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3-D Radiative Transfer Modelling of Massive-Star UV Wind Line Variability

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Abstract

We present detailed semi-empiric models for rotational modulations observed in ultraviolet wind lines of B0.5 supergiant HD 64760. We model the Rotational Modulation Regions (RMRs) with advanced 3-D radiative transfer calculations in the stellar wind and quantitatively fit the time-evolution of the Si IV λ1395 resonance line. We find that the RMRs are due to linearly-shaped narrow sector-like density enhancements in the equatorial wind. Unlike the Co-rotating Interaction Regions (CIRs) which produce Discrete Absorption Components in the line, the RMRs do not spread out with larger distance above the stellar surface. The detailed best fit shows that the RMRs of HD 64760 have maximum density enhancements of ~17% above the surrounding smooth wind density, about twice smaller than the hydrodynamic models of CIRs that warp around the star. The semi-empiric 3-D transfer modelling reveals that the narrow spoke-like RMRs must co-exist with broader and curved large-scale CIR wind density structures in the equatorial plane of this fast rotating Ib-supergiant.

Session: Atmospheres, mass loss and stellar winds Individual Objects: HD 64760, ξ Per, HD 150168

Introduction

Accurate mass-loss rates determined from quantitative spectroscopy are important to understand the wind-momentum luminosity relation of massive stars which is affected by large-scale wind structures and clumping (Puls, 2008). Rotational modulations and Discrete Absorption Components (DACs) are important tracers of large-scale wind dynamics in massive hot stars. DACs are recurring absorption features observed in ultraviolet resonance lines of many OB-stars. They drift bluewards in the absorption portion of P-Cygni profiles and result from spiral-shaped density- and velocity-perturbations winding up in or above the plane of the equator (see Fig. 1 of Lobel 2008). Lobel & Blomme (2008) demonstrated with 3-D radiative transfer (RT) modelling and hydrodynamic simulations for the detailed DAC evolution in HD 64760 (B0.5 Ib) that these wind spirals are large-scale density waves caused by two unequally bright equatorial spots rotating five times slower than the stellar surface. Hydrodynamic models of structured winds with the density waves (for historical reasons they are termed 'Co-rotating Interaction Regions' or CIRs) reveal only a very small increase of less than 1% in the smooth symmetric wind mass-loss rate. A characteristic property of the best fit CIR model is that the local increase of mass-loss from the bright spots creates lanes of enhanced density throughout the wind that always tend to broaden farther above the stellar surface. The CIR widths rapidly increase beyond their spot diameters, while the CIRs warp around the star over several tens of stellar radii, thereby producing two slowly migrating DACs with a period of 10.3 d. The rotational modulations of HD 64760, on the other hand, show a much shorter period of $\simeq$1.2 d and are morphologically very different from the DACs. They are nearly-flat absorption components lasting only 0.5 d to 0.75 d with velocities that range from $\sim$0 $\mathrm{km\,s^{-1}}$ to $\sim v_{\infty}$=1600 $\mathrm{km\,s^{-1}}$. They sometimes appear to intersect the slower DACs and can reveal a remarkable 'banana' or bow-shaped intensity pattern with broad flux minima around $\sim$930 $\mathrm{km\,s^{-1}}$. Blomme (2008) showed that hydrodynamic spot models are unable to match the modulations of HD 64760 quantitatively (as opposed to the DACs) because $v_{\rm rot}/v_{\infty}$ $\simeq$0.16, with $v_{\rm rot}$ $\simeq$265 $\mathrm{km\,s^{-1}}$. The Rotational Modulation Regions (RMRs) in these spot models fail to reach v_{∞} sufficiently rapidly (e.g., as they turn too quickly around the star) and therefore lack the nearly linear absorption structure of the modulations above $\sim$1000 $\mathrm{km\,s^{-1}}$.

In this paper we present a semi-empiric model for the RMRs that fits the modulations of HD 64760 in detail. We adapt the hydrodynamic two-spot CIR model with parameterized wind density structures that quantitatively match the modulations. Our approach is motivated by constraining the geometry and density profiles of RMRs with 3-D RT calculations using semi-empiric models before embarking upon more sophisticated multi-D hydrodynamic simulations.

3-D Radiative Transfer Modelling the Structured Wind of HD 64760

We use the WIND3D code developed in Lobel & Blomme (2008) for detailed modelling the winds of stars with extended atmospheres. WIND3D solves the non-LTE radiation transport problem in three geometric dimensions for arbitrary gas density structures and velocity fields, without assumptions of axial

