT method derives $v \sin i$ from the position of the first minimum in Fourier space, whereas the GOF method convolves synthetic line-profiles for a range of $v \sin i$ and macroturbulent velocities, creating a standard χ^2-landscape from which a best-combination of the two parameters is

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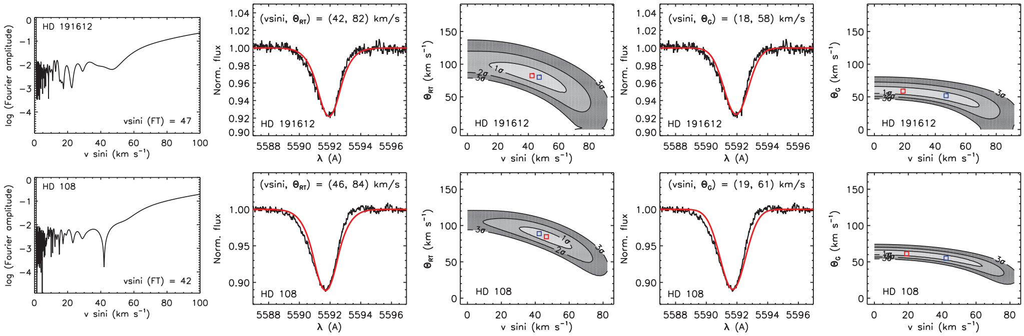

Figure 1. Projected rotation speeds $v \sin i$ and macroturbulent velocities θ for HD 191612 and HD 108, derived using standard FT (left panel) and GOF (middle/right panels) techniques. The contour-maps show 1,2,3σ confidence intervals for the fits in the $v \sin i$-θ plane. The blue and red squares on the contour-maps indicate the FT derived value and the best GOF model, respectively. The middle panel assumes a radial-tangential macroturbulence with equal contributions from both directions, $\theta_{\rm RT}$, and the right panel assumes isotropic velocity fields, $\theta_{\rm G}$. The true values for $v \sin i$ are < 1 km/s for both stars, see text. Adapted from Sundqvist *et al.* (2013b).

determined (see Simón-Díaz & Herrero 2014 for details). Fig. 1 illustrates how the FT method yields $v \sin i \approx 40 - 50\,{\rm km\,s^{-1}}$ for both stars, a severe overestimate compared to the true value $v \sin i < 1\,{\rm km\,s^{-1}}$. The best GOF model assuming radial-tangential macroturbulence also gives $v \sin i \approx 40 - 50\,{\rm km\,s^{-1}}$, whereas assuming isotropic macroturbulence actually results in lower $v \sin i \approx 20\,{\rm km\,s^{-1}}$, although then of course the results from the FT and GOF methods do not agree†. Agreement in the derived $v \sin i$ between these two methods has indeed been used as an argument in favor of the radial-tangential macroturbulence model (e.g., Simón-Díaz & Herrero 2014), but the analysis here shows clearly that such agreement does not necessarily mean the derived $v \sin i$ is correct. The GOF contour-maps in Fig. 1 further display quite wide ranges of allowed values of $v \sin i$. Particularly for isotropic macroturbulence the results are degenerate all the way down to zero rotation, rendering the "best" model from this GOF quite useless (in contrast to the well-constrained values of $\theta_{\rm G}$ in Table 1, derived using independent knowledge of $v \sin i$).

Overall, these results demonstrate a big problem regarding deriving $v \sin i$ in the presence of a macroturbulent broadening that significantly influences the appearance of the line profile. In the case here of slow rotators, blindly applying standard methods leads to drastic overestimates of $v \sin i$, where the results also depend on the assumptions made about the unknown velocity fields causing the additional broadening. The next section now shows how we may indeed use the magnetic O-stars to also shed some light on the physical origin of this enigmatic macroturbulence.

4. Constraining the origin of macroturbulence by exploring magnetic inhibition of hot-star sub-surface convection

Using the method described in Sundqvist *et al.* (2013a), the left panel of Fig. 2 shows fitted C IV photospheric line-profiles for three stars in the sample given in Table 1, namely HD 191612, NGC 1624-2, and the non-magnetic comparison star HD 36861. Since in the optical the magnetic broadening due to the Zeeman effect is only $\sim 1 - 2\,{\rm km\,s^{-1}}$ per

† Note also that the derived characteristic velocities are quite different depending on which form of macroturbulence is assumed, due to the markedly different shapes of a disc-integrated radial-tangential velocity field model and an isotropic one.

