A dynamical magnetosphere model for periodic Hα emission from the slowly rotating magnetic O star HD 191612

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ABSTRACT

The magnetic O star HD 191612 exhibits strongly variable, cyclic Balmer line emission on a 538-d period. We show here that its variable Hα emission can be well reproduced by the rotational phase variation of synthetic spectra computed directly from full radiation magnetohydrodynamical simulations of a magnetically confined wind. In slow rotators such as HD 191612, wind material on closed magnetic field loops falls back to the star, but the transient suspension of material within the loops leads to a statistically overdense, low-velocity region around the magnetic equator, causing the spectral variations. We contrast such ‘dynamical magnetospheres’ (DMs) with the more steady-state ‘centrifugal magnetospheres’ of stars with rapid rotation, and discuss the prospects of using this DM paradigm to explain periodic line emission from also other non-rapidly rotating magnetic massive stars.

Key words: MHD – stars: magnetic field – stars: rotation – stars: winds, outflows.

1 INTRODUCTION

Shortly after Donati et al. (2006) detected a strong magnetic field in the Galactic Of?p star HD 191612, Howarth et al. (2007) demonstrated that the variable equivalent widths of its optical Balmer and He i lines (e.g. Walborn et al. 2003) can be accurately phased according to a 538-d period, where in particular the outstanding Hα variation shows strict periodicity. Since this period is unrelated to the much longer orbital period $P_{orb} = 1542$ d of HD 191612 and its binary companion (Howarth et al. 2007), rotational modulation of a magnetically confined wind seems the most likely origin for the variability, as already suggested by Donati et al. (2006). But in contrast to centrifugally supported magnetosphere models, which have been successfully applied to Balmer line variability in rapid rotators such as the B star σ Ori E (Townsend, Owocki & Groote 2005), it is not clear how a very slow rotator such as HD 191612 can sustain a magnetosphere with sufficient accumulation of wind plasma to explain the strong and periodic Balmer emission.

To reproduce the Hα variation of HD 191612, Howarth et al. (2007) suggested two geometrical toy models. One of these was indeed inspired by the plasma distribution qualitatively expected from a magnetically confined wind; it is a tilted, limb-darkened, geometrically thin disc, where the sum of observer inclination $i$ and obliquity $\beta$ (the angle between the rotation and magnetic axes) must be $i + \beta \approx 100^\circ$ for the Hα modulation to be fitted.

Wade et al. (2011b) recently analysed Stokes V spectra of HD 191612. Assuming a dipole oblique rotator, these authors derived $i + \beta = 95^\circ \pm 10^\circ$, and by matching electron scattering modelling to the observed photometric variability further obtained $i \geq 30^\circ$. A tentative reference geometry $i = 30^\circ$ and $\beta = 67^\circ \pm 5^\circ$ was then suggested from speculating that the orbital and spin angular momenta of HD 191612 be aligned, and a surface dipole (polar) field $B_d = 2450 \pm 400$ G derived.

This Letter examines to what extent full radiation magnetohydrodynamical (MHD) simulations of a magnetically confined wind, along with detailed radiative transfer calculations, can actually reproduce HD 191612’s observed Hα variability, under the wind, magnetic and geometric constraints derived by Howarth et al. (2007) and Wade et al. (2011b).

2 Hα IN A SPHERICALLY SYMMETRIC WIND MODEL

To set the stage, we first compute synthetic Hα profiles for two different mass-loss rates using the spherically symmetric, unified (photosphere+wind) non-local thermodynamic equilibrium (NLTE) model atmosphere code FASTWIND (Puls et al. 2005), taking stellar and wind parameters from Howarth et al. (2007) (Table 1).

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symmetry in $\phi$. The energy equation is treated as by Gagné et al. (2005) and the radiation line force is calculated within the Sobolev approximation using standard CAK (Castor, Abbott & Klein 1975) theory. Since the rotation of HD 191612 is extremely slow, the inferred period of 537.6 d (Howarth et al. 2007) implies an equatorial rotation speed $v_{\text{rot}} = 1.4 \text{ km s}^{-1}$, we may neglect rotational effects on the dynamics (and thus use the same simulation for any choice of obliquity $\beta$).

