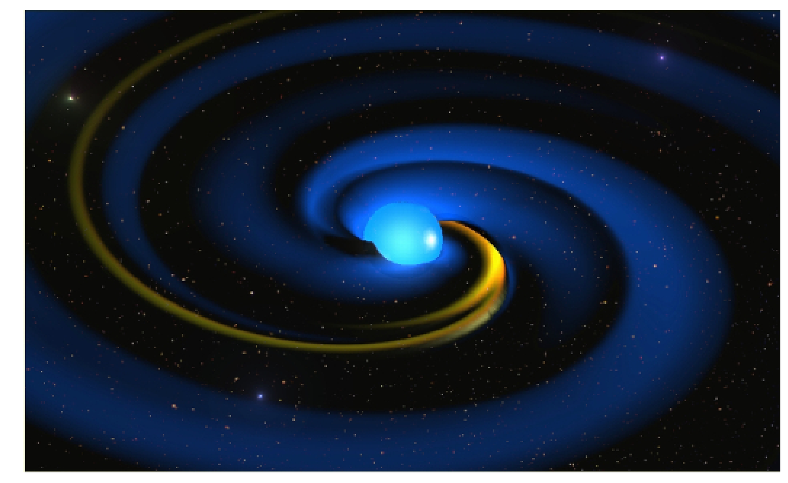
Radiative Transfer Modelling of Rotational Modulations in B Supergiant HD 64760



A. Lobel & R. Blomme

Royal Observatory of Belgium

ABSTRACT

We develop parameterized models for the large-scale structured wind of blue supergiant HD 64760 (B0.5 Ib) based on best fits to Rotational Modulations and Discrete Absorption Components (DACs) observed with IUE in Si IV λ1400. The fit procedure employs the Wind3D code with non-LTE radiative transfer (RT) in 3-D. We parameterize the density structure of the input models in wind regions (we term "Rotational Modulation Regions" or RMRs) that produce Rotational Modulations, and calculate the corresponding radial velocity field from CAK-theory for radiatively-driven rotating winds. We find that the Rotational Modulations are caused by a regular pattern of radial density enhancements that are almost linearly shaped across the equatorial wind of HD 64760. Unlike the Co-rotating Interaction Regions (CIRs) that warp around the star and cause DACs, the RMRs do not spread out with increasing distance from the star. The detailed RT fits show that the RMRs in HD 64760 have maximum density enhancements of ~17 % above the surrounding smooth wind density, about two times smaller than hydrodynamic models for CIRs. Parameterized modelling of Rotational Modulations reveals that nearly linear-shaped (or "spoke-like") wind regions co-exist with more curved CIRs in the equatorial plane of this fast rotating B-supergiant. We present a preliminary hydrodynamic model computed with Zeus3D for the RMRs, based on mechanical wave excitation at the stellar surface of HD 64760.

INTRODUCTION

Rotational modulations and Discrete Absorption Components (DACs) are important tracers of the large-scale wind dynamics in hot massive stars. DACs are recurring absorption features observed in UV resonance lines of many OB-stars. They slowly drift bluewards and result from spiral-shaped density- and velocity-perturbations in or above the plane of the equator. Lobel & Blomme (2008) demonstrated with 3-D RT modelling and hydrodynamic simulations for the detailed DAC evolution observed in HD 64760 (B0.5 Ib) that these wind spirals are large-scale density waves caused by bright equatorial spots. The rotational modulations, on the other hand, show a much shorter period of ~1.2 d and are morphologically very different from the DACs. They are nearly-flat absorption components lasting for only 0.5 d to 0.75 d, with velocities ranging from ~0 km s^{-1} to ~V_∞ =1560 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 ~930 km s^{-1}. We present a semi-empiric model for the RMRs that fits the modulations of HD 64760 in detail. We develop parameterized wind density structures that quantitatively match the modulations. Our approach is motivated by investigating the geometry and density profiles of the RMRs with 3-D RT calculations from semi-empiric models, before embarking upon more sophisticated hydrodynamic simulations.

