On magnetic inhibition of photospheric macro-turbulence generated in the iron-bump opacity zone of O-stars

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ABSTRACT

Massive, hot OB-stars show clear evidence of strong macroscopic broadening (in addition to rotation) in their photospheric spectral lines. This paper examines the occurrence of such “macro-turbulence” in slowly rotating O-stars with strong, organised surface magnetic fields. Focusing on the C\(_{\text{IV}}\) 5811\,\AA\ line, we find evidence for significant macro-turbulent broadening in all stars except NGC 1624-2, which also has (by far) the strongest magnetic field. Instead, the very sharp C\(_{\text{IV}}\) lines in NGC 1624-2 are dominated by magnetic Zeeman broadening, from which we estimate a dipolar field \(\sim 20\) kG. By contrast, magnetic broadening is negligible in the other stars (due to their weaker field strengths, on the order of 1 kG), and their C\(_{\text{IV}}\) profiles are typically very broad and similar to corresponding lines observed in non-magnetic O-stars. Quantifying this by an isotropic, Gaussian macro-turbulence, we derive \(v_{\text{mac}} = 2.2 \pm 0.9\) km/s for NGC-1624, and \(v_{\text{mac}} \approx 20 – 65\) km/s for the rest of the magnetic sample.

We use these observational results to test the hypothesis that the field can stabilise the atmosphere and suppress the generation of macro-turbulence down to stellar layers where the magnetic pressure \(P_B\) and the gas pressure \(P_g\) are comparable. Using a simple grey atmosphere to estimate the temperature \(T_0\) at which \(P_B = P_g\), we find that \(T_0 > T_{\text{eff}}\) for all investigated magnetic stars, but that \(T_0\) reaches the \(\sim 160\,000\) K layers associated with the iron opacity-bump in hot stars only for NGC 1624-2. This is consistent with the view that the responsible physical mechanism for photospheric O-star macro-turbulence may be stellar gravity-mode oscillations excited by sub-surface convection zones, and suggests that a sufficiently strong magnetic field can suppress such iron-bump generated convection and associated pulsational excitation.

Key words: line: profiles - stars: early-type - stars: atmospheres - convection - stars: magnetic fields

1 INTRODUCTION

Modern high-resolution, high signal-to-noise optical spectroscopy of hot stars show clearly that rotation is not the only macroscopic line-broadening agent operating in their photospheres. The additional broadening is typically seen over the complete spectral line, has a Gaussian-like shape and very large widths, \(\sim 50\) km/s, well in excess of the photospheric speed of sound, \(\sim 20\) km/s. Indeed, such very large “macro-turbulence” seems to be a ubiquitous feature of OB-star atmospheres (Howarth et al. 1997; Simón-Díaz & Herrero 2007; Leever, Puls & Aerts 2007; Simón-Díaz et al. 2010; Markova et al. 2011; Najarro, Hanson & Puls 2011; Bouret et al. 2012).

However, since early-type stars lack the vigorous surface convection associated with hydrogen recombination – which is responsible for such additional, non-thermal broadening in late-type stellar atmospheres (Asplund et al. 2000) – path (mfp), and micro-turbulence, with scales shorter than this mfp. For O-stars, inferred micro-turbulent velocities are normally on order a few km/s, i.e. much smaller than the macro-turbulence that is the focus of this paper.

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\(^1\) In stellar spectroscopy, one typically distinguishes between such macro-turbulence, with scales larger than the photon mean-free-
the physical origin of macro-turbulence in hot stars remains unclear. A long-standing suggestion has been stellar oscillations (Lucy 1976), and recently Aerts et al. (2009) showed that the collective line-broadening effect of numerous low-amplitude gravity-mode (g-mode) pulsations can indeed mimic the large inferred values of Gaussian-like macro-turbulence. Stellar structure theory predicts that this pulsational broadening excited by core convection becomes significant only in evolved massive stars, and while first results for OB supergiants do indeed seem to support a pulsational origin of macro-turbulence (Simón-Díaz et al. 2010), observations indicate the presence of significant turbulent velocities in hot stars of all evolutionary classes (Markova et al. 2011; Najarro, Hansson & Puls 2011; Simón-Díaz et al. in prep; Markova et al., in prep.). Recently, however, Shiode et al. (2013) (see also Cantiello et al. 2009) suggested that near-surface convection generated by the iron-bump opacity zone can trigger excited g-modes in main-sequence O-stars as well, and that such pulsations might be the origin of their observed turbulent broadening.

