Parametrized Structured Wind Modelling of Massive Hot Stars with Wind3D

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ABSTRACT

We develop a new and advanced computer code for modelling the physical conditions and detailed spatial structure of the extended winds of massive stars with three dimensional (3-D) non-LTE radiation transport calculations of important diagnostic spectral lines. The Wind3D radiative transfer code is optimized for parallel processing of advanced input models that adequately parameterize large-scale wind structures observed in these stars. Parameterized 3-D input models for Wind3D offer crucial advantages for high-performance transfer computations over ab-initio hydrodynamic input models. The acceleration of the input model calculations permits us to investigate and model a much broader range of physical 3-D wind conditions with Wind3D. We apply the new parameterization procedure to the equatorial wind-density structure of co-rotating Interaction Regions (CIRs) and calculate the wind velocity-structure from CAK-theory for radiatively-driven rotating winds. We use the parameterized CIR models in Wind3D to compute the detailed evolution of Discrete Absorption Components(DACs) in Si IV UV resonance lines. The new method is very flexible and efficient for constraining physical properties of extended CIR wind structures (observed at various inclination angles) from best fits to DACs in massive hot stars. We compare the results with an accurate hydrodynamical model for the DACs of B0.5 Ib-supergiant HD 64760, and apply it to best fit the detailed DAC evolution observed with IUE in B0 Iab/Ib-supergiant HD 164402.

INTRODUCTION

Co-rotating Interaction Regions (CIRs) in winds of massive hot stars have been pointed out as the origin of Discrete Absorption Components (DACs) observed in P-Cygni line profiles (Cranmer & Owocki, 1996; Lobel & Blomme, 2008). DACs are observed to propagate bluewards over time-scales comparable to the stellar rotation period (Massa et al. 1995; Prinja 1998). The CIRs are thought to originate from stellar surface irregularities such as bright spots (or dark spots), magnetic fields, or non-radial pulsations. Lobel & Blomme (2008) presented a detailed hydrodynamic model for the CIRs and fitted the DACs in IUE spectra of B-supergiant HD 64760 by matching the resonance doublet line profiles of Si IV λ1400.

Our goal here is to parameterize equatorial wind structures for fitting DACs in B-type supergiants HD 64760 and HD 164402 with the radiative transfer code Wind3D, so as to model the time-evolution of the Si IV line profiles in detail. We investigate and develop a new technique to substantially speed up calculations of large input grids for Wind3D that can properly model extended wind structures. The detailed modelling of these circumstellar wind structures is important for pinpointing the physical mechanisms that cause clumping in winds of massive hot stars.

WIND3D CODE

Wind3D computes 3D non-LTE radiative transfer for the 2-level atom in optically thick resonance lines formed in the scattering-dominated extended winds of massive hot stars. The line source function is lambda-iterated on a Cartesian grid of 71^3 points. The radiative transfer equation is solved over a parallelized grid of 701^3 points (Lobel & Blomme 2008). Typical calculation times with Wind3D are ~5 h for iterating the line source function, and ~12 h for computing the dynamic line spectrum at 90 viewing angles using 16 processors.

PARAMETRIZATION OF WIND3D INPUT MODELS

We parametrize the CIRs in order to match the hydrodynamic model of HD 64760 presented in Lobel & Blomme (2008), which is used as input of Wind3D (Fig. 1). We develop a new computer code (we are incorporating in Wind3D) for modelling the 2-D equatorial wind density- and velocity-structure around the star. The new code integrates the momentum equation for (isothermal) radiation-driven rotating winds following Castor, Abbott & Klein (1975). For a user-defined radial wind density structure we numerically solve for the radial velocity by setting the force multiplier parameter α=1/2. We find that the hydrodynamic radial wind velocity structure can accurately be calculated with this wind-momentum integration technique. The radial wind velocity contours in Fig. 2a are very close to the velocity contours of the hydrodynamic model in Fig. 2b. The tangential wind velocities are computed with V_{rot} / r, although they become negligibly small in the highly supersonic outer parts of the wind.