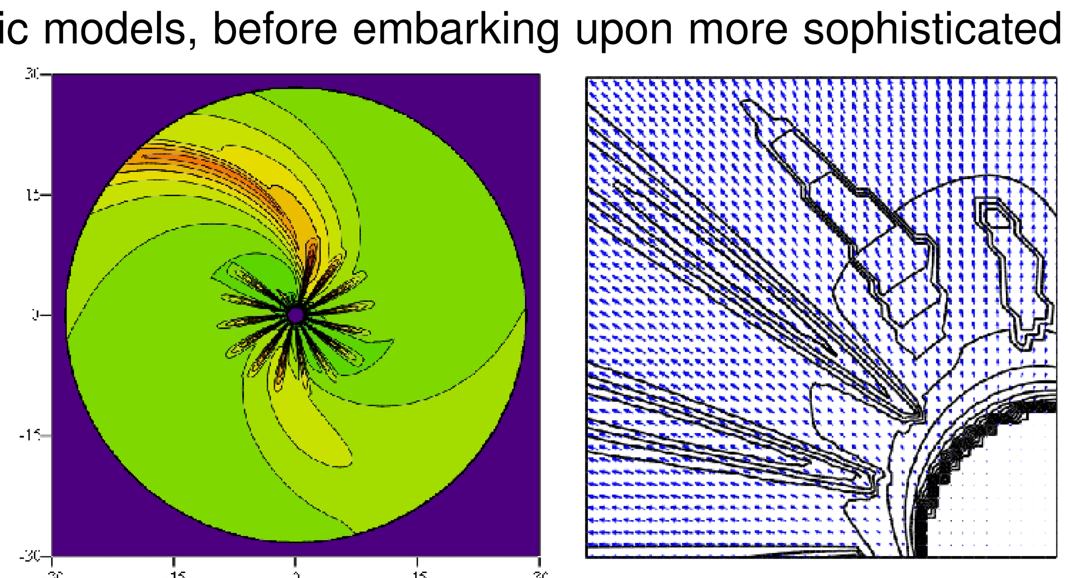


Figure 1. Semi-empirically parametrized model of the equatorial wind density structure of HD 64760 we compute with 3-D radiative transfer fits using Wind3D to the dynamic spectrum of Si IV λ1395. The right-hand panel shows the bow-shaped density contours (full drawn lines) for the modulations in Fig. 3. Blue arrows mark wind velocities to ~3 R_* above the stellar surface in the model.

PARAMETRIZED MODEL OF ROTATIONAL MODULATIONS

Figure 1 shows the best-fit parametrized density model for the structured wind of HD 64760. Two spiral-shaped CIRs and 16 RMRs (with small opening angles of ~10°) best fit respectively the DACs and the horizontal rotational modulations in the dynamic IUE spectrum of Si IV (right-hand panel of Fig. 2). This semi-empiric wind model for the modulations differs quantitatively from the kinematic model of Owocki, Cranmer, & Fullerton (1995) because the RMRs do not appreciably turn over ~10 R_*. The RMRs extend very linearly (in rather narrow "spoke-like" regions) throughout the wind above the stellar surface, with maximum widths below 1 R_*. The upper right-hand panel of Fig. 3 shows a portion of the dynamic spectrum in Fig. 2 observed between 0 d and 3.1 d. The lower DAC in Fig. 2 slowly accelerates from ~1100 km s^{-1} to ~1400 km s^{-1}, while two rotational modulations occur around 1.2 d ("lower modulation") and 2.5 d ("upper modulation"). The upper modulation is observed over ~0.7 d and shows a peculiar 'banana'-like shape, whereas the lower modulation occurs over ~0.5 d with a more irregular absorption pattern observed below ~800 km s^{-1}.

