Clumping in Hot Star Winds
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Large-scale wind structure due to magnetic fields

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Magnetic fields influence the dynamics of hot-star winds and create large scale structure. Based on numerical magnetohydrodynamic (MHD) simulations, we model the wind of θ^1 Ori C, and then use the SEI method to compute synthetic line profiles for a range of viewing angles as function of rotational phase. The resulting dynamic spectrum for a moderately strong line shows a distinct modulation, but with a phase that seems at odds with available observations.

1 Introduction

Magnetic fields can influence hot star winds significantly. Their overall influence on the wind dynamics can be characterized by a single magnetic confinement parameter,

$$\eta_* \equiv \frac{B_{eq}^2 R_*^2}{\dot{M} v_\infty}, \tag{1}$$

which characterizes the ratio between magnetic field energy density and kinetic energy density of the wind (ud-Doula & Owocki 2002).

Extensive magnetohydrodynamic (MHD) simulations show that, in general, for the stellar models with weak magnetic confinement ($\eta_* < 1$) field lines are stretched dynamical timescale into radial configuration by the strong outflow. However, even for magnetic confinement as weak as $\eta_* \sim 1/10$ the field can influence the wind density by diverting the wind material from higher latitudes towards the magnetic equator.

For stronger confinement ($\eta_* > 1$), the magnetic field remains closed over a limited range of latitude and height about the equatorial surface, but eventually opens into a nearly radial configuration at large radii. Within closed loops, material is channeled toward loop tops into shock collisions, leading to X-ray emission that is generally consistent with that derived in the original "magnetically confined wind shock" (MWCS) model first developed by Babel & Montmerle (1997). But in MHD simulations, once shocked material cools and becomes dense, it eventually is pulled by gravity back onto the star in quite complex and variable inflow patterns. Within open field flow, the equatorial channeling leads to oblique shocks that eventually forms a thin, dense, slowly outflowing disk at the magnetic equator (see Fig. 1).

Such large scale wind structures are inferred most directly from time variability in the blueshifted absorption troughs of UV P Cygni profiles. The study here thus uses the SEI (Sobolev with Exact Integration; Lamers et. al. 1987) to synthesize line profiles in MHD models of the O5.5 V star θ^1 Ori C, and then compares these with a sample UV line profiles observed by *FUSE*.

2 MHD model of θ^1 Ori C

θ^1 Ori C (O5.5 V) is the brightest member of the Orion Nebula. With a measured surface magnetic field of ca 1100 G (Donati et al. 2002), it is currently only one of two known magnetic O stars (the other being HD 191612, Donati et al. 2006). *Chandra* observations show that it is an unusually hard X-ray source with modulated flux on a rather long 15-day rotation period.

To model the magnetized outflow of of θ^1 Ori C, we perform 2D-MHD simulations wherein a dipole magnetic field with prescribed strength is suddenly introduce into an already relaxed spherically symmetric wind. Since the star rotates slowly, the rotation is relatively unimportant and can be ignored. The model then is allowed to evolve in time for a long period, ca. 1500 ksec or 17 days. Magnetic field quickly guides the wind material from opposite hemispheres towards the magnetic equator, where they shock and cool, emitting X-rays. The modeled emission matches remarkably well with X-rays observation (Gagné et al. 2005) with very little fine-tuning of free parameters.

This type of MCWS model also leads to a dense equatorial region wherein material within closed loops fall back onto the star as radiation is unable to drive the dense material, and the plasma in the outer region above the magnetosphere flows out relatively slowly. Such large-scale structure should leave distinct imprints on UV P Cygni profiles, and in this work we use these MHD models to compute synthetic UV line profiles with the SEI method, following closely the work of Cranmer & Owocki(1996).