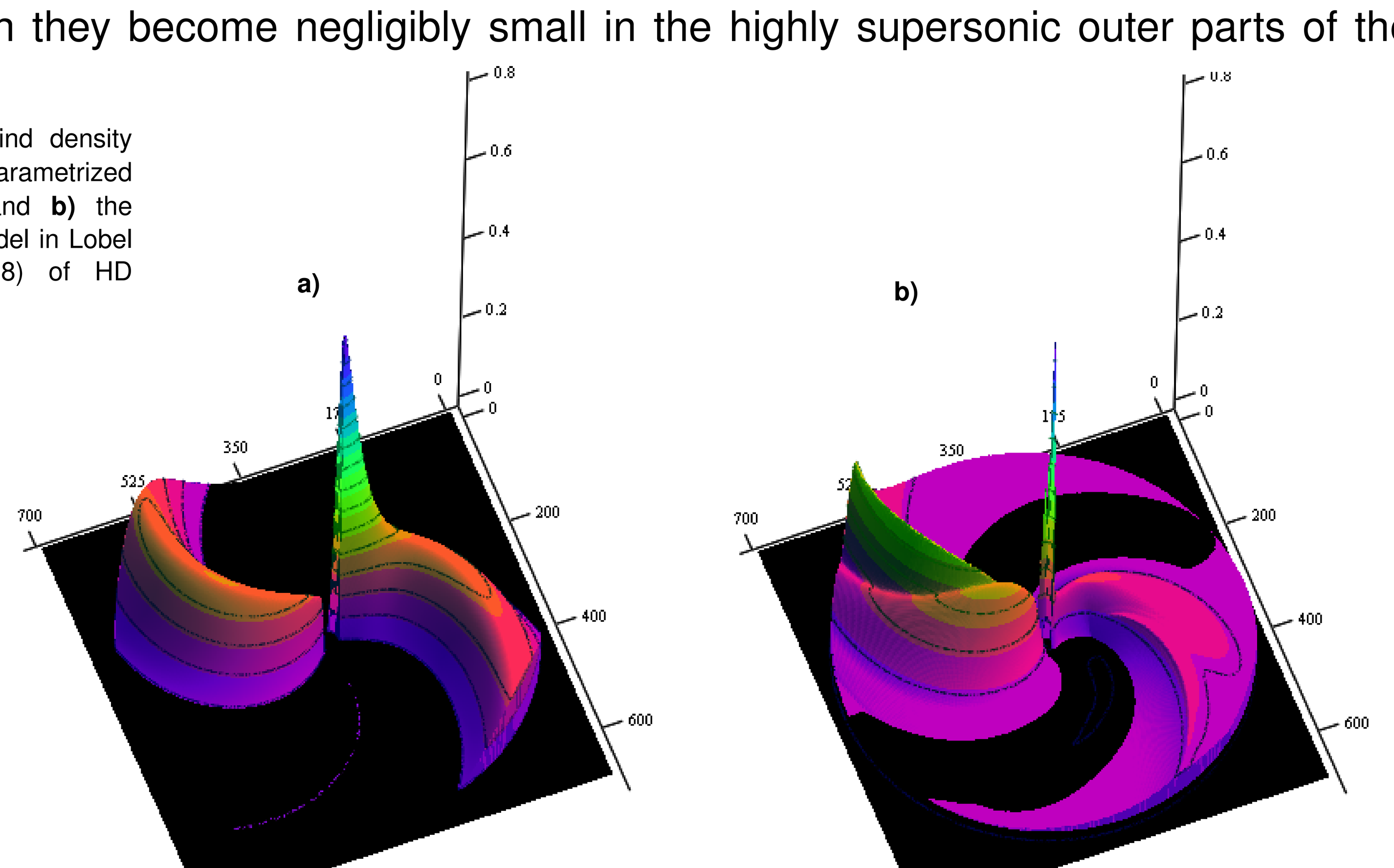


Figure 1. 2-D wind density surface with **a)** parametrized CIR structures and **b)** the hydrodynamic model in Lobel & Blomme (2008) of HD 64760.