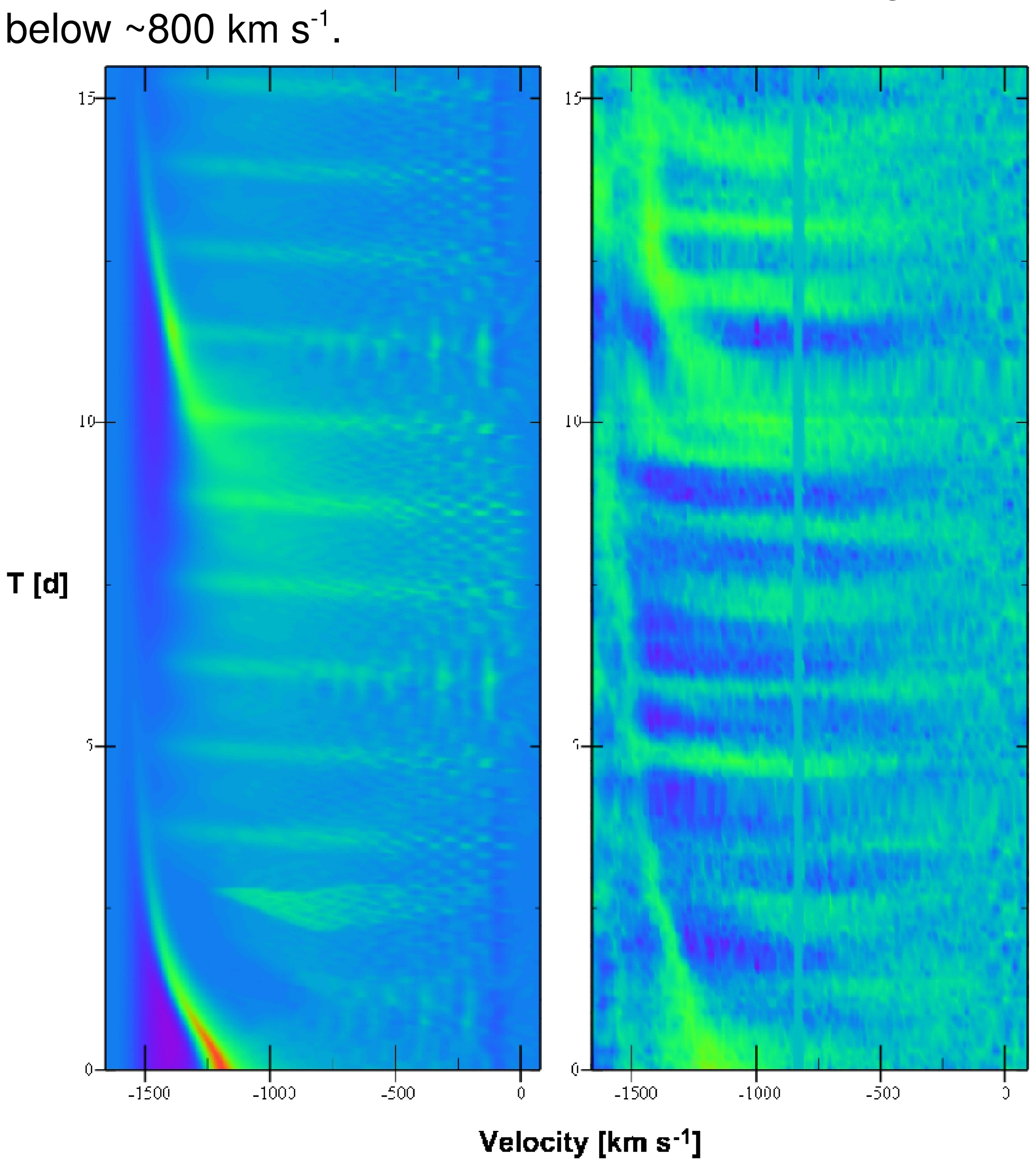


Figure 2. Dynamic spectrum of Si IV λ1395 observed during 15.5 d in HD 64760 (right-hand panel), compared to 3-D radiative transfer calculations (left-hand panel) with the parametrized structured wind model of Fig. 1. The slowly accelerating absorption features are DACs. The rather horizontal absorption features are the rotational modulations we model in detail in this poster.