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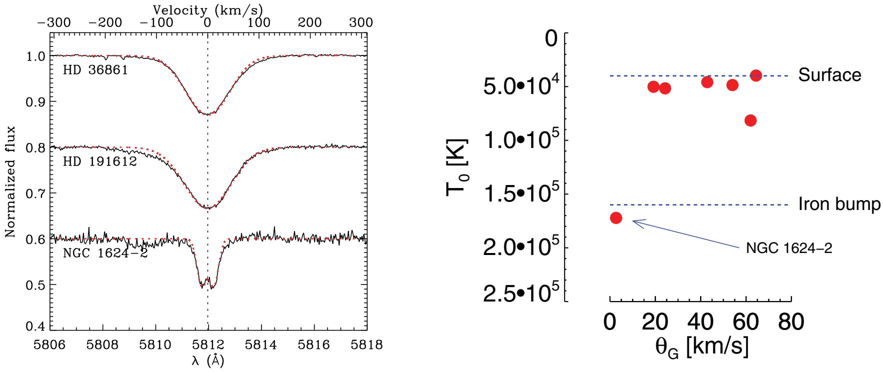

Figure 2. Left panel: Observed (black solid) and fitted (red dashed) C IV $\lambda\lambda5812$ line profiles for three stars in our sample, as labeled in the figure. The vertical dashed line marks line center, and the continua in the two lower curves have been shifted downwards by 0.2 and 0.4 normalized flux units. **Right panel:** Atmospheric temperature T_0 (see text) vs. macroturbulent velocity $\theta_{\rm G}$ for the magnetic stars in Table 1, with NGC 1624-2 explicitly labeled. The dashed blue lines mark approximate locations of the stellar surface and the iron-opacity bump. Figure adapted from Sundqvist *et al.* (2013a).

kG, both the magnetic (Table 1) and rotational contribution to the line-broadening is negligible for HD 191612, i.e., the total line broadening may be quite unambiguously associated solely with macroturbulence. Since the comparison star HD 36861 reveals very similar broad lines, this then suggests a common origin of the observed macroturbulence in magnetic and non-magnetic O-stars. By contrast, the observed line in NGC 1624-2 is qualitatively very different, much narrower and with magnetic Zeeman splitting directly visible (due to the very strong surface field, see Table 1). This indicates that the mechanism responsible for the large macroturbulent velocities in the other stars is not effective in NGC 1624-2. The quantitative analysis by Sundqvist *et al.* (2013a) results in $\theta_{\rm G} = 2.2 \pm^{0.9}_{2.2}$ km/s for NGC 1624-2. Such a very low (consistent with zero) macroturbulent velocity is in stark contrast with the rest of the sample, which displays $\theta_{\rm G} \approx 20 - 65\,{\rm km\,s^{-1}}$ (Table 1). Thus, macroturbulence seems to behave similar in non-magnetic and magnetic O-stars, except for in NGC 1624-2 where it is anomalously low or even completely absent.

A simple model for magnetic inhibition of macroturbulence. In intermediate-mass Ap-stars, it is believed that the strong magnetic field prohibits atmospheric motions between field lines and so suppresses surface convection (e.g. Balmforth *et al.* 2001; J. Landstreet, priv. comm.). The critical parameter controlling the competition between plasma and field in the atmosphere is the so-called "plasma β", the ratio between gas pressure and magnetic pressure, $\beta \equiv \frac{P_{\rm G}}{P_{\rm B}} = \frac{P_{\rm G}}{B^2/(8\pi)}$ for magnetic field strength B. Let us now thus assume the magnetic field stabilizes the atmosphere against motions approximately down to the stellar layer at which $\beta = 1$. By adopting a very simple, classical gray model atmosphere, and assuming a fossil field with no significant horizontal variations in pressure and density between field lines, we obtain an analytic expression for the temperature T_0 in the atmosphere at which $\beta = 1$ (see Sundqvist *et al.* 2013a for details),

$$T_0 = T_{\rm eff} \left(\frac{3}{32\pi} \frac{B^2 \kappa}{g} + \frac{1}{2} \right)^{1/4} \approx 0.42\, T_{\rm eff} B^{1/2} (\kappa/g)^{1/4}, \tag{4.1}$$

where B has units of Gauss and κ (cm^2/g) is a mean mass absorption coefficient. The second expression here neglects the 1/2 within the parenthesis, and so implicitly assumes

https://doi.org/10.1017/S1743921314007078 Published online by Cambridge University Press

a field strength significantly stronger than the $B \approx 400\,(10^{-4} g/\kappa)^{1/2}$ that yields $\beta = 1$ at $T_0 = T_{\rm eff}$.