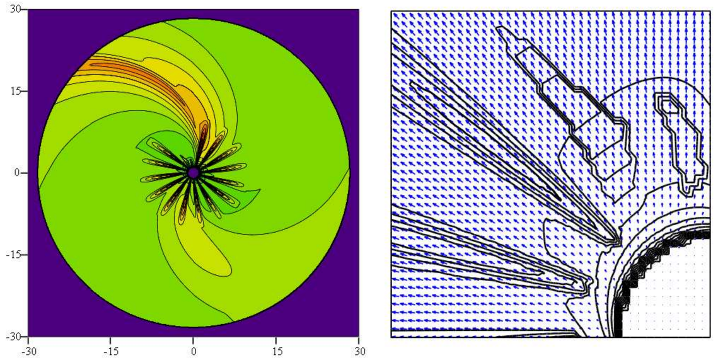

Figure 1: Semi-empiric model for the equatorial wind density of HD 64760 from 3-D radiative transfer fits to the dynamic spectrum of Si IV λ1395. The right-hand panel shows the bow-shaped density contours (*full drawn lines*) of the upper modulation in Fig. 3. Arrows mark the wind velocity in the hydrodynamic CIR model (*see text*).

symmetry. The numerical transfer scheme is very accurate for tracing small variations of local density- and velocity-gradients on line opacity in strongly scattering-dominated supersonically expanding stellar winds. The properties of the large-scale wind structures are constrained with detailed 3-D transfer fits to the slowly bluewards drifting DACs in Si IV λ1395 of HD 64760. A hydrodynamic model with two spots of unequal brightness and size on opposite sides of the equator, 20% and 8% brighter than the stellar surface, and with opening angles of 20° and 30° diameter, provides the best fit to the DACs.

While DACs are observed in many OB-stars, rotational modulations are often observed only in stars with large $v$sin$i$-values, such as HD 64760, ξ Per (O7), and HD 150168 (B1). Since these stars are observed almost equator-on it signals that RMRs are likely confined to the equatorial wind and become invisible toward smaller inclination angles. The RMRs therefore possibly result from unusual wind dynamics in the equatorial plane of fast rotating massive hot stars. Kaufer et al. (2006) investigate variability observed in optical lines of HD 64760 and propose a model with perturbations (spots) resulting from the interference of nonradial pulsations at the base of the wind.

Detailed Modelling Rotational Modulations with Wind3D

Figure 1 shows the best-fit density model computed with ZEUS3D for two CIRs in the wind of HD 64760. We insert 16 central spoke-like RMRs with small opening angles in the CIR model that best fit the horizontal rotational modulations

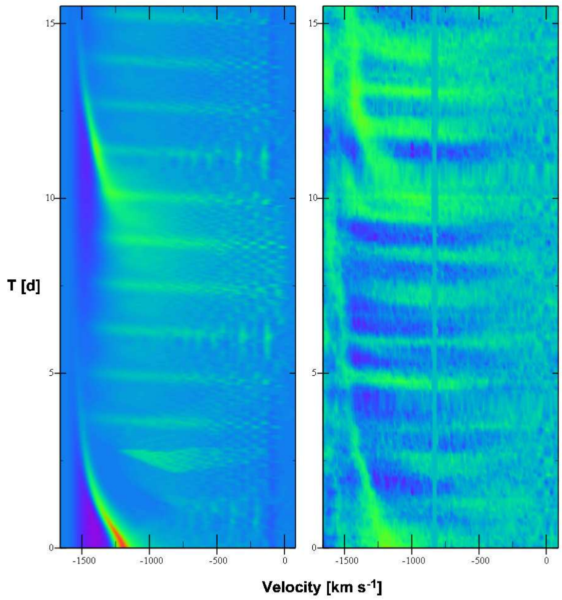

Figure 2: Dynamic spectrum of Si IV λ1395 observed during 15.5 d in HD 64760 (*right-hand panel)* compared to 3-D radiative transfer calculations (*left-hand panel*) with the wind model of Fig. 1. The horizontal absorptions are modulations.

in the dynamic IUE spectrum of Si IV (Fig. 2). Our semi-empiric wind model for the modulations differs quantitatively from the kinematic model of Owocki, Cranmer, & Fullerton (1995) because the RMRs do not appreciably curve over $\sim$10 R_*. The RMRs extend very linearly (in narrow sectors) throughout the wind, away from the stellar surface, with maximum widths below 1 R_*.

Figure 3 shows a portion of the dynamic spectrum of Fig. 2 observed between 0 d and 3.1 d (*upper right-hand panel*). The lower DAC in Fig. 2 slowly migrates bluewards in time from $\sim$1100 $\mathrm{km\,s^{-1}}$ to $\sim$1400 $\mathrm{km\,s^{-1}}$, while two rotational modulations appear around 1.2 d (*lower modulation*) and 2.5 d (*upper modulation*). The upper modulation is observed over $\sim$0.7 d and reveals a peculiar 'banana'-like shape, whereas the lower one occurs over $\sim$0.5 d with a more irregular absorption pattern below $\sim$800 $\mathrm{km\,s^{-1}}$.