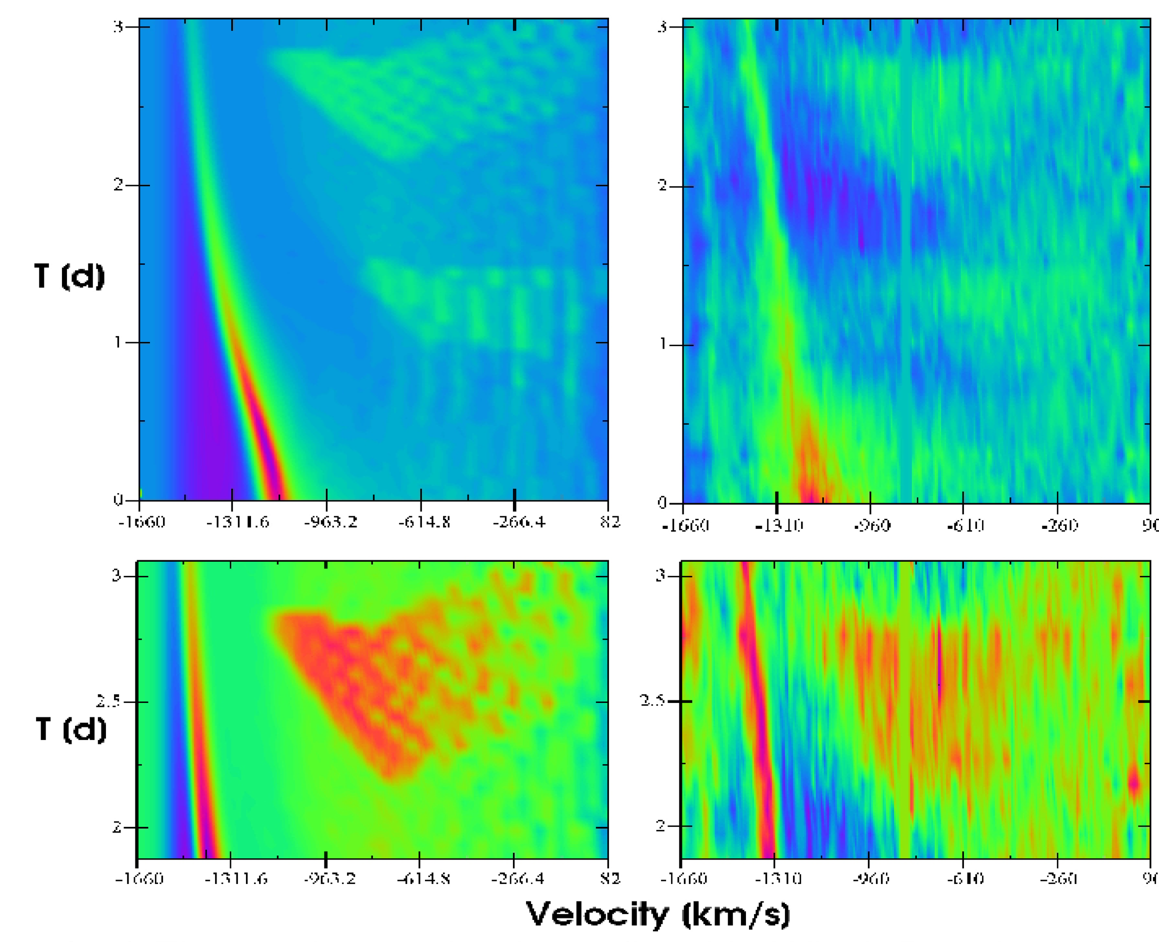


Figure 3. Rotational modulations computed with Wind3D (left-hand panels) and observed (right-hand panels) in Si IV λ1395 of HD 64760. The lower panels show the best fit and the observed upper "bow-shaped" rotational modulation in more detail.

The upper left-hand panel of Fig. 3 shows the best fit with Wind3D using the wind density model of Fig. 1. These parameterized wind density structures (left-hand panel of Fig. 1) quantitatively match the time- and velocity-position, and the relative absorption flux observed in the modulations. We semi-empirically delineate the borders of two RMRs (for the upper and lower modulations) and compute the radial wind velocity by integrating the CAK momentum-equation for radiatively-driven rotating winds (Lobel & Toalá 2009). 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 this modulation is correctly matched by the decrease in the opening angle of the RMR density enhancement beyond 1 R_* above the stellar surface (right-hand panel of Fig. 1). The radial wind velocities in the upper modulation do not exceed ~1200 km s^{-1} around 2.8 d. The upper modulation does not intersect the velocity position of the lower DAC around 1400 km s^{-1}. The density model for the upper modulation in Fig. 1 does therefore not exceed a distance of ~2.5 R_* above the stellar surface since the smooth wind velocity exceeds ~1200 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 ~17 % above the smooth wind density around ~3 R_* above the stellar surface in the parametrized model.