The effectiveness of the magnetic field in channelling the stellar wind outflow may be characterized by the ratio of magnetic to wind kinetic energy density:

$$\eta \equiv \frac{B^2/8\pi}{\rho v^2/2} = \eta_s (\rho R_*/v \rho v_{\infty})^{-1} (1),$$

where the second equality defines the so-called ‘wind confinement parameter’ $\eta_s \equiv B^2 R_*^2/(Mv_{\infty})$ (ud-Doula & Owocki 2002), with $B_0$ the dipole equatorial surface field strength. If $\eta_s > 1$, the dipole Alfvén radius $R_A \approx \eta_s/4 R_*$, at which the magnetic and wind energy densities are equal, is located away from the stellar surface, allowing then for some wind material to be channelled along closed loops towards the magnetic equator (see Fig. 2). But the much steeper radial decline of the dipole magnetic energy density ($\sim 1/r^6$) than the wind kinetic energy density ($\sim 1/r^3$) means that at large enough radii the wind will always force the field lines to open up and essentially follow the radial wind flow.

The simulation here assumes strong confinement, $\eta_s = 50$, in accordance with the magnetic field strength recently derived by Wade et al. (2011b) and the wind parameters derived by Howarth et al. (2007), adopting $f_{cl} = 1$. It is well established that the winds of hot, massive O stars are indeed clumped (see Sundqvist et al. 2011b, for a recent review). But a theoretical development of such stochastic, small-scale inhomogeneities, as caused by the strong instability inherent to line-driven winds (e.g. Owocki, Castor & Rybicki 1988), requires a non-Sobolev treatment of the radiation line force, and has yet to be implemented within any MHD simulation. However, in terms of the H$\alpha$ modelling that is the focus of this Letter, we are still effectively modelling $M\sqrt{f_{cl}}$ (see Section 2), but simply neglecting any dynamical effects such stochastic, small-scale structures might

3 SIMULATIONS

3.1 Modelling a dynamical magnetosphere

Following the general procedure outlined by ud-Doula & Owocki (2002), we compute a 2D radiation MHD wind simulation of HD 191612, assuming a dipole magnetic field. Hydrodynamical variables are specified on a standard, right-handed spherical grid $(r, \theta, \phi)$, defined relative to a Cartesian set $(x, y, z)$, where we assume

![Figure 1. Observed (Howarth et al. 2007) and synthetic H$\alpha$ spectra during phases close to minimum and maximum. Synthetic FASTWIND spectra are computed for two different mass-loss rates under the assumption of spherical symmetry (see Section 2).](https://academic.oup.com/mnrasl/article-abstract/423/1/L21/1074348)

![Figure 2. Contours of the density squared for two different snapshots of the MHD wind simulation (upper panels), and of time-averaged density squared (lower left) and radial velocity (lower right). Time averages are calculated from > 100 snapshots taken well after the simulation’s initial state. The Alfvén radius is here located at $r \approx 2.7 R_*$, whereas the Kepler corotation radius is at $r \approx 55 R_*$, i.e. outside the range of the plots.](https://academic.oup.com/mnrasl/article-abstract/423/1/L21/1074348)
have upon the large-scale wind structure imposed by the magnetic field.

The upper panels of Fig. 2 plot the density squared of two simulation snapshots. They illustrate how below $r \approx R_\Lambda \approx 2.7R_\odot$, the wind does indeed become trapped by the closed field-line loops, whereby the material is pulled back by gravity on to the star over a dynamical time-scale. But a key point here is that, despite the very dynamical behaviour, the transient suspension of material within such closed loops still results in a wind region, in the vicinity of the magnetic equator, that statistically is overdense (Fig. 2, lower-left panel). Further, as a result of the colliding wind material at individual loop tops, this overdense region is also characterized by very low velocities (Fig. 2, lower-right panel), in qualitative agreement with the narrowness of the observed H$\alpha$ emission discussed in Section 2.