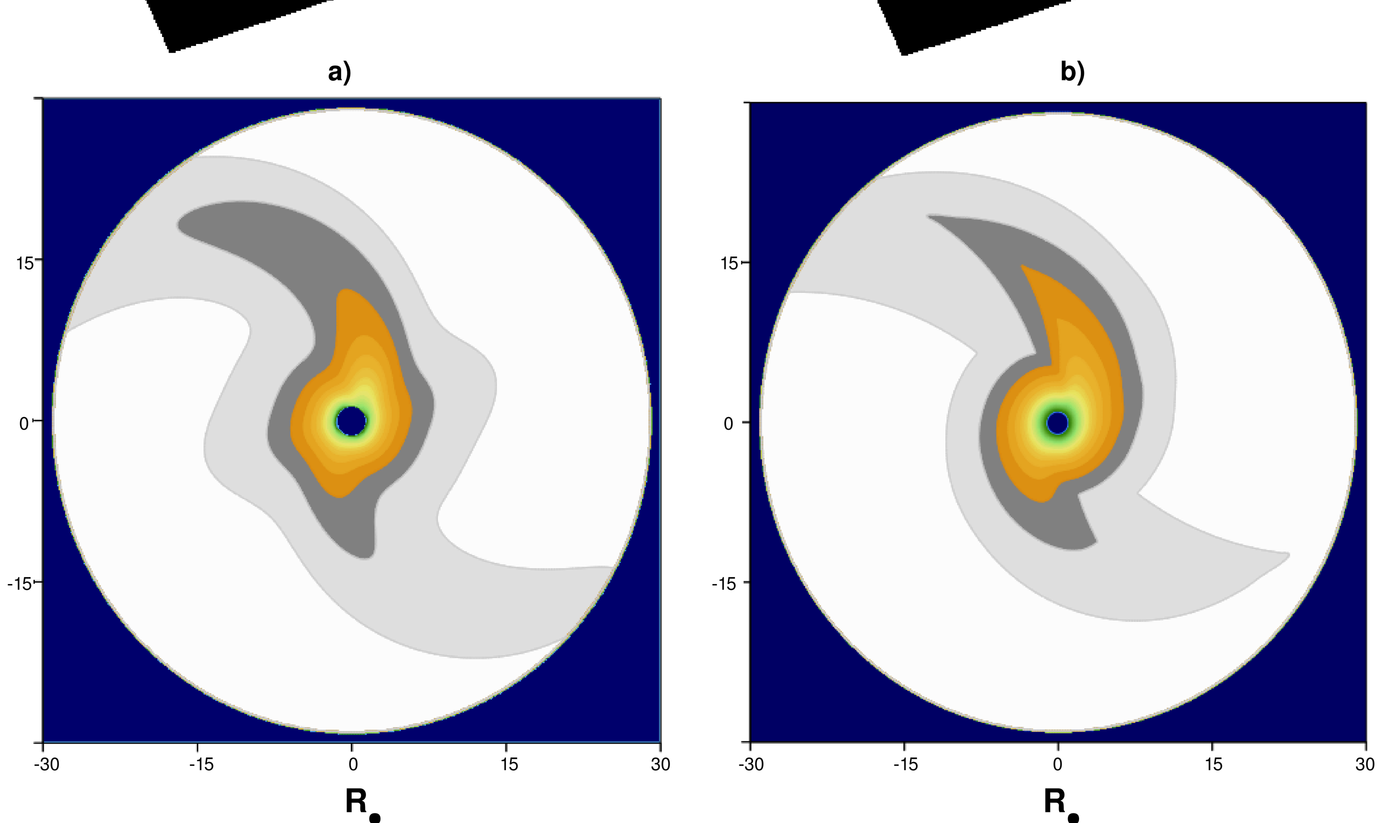