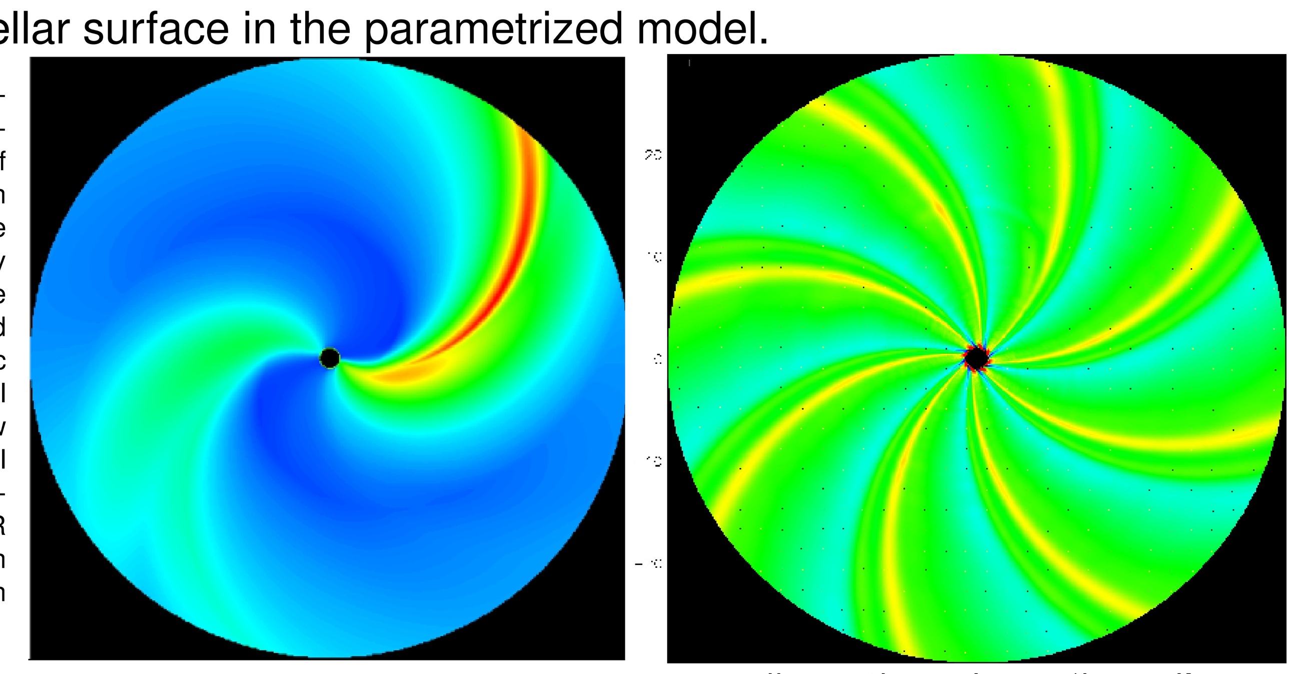


Figure 4. Density enhancements in the best-fit hydrodynamic model for the DACs of HD 64760 computed with Zeus3D (left-hand panel). The CIRs result from two unequally bright spots rotating over the stellar equator. The right-hand panel shows a hydrodynamic test model for the rotational modulations. The eight narrow RMRs result from mechanical wave excitation rotating clockwise at the surface. The RMR density contrast is about an order of magnitude smaller than for the CIRs.

CONCLUSIONS

We perform 3-D radiative transfer calculations for the rotational modulations observed in Si IV λ1395 of HD 64760. We find with semi-empiric best fits that these nearly 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 bright equatorial spots that lag behind the surface rotation. We propose that the RMRs result from mechanical wave action producing narrow spoke-like wind regions around the star due to non-radial pulsations (e.g. Kaufer et al. 2006) at the wind base of this fast-rotating supergiant.

REFERENCES

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