Clumping in Hot Star Winds
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Modeling DACs in UV lines of massive hot stars

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We apply the 3-dimensional radiative transport code WIND3D to 3D hydrodynamic models of Corotating Interaction Regions to fit the detailed variability of Discrete Absorption Components observed in Si IV UV resonance lines of HD 64760 (B0.5 Ib). We discuss important effects of the hydrodynamic input parameters on these large-scale equatorial wind structures that determine the detailed morphology of the DACs computed with 3D transfer. The best fit model reveals that the CIR in HD 64760 is produced by a source at the base of the wind that lags behind the stellar surface rotation. The non-corotating coherent wind structure is an extended density wave produced by a local increase of only 0.6% in the smooth symmetric wind mass-loss rate.

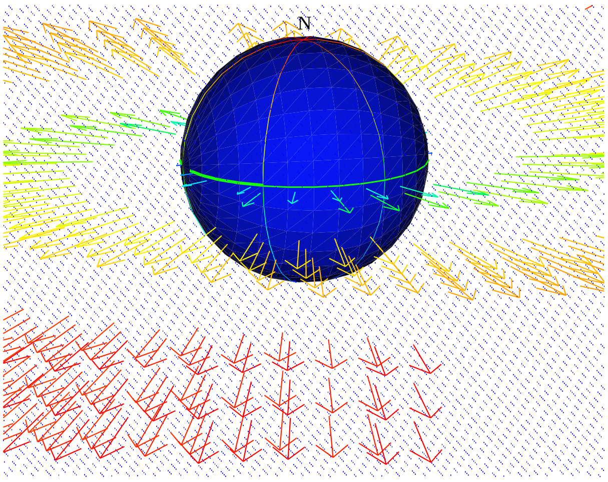

Figure 1: Schematic representation of two CIRs in the plane of the equator used in 3D radiative transfer calculations with WIND3D.

1 Introduction

Discrete Absorption Components (DACs) observed in the broad P Cygni profiles of UV resonance lines are important tracers of the dynamics of line driven winds in massive hot stars. DACs are observed to propagate bluewards through the UV line profiles on time scales comparable to the stellar rotation period (Massa et al. 1995; Prinja 1998). Hydrodynamic models of Corotating Interaction Regions (CIRs) have been proposed by Cranmer & Owocki (1996) to explain the observed DAC properties qualitatively. These large-scale wind structures are spiral-shaped density- and velocity-perturbations winding up in or above the plane of the equator that can extend from the stellar surface to possibly several tens of stellar radii. The CIRs can be produced by intensity irregularities at the stellar surface, such as dark and bright spots, magnetic loops and fields, or non-radial pulsations. The surface intensity variations alter the radiative wind acceleration locally, which creates streams of faster and slower wind material.

We investigate to what extent the CIR wind model can *quantitatively* explain the *detailed* DAC properties observed in B0.5 Ib supergiant HD 64760. Fullerton et al. 1997 pointed out how exceptional IUE data from the MEGA campaign (Massa et al. 1995) have made it a key object for studying the origin and nature of hot-star wind variability. We discuss the development of a new 3D radiative transfer code WIND3D to best fit the DAC morphology (e.g. shape and flux changes) observed in the unsaturated absorption portion of the Si IV λ1395 line. The hydrodynamic CIR models developed for this purpose are discussed in a companion paper (Blomme 2007). Animations are online at `alobel.freeshell.org/conference.html`.