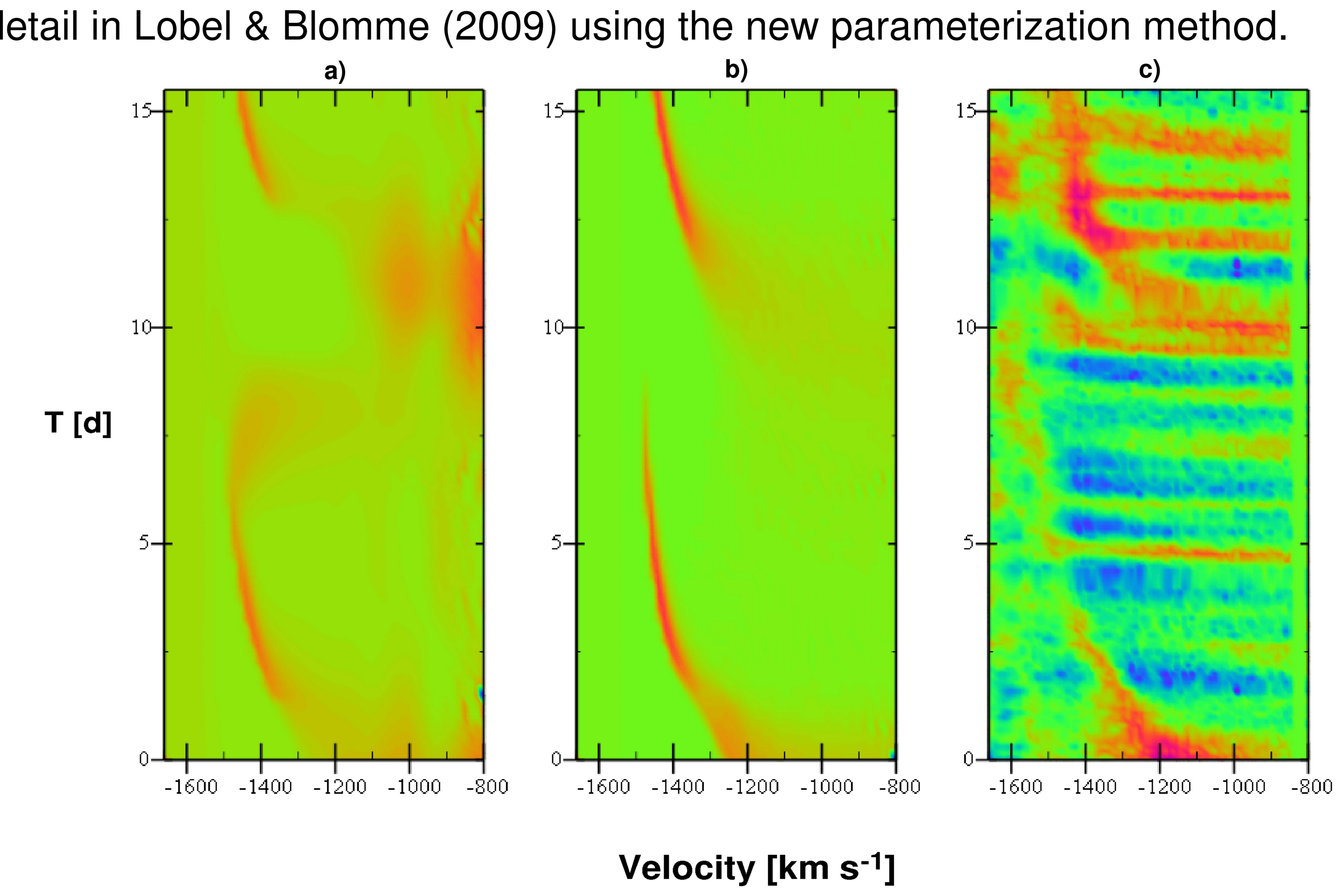