A key empirical issue regards the actual quantification of macro-turbulence. In particular, additional broadening due to a basically asymmetric process like stellar oscillations will affect the first zero in the Fourier power spectra of spectral lines, which typically is used to infer the projected stellar rotation (e.g., Simón-Díaz & Herrero 2007), and so make it difficult to disentangle and quantify the relative amounts of macro-turbulent and rotational broadening present in the atmosphere (Aerts et al. 2009). Here we circumvent this issue by focusing on O-stars with detected organised surface magnetic fields, using high-quality spectra collected within the Magnetism in Massive Stars project (MiMeS; Wade, Grundahl & MiMeS Collaboration 2012). In particular, all these magnetic O-stars have very long measured rotation periods, likely because they have been spun down through magnetic braking by their strong stellar winds (see Petit et al. 2013); their (in most cases) negligible rotational broadening makes them ideal targets for the present study.

From studies of the chemically peculiar Ap stars, it is well known that the presence of a sufficiently strong surface magnetic field can stabilise the atmosphere against large-scale motions and suppress convectively induced turbulent line-broadening (J. Landstreet, T. Ryabchikova, O. Kochukhov, priv. comm., see also, e.g., Michaud 1970; Landstreet 1996). Building on these concepts, we compare here the narrow lines observed in NGC 1624-2 (measured surface dipolar field ∼20 kG, Wade et al. 2012) with the broader lines observed in other magnetic O-stars (surface fields on order ∼1 kG), in an attempt to place first observational constraints on the depth of the source region for the enigmatic macro-turbulence in hot main-sequence stars.

The paper is organised as follows: sect. 2 presents the observational sample and describes our method for deriving macro-turbulent velocities. Sect. 3 gives the results of the analysis, and Sect. 4 presents a simple model for interpreting magnetic inhibition of macro-turbulence. Finally, Sect. 5 discusses the results, gives our conclusions, and outlines directions for future work.

2 OBSERVATIONS AND METHOD

We select magnetic O-type stars with well constrained rotational periods and strong magnetic fields from the compilation by Petit et al. (2013). The sample, listed in Table 1, consists of 7 magnetic stars, including NGC 1624-2 which hosts an order of magnitude stronger field than any other known magnetic O star (Wade et al. 2012). For comparison purposes, we also include and analyse the non-magnetic star HD 36861 (AKa Ori A), which has stellar parameters similar to those of our magnetic sample.

For all sample stars, we retrieve high-quality spectra from the extensive MiMeS database. The observations were obtained with the high-resolution (R ~ 65 000) spectropolarimeter ESPaDOnS at the Canada-France Hawaii Telescope, or with its twin instrument Narval located at the Telescope Bernard-Lyot. We focus on analysing the magnetic O-stars’ low states, defined according to when the cyclic Hα emission originating from their “dynamical magnetospheres” (Sundqvist et al. 2012) is at minimum. This should minimise any contamination of the photospheric lines by magnetospheric emission (for a review of massive-star magnetospheric properties, see Petit et al. 2013). However, at the end of Sect. 5 we also comment briefly on line-profile variability between this low state and the corresponding high state (defined by maximum Hα emission).