The structures predicted by these simulations are physically distinct from those predicted for rapidly rotating magnetic stars with $R_\Lambda > R_K$ (Townsend & Owocki 2005; Townsend, Owocki & Ud-Doula 2007; ud-Doula, Owocki & Townsend 2008), where $R_K = (v_{\text{rot}}/c_\text{crit})^{-2/3} R_\odot$ is the Kepler corotation radius for critical rotation speed $v_{\text{crit}}$. For such stars, the centrifugal forces can support any trapped material above $R_K$, allowing then the magnetically confined wind to accumulate material and form a centrifugal magnetosphere (CM). In contrast, the characteristic structure described above, appropriate for slowly rotating massive stars with $R_\Lambda > R_K > R_\odot$, instead establishes the concept of a dynamical magnetosphere (DM) (see also Petit et al. 2011).

In hot coronae from the sun and some magnetically active cool stars, there are analogous examples of regions of dynamical infall (‘coronal rain’, e.g. Eibe et al. 1999) or centrifugally supported prominences (Collier Cameron et al. 2003; Jardine & van Ballegooijen 2005), fed largely by the transient eruptive propulsion of stellar flares. By contrast, hot-star magnetospheres are fed by the quasi-steady wind upflow driven by the star’s radiation, allowing for persistent Balmer emission that has been monitored over multi-year time-scales spanning many rotation periods.

Note that even rapid rotators will have a DM component at $r \ll R_K$. But the H$\alpha$ emission contribution from this part will be insignificant because of the much higher densities at $R_K < r < R_\Lambda$ (see, e.g. fig. 7 in Townsend et al. 2007). These higher densities stem from the much longer accumulation time-scale associated with a CM (typically months/years; see appendix A in Townsend & Owocki 2005) than with a DM (typically hours, the dynamical time-scale). But a star such as HD 191612, with $R_\Lambda \approx 2.7R_\odot < R_K \approx 55R_\odot$, only has a DM contributing to the H$\alpha$ emission. So whereas rapidly rotating magnetic B stars can indeed show substantial Balmer line emission, as observed in e.g. $\sigma$ Ori E, the short accumulation time-scale of a DM requires the relatively high mass-loss rate of an O star to produce observable H$\alpha$ emission in these slowly rotating stars.

3.2 Radiative transfer

To model the observed variation of Balmer emission, we compute synthetic H$\alpha$ flux profiles directly from the MHD simulations by solving the formal integral of radiative transfer in a 3D cylindrical coordinate system ($p, \xi, z'$). This system is aligned towards the observer by rotating the stellar system ($r, \theta, \phi$) by an angle $\alpha$ about its $y$-axis, so that $\cos \alpha = \xi = z'$. The angle $\alpha$ thus defines the observer’s viewing angle with respect to the magnetic pole. For given $\beta$ and $i$, we have

$$\cos \alpha = \sin \beta \cos \Phi \sin i + \cos \beta \cos i,$$

(2)

which then readily gives the observer’s viewing angle as function of rotation phase $\Phi$. We note that even though the MHD models are 2D, the radiative transfer must be performed in 3D, as the axial symmetry is broken for any observer with $|\cos \alpha| \neq 1$.

The transfer equation is solved only in the wind, with a pre-specified photospheric profile $P_\odot$ as a lower boundary condition, taken from NLTE model atmosphere calculations assuming negligible wind contamination. While not truly self-consistent, this procedure has been shown to be very accurate for H$\alpha$ line profile calculations in 1D smooth (Puls et al. 1996) as well as multidimensional clumped (Sundqvist et al. 2011b) O star wind models without magnetic fields.