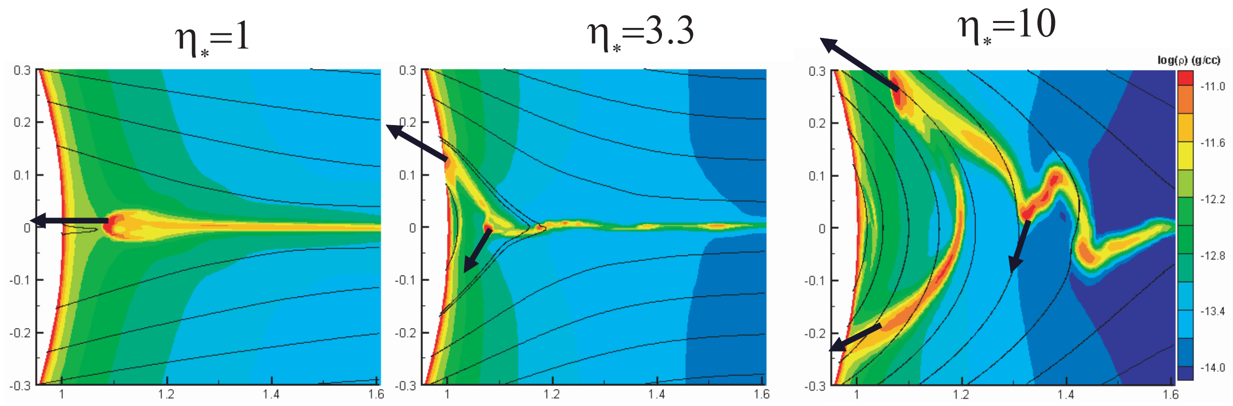

Figure 1: Logarithmic density for models with various magnetic confinement parameter η_*, as indicated, at arbitrarily chosen time to show structure created by magnetic fields.

3 Dynamical SEI line profiles

Ultraviolet P Cygni profiles are excellent diagnostics for probing wind structure in hot stars. Their time variations tell us something about the temporal evolution of the structure as well.

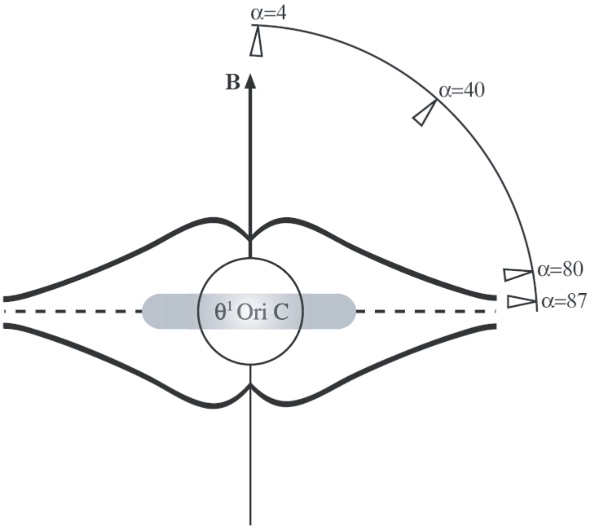

Figure 2: Schematic view of θ^1 Ori C. The vector indicates the magnetic axis and the semicircle represents the viewing angles in degrees spanning the rotational phases of 0 to 1.0. [Figure adopted from Gagné et al. (2005).]

Here we compute time variable synthetic UV line profiles from our simulations by positioning an 'observer' at different viewing angles α between the line of sight and the magnetic pole. If β is the obliquity (the angle between the rotational and magnetic axes), i the inclination angle, and ϕ is the rotational phase of the observations, then α can computed from (Gagné et al. 2005):

$$\cos\alpha = \sin\beta\cos\phi\sin i + \cos\beta\cos i\,. \qquad (2)$$

Quite fortuitously, for θ^1 Ori C $\beta \approx i \approx 45^o$. This implies that the viewing angle α covers a full hemisphere, i.e. from co-latitude $\theta = 0$ to 90 degrees for the northern part, as shown in Fig. 2, or possibly from 90 to 180 degrees for the southern part, as there is an ambiguity about which pole of the star is facing the earth. Our 2D-MHD simulations are fairly north-south symmetric, and so either choice yields similar results. To mimic time variability on a rotational time scale, we choose time $t = 0$ to be an arbitrary time snapshot from our simulation, and then allow the observer to move around the star, as depicted in Fig. 2 (see also, Gagné et al. 2005).

The left panel of Fig. 3 shows the total SEI flux quotient, the absorption plus the emission, expressed as the deviation from the time average, and computed for a relatively strong line. Over the poles (near phases 0 and 1) the strong absorption of relatively dense and fast wind broadens the line by ca. 4000 km/s. By contrast, near the magnetic equator (phase 0.5), the absorption trough is relatively narrow, due to slowly moving, very dense, equatorial disk-like outflow. There is also a weak signature of red-shifted absorption from the dense material that falls backs onto the stellar surface near the magnetic equator (phase 0). Although the equator represents only a geometrically small region in this figure, in the phase variation it occupies a relatively large interval, due to the particular geometry that keeps the equator facing the earth for longer period of time than the poles (see Eq. 2).