To obtain macro-turbulent velocities we analyse the photospheric C iv 5811 Å line, accounting also for rotational and magnetic broadening when needed. Surface magnetic field properties of OB stars are generally derived from polarimetric measurements, as the Zeeman splitting typically is too small to be separated from other broadening mechanisms (see Donati & Landstreet 2009). In the optical, the Zeeman broadening is only ~1-2 km/s per kG, i.e. in the current sample only NGC 1624-2 has a surface field strong enough to display significant magnetic broadening in the line profiles (see Figure 1). Nevertheless, for consistency we include a proper treatment of the Zeeman effect for all stars, using the literature dipolar field values listed in Table 1.

We note that, due to the sometimes unknown observer inclination angle i, these inferred field strengths are uncertain by up to ~50%; this uncertainty, however, does not affect the macro-turbulent velocities derived in this paper. The Zeeman pattern of the C iv 3s2S1/2 → 3p2P1/2 transition, calculated under LS coupling, has two strong g components and two well-spaced, weaker π components. This pattern, along with a high magnetic sensitivity (effective Landé factor g = 1.33), makes this unblended line particularly suitable for the present analysis.

The rotation period of magnetic stars can be readily obtained from the observed variation of the longitudinal field (e.g., Borra & Landstreet 1984; Bychkov, Bychkova & Madej 2005) or photometric/spectral variations caused by their magnetospheres (e.g., Landstreet & Borra 1978; Howarth et al. 2007). Most of the magnetic O-stars have very long periods and so have negligible rotational broadening, except for HD 148937 and

2 Spectropolarimetric observations available for this star constrain the dipolar surface field to be below 80 G (David-Uraz et al. in prep).
HD 37022 (=θ1 Ori C), for which we include broadening due to the modest rotation listed in Table 1.

We compute emergent intensities at each point on the stellar surface using the Unno-Rachkovsky solution for a Milne-Eddington atmosphere (Unno 1956; see also Ch. 9 in Landi degl’Innocenti & Landolfi 2004). Synthetic flux profiles are then obtained by numerically integrating the emergent intensities over the projected stellar disc, assuming a dipolar surface field matching the simple geometry of the (presumed fossil) fields observed in these stars. Formally, the Zeeman splitting is sensitive to the surface field modulus; however, for equal disk-integrated values of the modulus the actual position of the magnetic pole on the visible hemisphere does not change the structure of the line profile significantly. Therefore we place the magnetic equator at the center of the stellar disc for all stars, as the best representative viewing angle for their low states.

This simplified approach allows for a fast treatment of the Zeeman effect and derivation of macro-turbulent velocities, and further avoids model dependencies on e.g. stellar parameters and chemical abundances, which are not important for the analysis here. Within the Unno-Rachkovsky approximation, the source function \( S \) is linear in the continuum optical depth, \( S(\tau_c) = S_0[1 + \beta\tau_c] \), and the polarised radiative transfer equations can be solved analytically. Specifically, we use \( \beta = 1.5 \), Voigt-shaped line profiles with damping constant \( a = 0.02 \), and a thermal speed \( v_{\text{th}} = 10 \text{ km/s} \). We then fit the core of the line over a grid of profile strengths (set by the line-to-continuum opacity ratio) and isotropic Gaussian macro-turbulence of the form \( e^{-v^2/v_{\text{mac}}^2} \). To estimate the admissible \( v_{\text{mac}} \), we calculate the Bayesian probability density function marginalised over the profile-strengths. The prior probability density is constant, and any deviations not explained by the model are treated as additional Gaussian noise, which results in the most conservative estimate of the parameters under the maximum entropy principle (e.g., Gregory 2005).

### 3 RESULTS

Using the method described above, Figure 1 shows fitted \civ line profiles for three stars in our sample, namely HD 191612, NGC 1624-2, and the non-magnetic comparison star HD 36861.