2 3D radiative transfer: Wind3D

WIND3D computes 3D spatial non-LTE radiative transfer in the 2-level atom approximation for optically thick resonance lines formed in scattering dominated extended winds of massive hot stars. Its implementation is based on the finite element method described by Adam (1990). The code accepts arbitrary 3D wind-density and -velocity distributions. The 3D transfer scheme further extends Adam's Cartesian method with three new aspects: (i) We considerably accelerate the (exact) lambda iteration of the source function on 71^3 grid points with appropriate starting values from the Sobolev approximation. (ii) Since the lambda iteration is the bottleneck of the numerical transfer problem we fully parallelize the mean intensity integration over 80^2 spatial an-

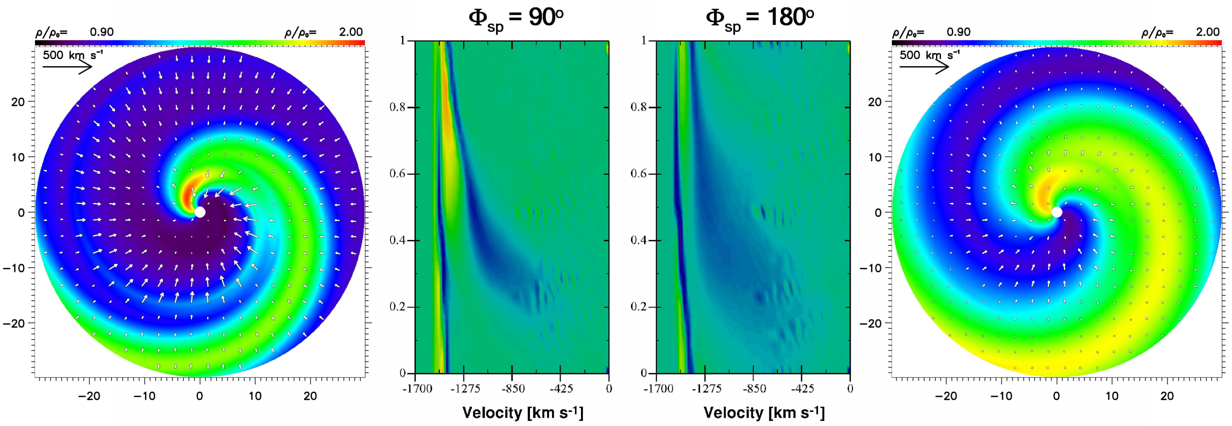

Figure 2: Hydrodynamic CIR models for spot opening angles $\Phi_{\rm sp}$=90° (left-hand panel) & 180° (right-hand panel). The dynamic spectra (middle panels) reveal width changes of the DAC base for an observer viewing the rotating models from the south side of the images in the equatorial plane.

gles. (iii) We introduce a new technique that 3D interpolates the converged (non-Sobolev) source function to a higher resolution (spatial) grid of 700^3 grid points to solve the final 3D transfer equation for very narrow line profile functions. This method resolves the small flux variations in the absorption portions of very broad unsaturated P Cygni profiles.

Parameterized 3D models of CIRs already provide comprehensive comparisons to general properties observed in DACs. We consider a β-velocity law for an isothermal wind with $\beta \simeq 1$. The smooth wind is perturbed with 3D spiraling density enhancements wound around the central star (Fig. 1). The wind velocities inside the CIRs also assume the β-law and are directed radially (velocity vectors drawn in the equatorial plane). The CIR model of Fig. 1 causes the width of DACs computed for an observer in the plane of the equator to decrease because the range of velocities in the CIR projected in the observer's line of sight (inside the cylinder in front of the stellar disk) decreases at larger distances from the star.

For the hydrodynamic CIR models a local radiation force enhancement (or surface 'spot') is introduced at the base of the stellar wind (Blomme 2007). The resulting equatorial density- and velocity-structures are inserted around the star with a thickness of 1 R_* around the equatorial plane. Outside this region, the model density and velocity assume the smooth wind values. In Fig. 2 the spot opening angle $\Phi_{\rm sp}$ is increased from 90° to 180°. The spot co-rotates with the stellar surface $v_{\rm sp} = v_{\rm rot}$, and the spot intensity $A_{\rm sp} = 0.5$. The increase of $\Phi_{\rm sp}$ considerably alters the FWHM evolution of the DAC computed in Si IV λ1395. The DAC base broadens because extra wind material injected by the spot becomes more spread out over the equatorial plane. The maximum of ρ/ρ_0 in the CIR occurs within ~5 R_* above the stellar surface. Inside this region extra wind material is distributed over a larger geometric region above the bright spot, which also considerably broadens the density contrast in the tail of the CIR. When this region rotates in front of the stellar disk (around rotation phase 0.2 in the dynamic spectra) the DAC base broadens because the range of velocities projected in the observer's line of sight (that contribute to the DAC opacity) increases. The wind streams almost radially through the CIR density structure. The wind flow decelerates due the relative increase of wind density in a region behind the CIR density contrast maximum. It causes a trailing velocity plateau (between the star and CIR) which strongly contributes to the DAC absorption at larger distances from the star since the line optical depth in the Sobolev approximation is $\tau \simeq \rho \, / \, |dv/dr|$.