The right panel in the same figure shows the ob-

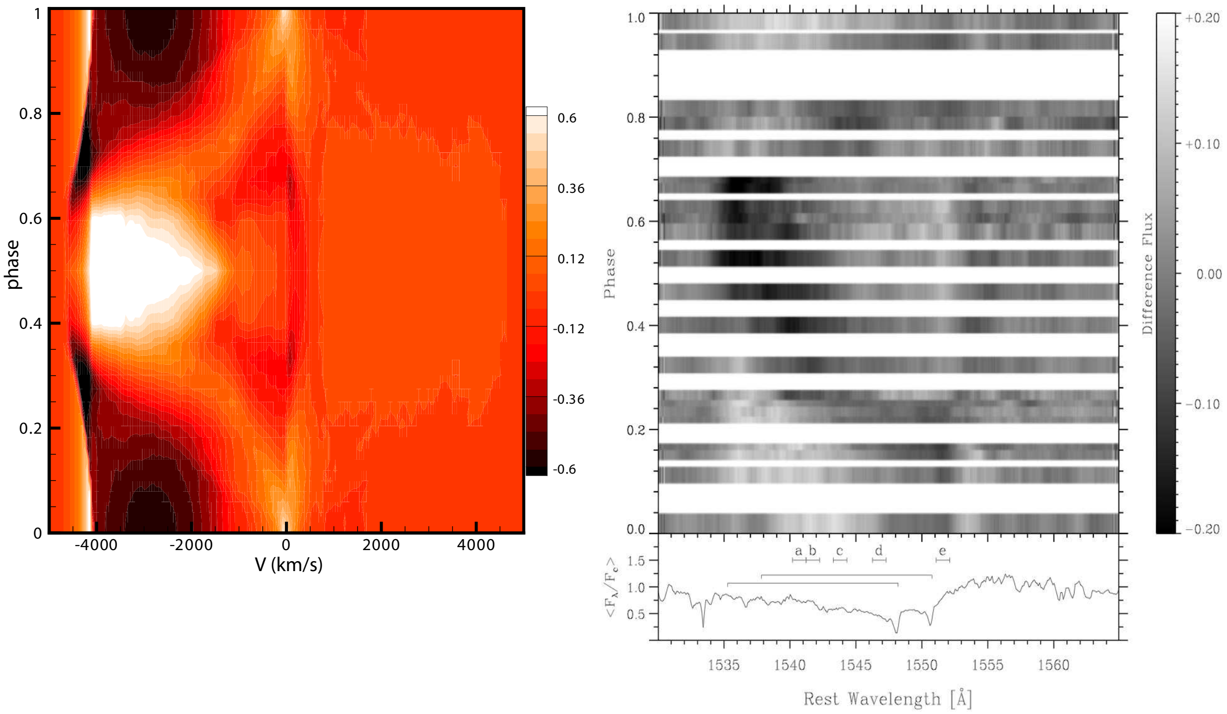

Figure 3: Left Panel: Computed SEI flux quotient (deviation from the time average) for a strong line. Right panel: Observed flux quotient (courtesy of Alex Fullerton).

served *FUSE* UV profile for the C IV doublet line (courtesy of Alex Fullerton), plotted also as a flux quotient. The model variability is a factor two or so stronger than the observations, and moreover exibits almost an opposite sense with phase. However, there is a possibility that phase of the observed data has been miscalculated by ca 0.6 or so, in which case the match will be significantly better. This issue is currently under investigation. Moreover, the observed data also lacks the clear symmetry around the phase 0.5 that our simulation model predicts. Such discrepancies are puzzling and will require further study.

4 Conclusion

In this work, we have shown that the magnetic fields can create large scale structure that is directly related to wind magnetic confinement parameter, η_*. Computed SEI synthetic UV P Cygni profiles show clear temporal and spatial variation. However, such computed profiles do not match the observed data very well. Further studies are under way to investigate this discrepancy.

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Townsend: Just a remark: I believe redshifted absorption features have already been detected in the wind of θ' Ori C. So, already there is an encouraging match between observations and your model for the star.

Feldmeier: Owocki, Cranmer & Gayley showed a few years ago how important non-radial forces are in wind-compressed disk calculations: these forces may be small, but they alter velocities that are themselves small, so may be important. How significant is the neglect of non-radial forces in your model?

ud-Doula: Non-radial forces in MHD models are not very important, because magnetic fields make the wind flow in a constrained motion towards the magnetic equator. In WCD models only a small force can disrupt the "disk", but here you need a much larger force. In my direct comparison models, non-radial forces make a difference on a scale $10 - 15\,\%$.

Cohen: Soft X-ray lines are broad in θ' Ori C (implying that instabilities are present), but hard X-ray lines are narrow (they come from magnetically confined wind shocks). So, both small and large structures co-exist. What is the lateral scale of structure in your 3D simulation?

ud-Doula: My simulation extends to $R = 10\,R_*$, and covers a cone of $45°$. As such, I estimate lateral structures to be a few tenths of a stellar radius.

Owocki: Just to be explicit, these 2D and 3D MHD models are based on a CAK/Sobolev method for the line force. Such models would be far more difficult with non-local force treatments (SSF), because these require computationally expensive integrations.