To estimate T_0 for the magnetic O-stars, the stellar parameters in Table 1 are used together with the averaged surface field for B. For simplicity, $\kappa = 1$ is further assumed for all stars; inspections of Rosseland opacities in detailed FASTWIND non-LTE model atmospheres (Puls *et al.* 2005) show that for atmospheric layers with $\tau_{\rm Ross} \geqslant 0.1$, such constant $\kappa \approx 1$ actually is a quite good opacity-estimate for Galactic O-stars that are not too evolved. The right panel of Fig. 2 shows T_0 vs. the $\theta_{\rm G}$ values given in Table 1 for the magnetic O stars. The figure illustrates the influence of the magnetic field reaches down to much deeper layers in NGC 1624-2 than in any other star. This suggests that the physical mechanism causing the large macroturbulence in O-stars likely originates in stellar layers between 100 000 K and 200 000 K, consistent with a physical origin in the iron-peak opacity zone located roughly at $T \approx 160\,000$ K. Since the increased opacity in this sub-surface zone is believed to trigger extensive convective motions (e.g., Cantiello *et al.* 2009), this makes the analogy with suppression of surface convection in magnetic Ap-stars quite appealing.

5. Summary and conclusions

Sect. 3 in this paper shows that the presence of significant macroturbulence can result in severe overestimates of $v \sin i$ (at least for slow rotators) when applying standard spectroscopic methods (see also Simón-Díaz & Herrero 2014; Aerts *et al.* 2014). This may have important consequences, e.g., for determining the statistical distribution of rotation rates for populations of massive stars (e.g., Ramírez-Agudelo, this Volume).

The key for obtaining better constrained values of $v \sin i$ is a more robust description of the so-called macroturbulent line-broadening. Following Sundqvist *et al.* (2013a), Sect. 4 places first empirical constraints on the formation depth of such macroturbulence, locating it to the region around the iron opacity-bump at $T \approx 160\,000$ K. An attractive scenario then is that the responsible physical mechanism is related to the convection believed to occur in this region (e.g., Cantiello *et al.* 2009), perhaps via stellar pulsations excited by the convective motions (Aerts *et al.* 2009; Shiode *et al.* 2013).

Acknowledgements

JOS gratefully acknowledges support by the German DFG, under grant PU117/8-1.

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Discussion

HERRERO: I agree that we badly need a better description of the broadening we observe in O-stars. Conserning the accuracy of classical methods (FT, GOF), in the recent paper by Simon-Diaz and myself we show that if there are other broadening mechanisms than $v \sin i$ and macroturbulence, we may obtain too large $v \sin i$ values. On the other hand, in θ^1 Ori C we get $v \sin i$ values that agree with the rotation period derived from spectroscopic variations and B-field inclinations.

SUNDQVIST: Yes, I am aware that in Simón-Díaz & Herrero (2014) you show that $v \sin i$ may be overestimated in the presence of large *micro*-turbulence. I was not aware, however, that you obtained good agreement for θ^1 Ori C. Note that I did not include this star here, since its rotation period 15 days actually implies a “non-zero” rotation speed. As such, the exact value of $v \sin i$ then depends on the uncertain stellar radius. But we should definitely investigate this further.

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IBADOV: What can you say about generation of spots on massive stars surfaces, like sun-spots?

SUNDQVIST: Note first that the magnetic fields I have been discussing here are large-scale, organized fields, with a dominant dipolar component and presumably of fossil origin. These fields are quite different from the complex, dynamo-generated fields in the Sun and other cool stars. That said, there have been some investigations regarding how a hypothetical magnetic field generated in the near-surface convection zone of massive stars could give rise to spots on the surface (e.g. Cantiello & Braithwaite 2011). Such spots, however, would be *hot and bright*, since the energy near the surface of massive stars is transported by radiation.

LOBEL: An important spectroscopic characteristic of yellow hypergiants ($T_{\rm eff} < 10\,kK$) are very broad photospheric absorption lines. They are slow rotators with large supersonic macroturbulence. Would you attribute its physical origin to g-modes in these cool massive stars as well?

SUNDQVIST: That is difficult to say. The situation definitely seems reminiscent of that in blue supergiants, in which g-modes may indeed be the physical origin (e.g., Aerts *et al.* 2009). But without looking further into the situation, I unfortunately cannot say much more than that at the moment.

AERTS: Remark: We are including velocity fields due to 2-D (ideally in the future in 3-D) hydro simulations, and we do get broadened wings as suggested observationally. This is probably best explained with pulsations in gravity modes, as a “natural” explanation for un-evolved B stars near the main sequence.