The monochromatic optical depth along a ray is

$$\tau_\nu = \int \chi_\nu dz',$$

(3)

where $\chi_\nu$ is the frequency-dependent opacity per unit length. The opacities are calculated assuming an optically thin continuum and occupation numbers for the H$\alpha$ atomic levels $i$ given in terms of the NLTE departure coefficients $b_i = n_i/n_\star$. The occupation number of level $i$ in LTE with respect to the ground state of the next ionization state (e.g. Mihalas 1978). The line profile is a Gaussian of Doppler width $\Delta V_\text{D}$, set by the local wind electron temperature $T_e$ and centred at zero comoving frame frequency $\nu_{\text{com}} = \nu_{\odot} - \nu'$. $\nu_{\text{com}}/\nu_{\odot}$, where $\nu = (\nu/\nu_0 - 1)/\nu_{\odot}$.

The emergent intensity for a given ray then is

$$I_\nu = P_\odot I_0 \exp \left( - \tau_\nu \right) \int_0^{\tau_\nu} S_\nu(\tau_\nu) \exp \left( - \tau_\nu \right) d\tau_\nu,$$

(4)

where $I_0$ is the stellar photospheric continuum intensity, $S_\nu$ the NLTE line source function, and $\tau_\nu$ the optical depth integrated over the complete ray. $I_0$ is taken from FASTWIND model atmospheres for rays that intersect the stellar core and set to zero otherwise. $S_\nu$ is fixed by the H$\alpha$ departure coefficients and the local wind electron temperature. The emergent flux is then, finally, obtained by integrating the emergent intensity over the projected stellar disc.

3.2.1 Electron temperatures and H$\alpha$ occupation numbers

As described, the H$\alpha$ synthesis problem requires estimates of $T_e$ and the hydrogen departure coefficients. But the energy equation as treated in the MHD simulations described in Section 3.1 yields only a rough approximation of the wind temperature balance, with the local temperature artificially never allowed to drop below a certain floor value (on the order of the stellar effective temperature). In our H$\alpha$ calculations, we therefore estimate the wind temperature balance using the results of a spherically symmetric FASTWIND model, except in regions shock heated to $T_e > 10^7$ K, where we set the H$\alpha$ opacity and source function to zero.

To consistently calculate NLTE departure coefficients for a full multidimensional MHD wind simulation is a daunting task, well beyond the scope of the present Letter. However, for now we take advantage of the fact that hydrogen is almost fully ionized in typical O star winds. The H$\alpha$ line formation is then controlled by recombination, a thermal process, and the participating atomic levels are therefore very close to LTE with respect to ionized hydrogen. For HD 191612, FASTWIND calculations show deviations smaller than a factor of 2, a typical number for most ‘normal’ O star winds without strong magnetic fields (Puls et al. 1996; Sundqvist et al. 2011b). As a first approximation then, we here take the simplest approach possible and assume LTE conditions, whereby $b_i = 1$. 

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4 Hα Variability in a Dynamical Magnetosphere

We calculate an Hα line profile for more than 100 snapshots of the 2D MHD simulation of HD 191612. Fig. 3 shows that such profiles are highly variable, mimicking the wind’s dynamical nature. To obtain a mean profile at each phase, we average over such profiles for ~100 randomly selected snapshots; this is intended to be a simple proxy for the real 3D nature of the wind dynamics, effectively using the complex and non-linear variations in time in our 2D simulation to mimic the expected variations in azimuth in a full 3D model.\footnote{For this type of line transfer, which often is optically thick, such post-averaging of the line profiles computed for many time snapshots is more realistic than the simple pre-processed, time-averaged wind density used by Wade et al. (2011b) to model polarized electron scattering, which is more nearly optically thin.}

While approximate, this seems a reasonable first approach to account for the limited lateral coherence or synchronization of an actual 3D magnetized wind. Also, each phase is constructed by further averaging the two phases having equal $\Phi$ values when reversing the magnetic poles, to ensure the expected long-term north/south symmetry of our simulation. The procedures described above effectively smooth out most of the short-time variability of our simulation, in agreement with the observations (Howarth et al. 2007).