Since HD 191612’s rotation period is 538 days and its surface magnetic field is “only” 2.5 kG (Table 1), both rotational and magnetic broadening are negligible for this star; thus the total line broadening may be quite unambiguously associated purely with macro-turbulence. Comparing this with HD 36861 reveals very similar Gaussian-like and broad \civ lines, indicating a common origin of the observed macro-turbulence 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). This indicates that the mechanism responsible for the large macro-turbulent velocities in HD 36861 and HD 191612 is not effective in NGC 1624-2.

Figure 2 further shows probability-density distributions of macro-turbulent velocities for the full stellar sample described in Sect. 2 and Table 1 lists the corresponding median values along with the 68% confidence regions. For NGC 1624-2, we allow the (dipole) magnetic field strength to be a free parameter, in order to properly model the observed Zeeman splitting and obtain a more conservative estimate of...
the macro-turbulent velocity. Figure 3 illustrates the resulting joint-probability contour-map of magnetic field strength and macro-turbulence.

This simple analysis for NGC 1624-2 results in a very strong dipole field \( B_{\text{pole}} \approx 20 \text{ kG} \) (consistent with Wade et al. 2012) and a very low \( v_{\text{mac}} = 2.2 \pm 0.3 \text{ km/s} \). Such a low macro-turbulent velocity is in stark contrast with the rest of the sample, which displays much higher values, \( v_{\text{mac}} \approx 20 - 65 \text{ km/s} \) (see Figure 2). Thus, among the known slowly rotating magnetic O-stars, macro-turbulence is anomalously low in NGC 1624-2.

We have here focused on fitting profiles during the spectral “low state” (see Sect. 2). Comparing the observed C IV lines in the low and high states of the magnetic stars indeed reveals variable and asymmetric profiles, but it is difficult to judge whether this variability is of photospheric origin or stems from reffiling by magnetospheric emission during the high state. Thus we defer a detailed investigation of such line-profile variability to a future paper, noting simply that the inferred macro-turbulent velocities during the low and high states typically differ only by a few km/s, which does not affect our basic results or conclusions.

4 INTERPRETING MAGNETIC INHIBITION OF O-STAR MACRO-TURBULENCE

Let us now interpret the results of the previous section using a very simple model for magnetic inhibition of macro-turbulence. Assuming the magnetic field stabilises the atmosphere against large-scale motions approximately down to a stellar layer at which the magnetic pressure \( P_B = B^2/(8\pi) \) equals the gas pressure \( P_g \), we can analytically estimate the corresponding temperature \( T_0 \) by adopting a classical grey atmosphere with temperature structure at given optical depth

\[
T(\tau) \approx T_{\text{eff}} \left( \frac{3}{8} \tau + \frac{1}{2} \right)^{1/4}.
\]

For gravity \( g \) (in cm/s\(^2\)) and a nearly constant mass absorption coefficient \( \kappa \) (in cm\(^2\)/g), the optical depth becomes

\[
\tau = \int \kappa \rho dz \approx \kappa m_c = \kappa P_b / g.
\]

where the last equality uses hydrostatic equilibrium to evaluate the column mass \( m_c \). For a large-scale magnetic field with arbitrary, and possibly even variable, tilt to the vertical direction, the variation of density along a field line depends only on the vertical depth. With the further assumption that there is no horizontal variation in pressure or density between field lines, this standard hydrostatic condition between pressure and column mass still holds, i.e. \( P_b = m_c g \).

Since the extent of the photosphere is very small compared to the stellar radius, we may further neglect the radial dependence of the magnetic field and use the inferred surface field strength \( B \) throughout the atmosphere. Setting then \( P_b = P_g = B^2/(8\pi) \), one obtains the temperature \( T_0 \) in the layer at which the gas and magnetic pressure are equal,

\[
T_0 = T_{\text{eff}} \left( \frac{3}{8} \frac{B^2 \kappa}{g} + \frac{1}{2} \right)^{1/4} \approx 0.42 T_{\text{eff}} B^{2/3} (\kappa/g)^{1/3},
\]

where \( B \) has units of Gauss. The second expression here neglects the 1/2 within the parenthesis, and so implicitly

\[
\text{Note also here that since these large-scale, organised magnetic fields presumably are of fossil origin, they should not exhibit the increase in field strength with density that may be expected for fields in energy equipartition generated by stellar dynamos.}
\]
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assumes a field strength significantly stronger than the \( B \approx 400 (10^{-4} \text{g/s})^{1/2} \) that yields \( P_B = P_g \) at \( T_0 = T_{\text{eff}} \).