The upper left-hand panel of Fig. 3 shows the best fit with WIND3D using the wind density model of Fig. 1. We insert parameterized wind density structures in the CIR hydro model of HD 64760 (*left-hand panel of Fig. 1*) that quantitatively match the time- and velocity-position and relative absorption flux of the modulations. We semi-empirically delineate the borders of two

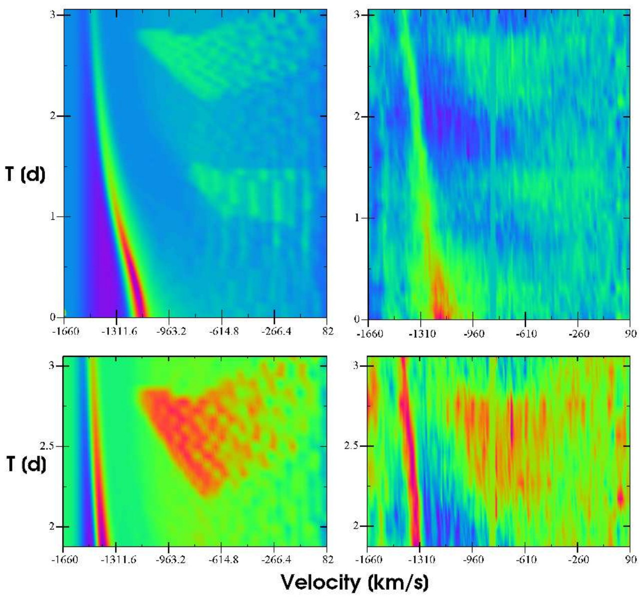

Figure 3: Rotational modulations computed with WIND3D (*left-hand panels*) and observed (*right-hand panels*) in Si IV λ1395 of HD 64760. The lower panels show the best fit and observed upper 'bow-shaped' rotational modulation in more detail.

RMRs (for the upper and lower modulations) to compute the best-fit structured-wind density model. The lower panels of Fig. 3 show the best-fit theoretical (*left-hand panel*) and observed (*right-hand panel*) flux contrast of the upper modulation between 1.8 d and 3.1 d in the upper panels. The peculiar 'wedge-like' shape at the short-wavelength side of the modulation is properly matched with the decrease of opening angle in the RMR density enhancement beyond 1 R_* above the stellar surface (*right-hand panel of Fig. 1*). The wind velocities in the upper modulation do not exceed $\sim$1200 $\mathrm{km\,s^{-1}}$ around 2.8 d. The upper modulation does not intersect the velocity position of the lower DAC around 1400 $\mathrm{km\,s^{-1}}$. The upper modulation density model in Fig. 1 does therefore not exceed a distance of $\sim$2.5 R_* above the stellar surface since the smooth wind velocity exceeds $\sim$1200 $\mathrm{km\,s^{-1}}$ only beyond that radius. We therefore attribute the remarkable 'banana'-shape observed in the upper modulation to the intrinsically bow-shaped front- and back-side density enhancement borders of the RMR in the right-hand panel of Fig. 1. The flux minimum observed in the upper modulation requires a RMR density maximum of $\sim$17% above the smooth wind density around $\sim$3 R_* above the stellar surface in the model.

The semi-empiric wind model of HD 64760 in Fig. 1 provides a reliably accurate approximation of the equatorial wind structure we will investigate elsewhere with ab-initio 3-D hydrodynamic simulations. The narrow spoke-like RMRs are centered around the star with small inclination angles of 6° from the radial direction, having equatorial opening angles of 10°. Similar as for both CIRs in the model, the RMRs are large-scale density- and velocity-structures in the fast radiatively accelerating equatorial wind. We do not semi-empirically model the RMRs beyond 10 R_{*} above the surface because the modulations in Fig. 2 are observed up to v_{∞}, while the wind velocity assumes already ∼95% of v_{∞} at that distance. The 3-D RT modelling reveals that *linear* RMR wind density enhancements are required to quantitatively fit the horizontal modulations. The RMRs are *linear* density structures in the equatorial wind because the modulations stay flat beyond 1000 $\mathrm{km\,s^{-1}}$. The maximum RMR density contrast of ∼17% is about half the maximum of ∼31% in the CIR model of the lower DAC. The RMRs can therefore not appreciably alter the mass-loss rate of the smooth wind model. This was also concluded from detailed 3-D RT modelling the DACs of HD 64760 in Lobel & Blomme (2008).

Conclusions

We perform 3-D radiative transfer calculations for the rotational modulations in Si IV λ1395 of HD 64760. We find with semi-empiric best fits that these horizontal line absorptions are caused by very linearly shaped density enhancements in the equatorial wind up to ∼10 R_{*}. The RMRs do not exceed ∼17 % of the smooth wind density, and do therefore not significantly change the stellar mass-loss rate. Lobel & Blomme (2008) showed that the DACs in Si IV are caused by extended density waves of CIRs due to two bright equatorial spots that lag behind the surface rotation. We propose that the RMRs result from mechanical wave action producing narrow spoke-like wind collision regions around the star due to stellar nonradial pulsations at the fast-rotating wind base.

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