Figure 2. 2-D radial wind velocity contours of **a)** parametrized CIR structures and **b)** the hydrodynamic model in Lobel & Blomme (2008) for HD 64760. We compute that density contrasts of ~20% to 30% in the CIRs correspond to a radial wind velocity deceleration of ~100 to 200 km s^{-1}. White corresponds to the terminal wind velocity of 1560 km s^{-1}.

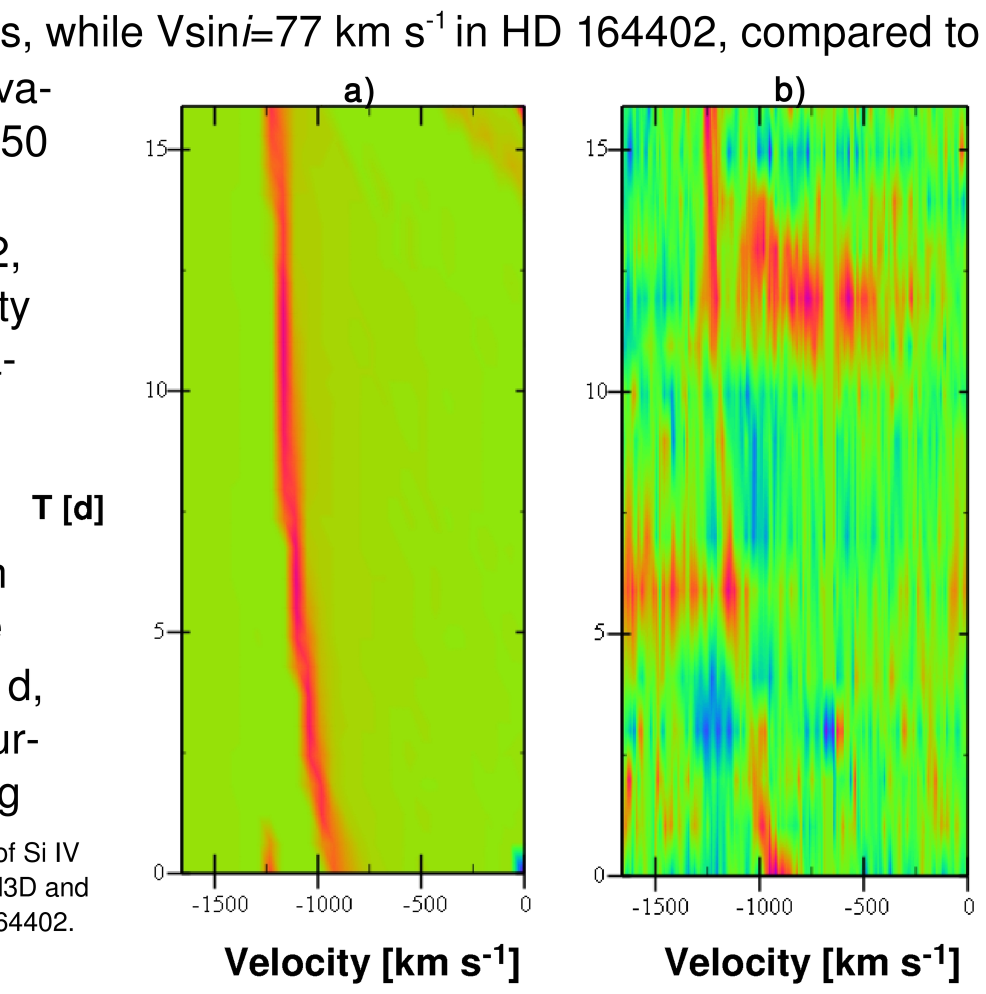
COMPARISON WITH IUE OBSERVATIONS

Figure 3 shows a comparison of the observed dynamic spectrum of HD 64760 and spectra we compute with Wind3D using parametrized and hydrodynamic input models. The parametrized model calculations fit the observed DACs with almost the same accuracy of the hydrodynamic model calculations. We also properly model the DAC base (the broad absorption feature around -1300 to -1100 km s^{-1} at T = 0 d). The parametrized model yields the same DAC acceleration over time. The radial wind velocities we compute with the parametrized density structure provide almost the same DAC shape and amounts of absorption compared to DACs we compute from the hydrodynamic input model. The rotational modulations (horizontal features) are modeled in detail in Lobel & Blomme (2009) using the new parameterization method.

Figure 3. Dynamic spectra of Si IV λ1395 computed with Wind3D for the parametrized best model **a)** and **b)** the hydrodynamic model of Lobel & Blomme (2008), compared to **c)** the IUE observed dynamic spectrum of HD 64760.



We apply the new model parameterization method to the spectroscopic binary supergiant HD 164402 (B0 Ib), for which there is currently no hydrodynamic model available. In Fig. 4b the DAC accelerates from ~-850 km s^{-1} to -1250 km s^{-1} over 15.9 d. It remains narrow with a maximum width of ~150 to 200 km s^{-1}. T_{eff} ($\simeq$28,500 K) and R_* ($\simeq$25 $R_\odot$) are very similar for both supergiants, while Vsin*i*=77 km s^{-1} in HD 164402, compared to 265 km s^{-1} in HD 64760. IUE observations of HD 164402 signal a $V_\infty \simeq$1750 km s^{-1}. We also develop a parametrized density model for HD 164402, and compute the radial wind velocity by integrating the momentum equation using these parameters. Fig4a shows the DAC we compute for a CIR model that co-rotates with the stellar surface. Since the maximum rotation period $P_{rot}\simeq$13.3 d, and the DAC is observed over at least 15.9 d, we find that a single CIR entirely surrounds the star well before reaching the V_∞.



Figue 4. Dynamic spectrum of Si IV λ1395 **a)** calculated with Wind3D and **b)** observed with IUE in HD 164402.

CONCLUSIONS

We have developed and tested a new method to compute dynamic wind structures around hot stars by integrating the momentum equation of line-driven rotating winds. We find that the 2-D radial velocity structures we calculate with a 2-D density input structure are almost identical to 2-D hydrodynamic models we compute with the Zeus code. The new parameterization technique is used to compute large grids of input models for Wind3D, because it drastically reduces computation times compared to time-consuming hydrodynamical simulations. The new method is fast and flexible for searching the space of parameters to compute best fits with Wind3D to dynamic spectra observed in hot stars. The successful application of this new technique to the B-type supergiants HD 64760 and HD 164402 shows that it can be further developed to also compute fully three-dimensional parameterized circumstellar wind structures.

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