Table 1 lists stellar and magnetic parameters used to estimate \( T_0 \) for the stars in our sample. We use the averaged surface field for \( B \) and, for simplicity, we further take \( \kappa = 1 \approx 3 \kappa_e \) for all stars, where \( \kappa_e = 0.34 \) is the electron scattering opacity for a hot star of standard solar composition. Inspections of Rosseland opacities in detailed FAWIND non-LTE model atmospheres (Puls et al. 2003) show that for atmospheric layers with \( \tau_{\text{Ross}} \gtrsim 0.1 \), such constant \( \kappa \approx 3 \kappa_e \) actually is a quite good opacity-estimate in Galactic O-stars that are not too evolved (see also, e.g., Fig. 1 of Cantiello et al. 2009).

Figure 3 displays \( T_0 \) vs. the \( v_{\text{mac}} \) values derived in Sect. 3 for the magnetic O stars. The figure shows that although the magnetic field likely affects the atmosphere of all investigated stars to some extent, this influence reaches down to much deeper layers in the sharp-lined NGC 1624-2 than in any other star. A simple comparison of NGC 1624-2 (\( v_{\text{mac}} = 2.2 \pm 0.2 \text{km/s} \)) with HD 191612 (\( v_{\text{mac}} = 62.0 \pm 0.5 \text{km/s} \)), which gives the second highest \( T_0 \), then suggests that the physical mechanism causing the large values of macro-turbulence likely originates in stellar layers with 100 000 K \( \lesssim T \lesssim 200 000 \text{ K} \). This is consistent with a physical origin of O-star photospheric macro-turbulence in the iron-peak opacity zone located roughly at \( T \approx 160 000 \text{ K} \).

5 DISCUSSION AND CONCLUSIONS

The central result of this paper is that strong macro-turbulence is present in the photospheres of all known slowly rotating magnetic O stars except for NGC 1624-2, which has (by far) the strongest surface field, and in which such non-thermal line-broadening seems to be largely suppressed. Moreover, the broad lines observed in the other magnetic O stars are typically quite similar to those seen in non-magnetic stars, suggesting a common origin of macro-turbulence. As in non-magnetic stars (e.g., Markova et al. 2011), it is not clear why these less extreme magnetic stars show such a large range of macro-turbulent velocities.

Using these unique constraints derived from the magnetic O stars, we assume (in analogy with Ap stars) that the organised, presumed fossil field can inhibit large-scale atmospheric motions down to stellar layers where the magnetic and gas pressures are comparable. The analysis here then indicates that the physical mechanism responsible for macro-turbulence in O stars likely originates in atmospheric layers with temperatures corresponding to 100 000 K \( \lesssim T \lesssim 200 000 \text{ K} \).

An attractive scenario then is that this physical mechanism may be stellar oscillations excited by convection in the near-surface, iron-bump opacity zone of hot stars (Shiode et al. 2013). Future theoretical studies should calculate the excitation of such pulsational modes and their effects on spectral line formation, extending the work by Aerts et al. (2006) who computed line-profiles from the collective effect of more deep-seated g-mode pulsations in evolved hot stars.

Finally we note also that the iron opacity-bump becomes weaker for lower metallicity (Cantiello et al. 2009). Thus, if indeed sub-surface convection is ultimately responsible for the observed non-thermal line broadening in early-type main-sequence stars, it would imply that lower metallicity stars should have lower macro-turbulence. This should be observationally examined by comparing inferred macro-turbulent velocities in the Galaxy and the Magellanic Clouds.

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