3 Modeling DACs in HD 64760

We determine a recurrence period of 10.3±0.5 d for the two DACs (right-hand panel of Fig. 3) observed in the Si IV lines of HD 64760 in 1995 January 13-29 (Massa et al. 1995) by flux filtering the nearly horizontal rotational modulations (Lobel & Blomme 2007). We can assume that this star is observed equator-on (sin $i \simeq 1$). The surface rotation velocity of the fast-rotating supergiant is $v_{\rm rot}$=265 km s^{-1} which, for R_*=22 $R_\odot$, yields a rotation period of 4.13 d. The latter period is 2.5 times shorter than the observed DAC recurrence period. It reveals that the spot cannot co-rotate with the stellar surface. We therefore use a single bright spot with the spot parameter $v_{\rm sp}$ set equal to $v_{\rm rot}$ / 2.5 in the hydrodynamic wind models. We compute a large grid of dynamic spectra from a grid of hydrodynamic mod-

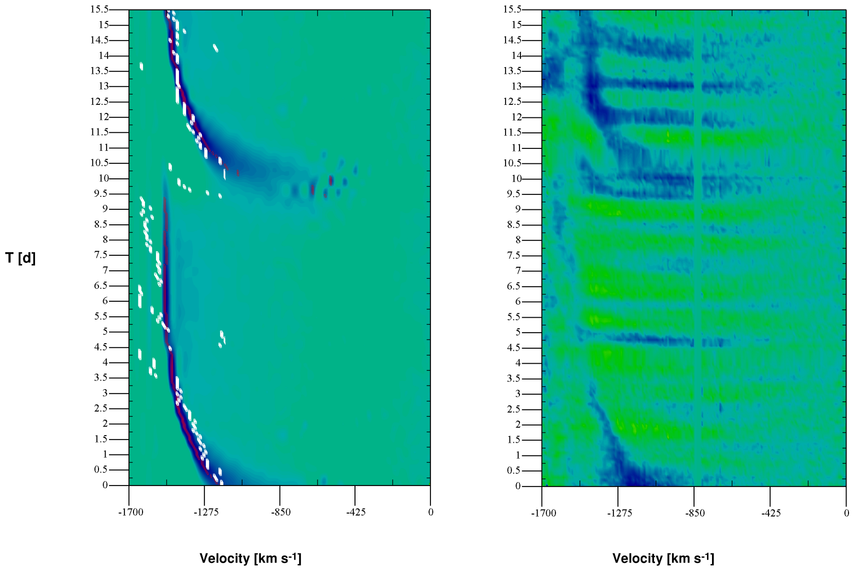

Figure 3: Best fit dynamic spectrum (left-hand panel) of Si IV $\lambda1395$ compared to the observed spectrum (right-hand panel) of HD 64760. The computed DAC shape fits the observations in detail.