Fig. 4 compares observed and synthetic time-averaged dynamic Hα spectra, plotted as functions of rotational phase assuming $\beta = i = 30^\circ$. This is consistent with the $\beta + i = 95^\circ \pm 10^\circ$ derived by Wade et al. (2011b), but differs slightly from the $i = 30^\circ$ adopted there (see further below). The observed general trends, with peak flux at phase 0 and an extended minimum around phase 0.5, are both well reproduced. The flux variations are caused by differences in the projected surface area of overdense Hα emitting material as the observer changes viewing angle when the star rotates. Fig. 5 demonstrates this by plotting the Hα emergent intensity (surface brightness) at line centre for observers located along the axes of magnetic pole and equator. The figure clearly shows how the flux, which is just the integral of the intensity over this projected area, is much higher for the observer along the polar axis.

The large observed Hα variability puts rather tight constraints on the system’s geometry. The equivalent width curves in Fig. 5 directly refute very low values of $i$, but also show that the $i = 30^\circ$, $\beta = 70^\circ$ assigned as a tentative reference geometry by Wade et al. (2011b) results in somewhat weaker variation than the $\beta = i = 50^\circ$ adopted here. This is simply because, for a given sum $i + \beta = 100^\circ$, an observer at $i = 30^\circ$ never looks closer to the magnetic pole than $\alpha \approx 40^\circ$, whereas for an observer at $i = 50^\circ$, $\alpha$ spans the entire range from pole to equator, and back again, in one rotation period, thus resulting in larger flux variations.

There are discrepancies, of course. Whilst the observed and simulated equivalent width curves qualitatively agree well, the simulated variation is quantitatively somewhat too low. These deviations could however be remedied if the DM were more concentrated, which would result in a larger surface brightness difference between pole and equator (Fig. 5). Such stronger wind confinement could occur from either a lower mass-loss rate or a stronger magnetic field, where the former choice seems more likely (due to clumping, Section 3.1), since the $i = 50^\circ$, $\beta = i = 50^\circ$ adopted here actually would result in a slightly reduced magnetic field strength as compared to that derived by Wade et al. (2011b), who adopted $i = 30^\circ$. Another possibility is of course that these slight discrepancies simply are related to insufficient assumptions for the wind electron temperature structure and/or the hydrogen occupation numbers (Section 3.2.1).

In addition, the velocity dispersion in the models is too low, predicting narrower and sharper peaked profiles than observed (Fig. 4, upper panel). To illustrate this further, the lower panel of Fig. 4 displays the same line profiles as the upper panel, but now with the model profiles convolved with an isotropic ‘macroturbulence’ of 100 km s$^{-1}$.\footnote{For the type of line transfer, which often is optically thick, such post-averaging of the line profiles computed for many time snapshots is more realistic than the simple pre-processed, time-averaged wind density used by Wade et al. (2011b) to model polarized electron scattering, which is more nearly optically thin.}
5 DISCUSSION AND CONCLUSIONS

We have demonstrated that radiation MHD simulations of a confined wind, together with detailed radiative transfer modelling, reproduce well the distinct periodic Hα emission observed in the magnetic O star HD 191612. We interpret this within the context of a DM, wherein the rotationally modulated spectral variations are results of a statistically overdense, low-velocity wind region around the magnetic equator.

While applied here only to HD 191612, the DM model may also well describe optical Balmer line variability in other magnetic O stars with $R_K > R_A$, such as $\theta^1$ Ori C and HD 148937 (Wade et al. 2006; Wade et al. 2011a). Indeed, the narrow Hα emission observed in HD 148937 suggests a line formation scenario in a DM, with the only significant difference to HD 191612 then being the stellar and/or magnetic geometry (Wade et al. 2011a), resulting in much smaller spectral variations for the former star. In future work, we intend to develop further this DM model and apply it to a broader sample of magnetic massive stars that show variable Balmer emission and are characterized by $R_K > R_A$.

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