els for a broad range of spot parameters $\Phi_{\rm sp}$ and $A_{\rm sp}$, using the smooth wind properties of HD 64760. We obtain a best fit from a least-squares fit procedure between the observed and computed DACs for $\Phi_{\rm sp} = 50^\circ \pm 5^\circ$ and $A_{\rm sp} = 0.1 \pm 0.05$ (see the hydrodynamic model in Fig. 1 of Blomme 2007). In the left-hand panel of Fig. 3 the velocity positions of the flux minima in the computed DAC differ by less than $\sim$50 $\mathrm{km\,s^{-1}}$ from the observed velocity positions (white dots) for $0\ \mathrm{d} \le T \le 3.5\ \mathrm{d}$, and $10\ \mathrm{d} \le T$ 15.5 d. The FWHM of the computed DAC decreases from $\sim$100 $\mathrm{km\,s^{-1}}$ at $T = 0$d to $\sim$ 20 $\mathrm{km\,s^{-1}}$ around $T = 3.5$d, in agreement with the narrowing of the observed DAC. The DAC width remains almost constant over the following 6.5 d, after which it fades away. The ‘tube-like’ extension of the DAC base is also observed (right-hand panel). This characteristic DAC morphology can only correctly be computed with hydrodynamic structured wind models.

4 Conclusions

We demonstrate with 3D radiative transfer calculations in hydrodynamic CIR models of HD 64760 that the DACs observed in the Si IV UV resonance lines are due to a region of enhanced mass-loss at the base of the wind that lags 2.5 times behind the surface rotation. Our detailed DAC modeling reveals that this region is not locked to the stellar surface. It indicates that magnetic fields at the equator are an unlikely source for additional wind material yielding an asymmetric structured wind with an extended density wave in the equatorial plane. The integration of the best fit hydrodynamic CIR model for HD 64760 provides a very small increase of only 0.6% in the mass-loss rate of the spherically symmetric smooth wind model. It signals that DACs are generally expected in hot-star winds since they result from rather small variations of the spherically symmetric mass-loss rate. These coherent CIR structures may become perturbed by wind clumping on much smaller length scales. They will however built up again very rapidly as well, provided that the perturbation time-scales are sufficiently short for the large-scale wind structures to completely develop and to produce the slowly blueward drifting recurring DACs in unsaturated UV spectral lines.

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Massa: First, I am happy to see data we obtained over 15 years ago still being used. Second, do you have any thoughts on how to put all of the different effects into the wind, i.e. DACs, CIRs and clumps?

Lobel: Thank you. These IUE data are a real treasure. My detailed fits to DACs with WIND3D show that the mass source of the "large-scale" wind structures (CIRs) is not locked onto the stellar surface. It reveals something fundamental about this source at the base of the wind (possibly an interference pattern caused by non-radial pulsations). Since I find a density increase in CIRs of only $\sim 20\%$, any other kind of wind perturbation (large or small scale) can break them up, but only small mass loss rate enhancements suffice to build them up again. My best guess for the source of the clumps is a cascading phenomenon down to smaller length scales due to Rayleigh-Taylor instability. The horizontal "modulations" in the lines are hard to fit with hydrodynamic models (as opposed to kinematic models), so my best guess is that their origin is very different from the DACs, possibly some unusual hydrodynamic effect at the photosphere in the plane of the equator.

Fullerton: I like the simulations of DACs in HD 64760 very much. I think this is the first time these features have been modelled, and your success is very encouraging. Could you comment further on the hydrodynamic problems associated with trying to reproduce the modulations? I am puzzled that they do not figure in your CIR simulations, since their "phase bowing" is thought to be a signature of spiral-shaped structures.

Lobel: The main problem with calculations of bow-shaped modulations in HD 64760 is that the ratio $v_\infty \, / \, v_{\rm rot}$ makes them to drift too slowly bluewards compared to the IUE observations in Si IV. The spot model is adequate to explain the "slowly" shifting DACs, but for the modulations it fails to match them quantitatively. Kinematic models with sector-like density enhancements do produce the phase bowing on nearly horizontal line structures, but with full hydrodynamic models they always drift too slowly using simple spot models at the surface. Perhaps some kind of highly supersonic expansion at the base of the wind near the photosphere (much faster than what the spot models produce) could provide models that work?