Clumping in Hot Star Winds
W.-R. Hamann, A. Feldmeier & L.M. Oskinova, eds.
Potsdam: Univ.-Verl., 2008
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

Corotating Interaction Regions and clumping

R. Blomme
Royal Observatory of Belgium

We present hydrodynamical models for Corotating Interaction Regions, which were used by Lobel (2007) to model the Discrete Absorption Components in HD 64760. We also discuss our failure to model the rotational modulations seen in the same star.

1 Introduction

Discrete Absorption Components (DACs) seen in ultraviolet lines are one of the clearest indicators of large-scale structure in the winds of hot stars. Cranmer & Owocki (1996) attributed these DACs to Corotating Interaction Regions (CIRs) which are formed when slow and fast streams collide in the wind. In their model, CIRs are produced by introducing a spot on the stellar surface. The spot can literally be a spot, but can also simulate the effect of non-radial pulsations, or a magnetic field.

In the present work, we attempt a *quantitative* fit to the DACs seen in the Si IV λ 1395 line of the B0.5 Ia star HD 64760. This paper describes the hydrodynamical models used for this fit and discusses the problems in fitting the rotational modulations, which are an additional feature seen in the P Cygni profiles of this star. In a companion paper (Lobel 2007), the radiative transfer code and the fitting of the observed DACs is discussed.

2 Hydrodynamics

To construct the hydrodynamical models, we use the Zeus3D code (Stone & Norman 1992). We solve the 3-dimensional equations of hydrodynamics, limited to the equatorial plane. This approximation is justified by the high $v \sin i$ value of HD 64760, which suggests that it is seen (nearly) equator-on.

In our model, we largely follow Cranmer & Owocki (1996). We include the radiative acceleration due to the spectral lines as well as the rotation of the star and the wind (through angular momentum conservation). The energy equation is also solved (including radiative cooling and a floor temperature), but this turned out to be unimportant in the present calculations. We further introduce a circularly symmetric spot on the stellar surface, with its centre on the equator. This spot is specified by its brightness $A_{\rm sp}$ and its angular diameter $\Phi_{\rm sp}$.

Contrary to Cranmer & Owocki, we allow the spot to rotate with a velocity $v_{\rm sp}$ *that can be different from the rotational velocity* $v_{\rm rot}$. The main justification for this is that the recurrence time of the DAC is measured to be 10.3 d while the rotation period is only 4.1 d (see Lobel 2007). A similar assumption was also made by Kaufer et al. (2007) in their model for the Hα variations in HD 64760.

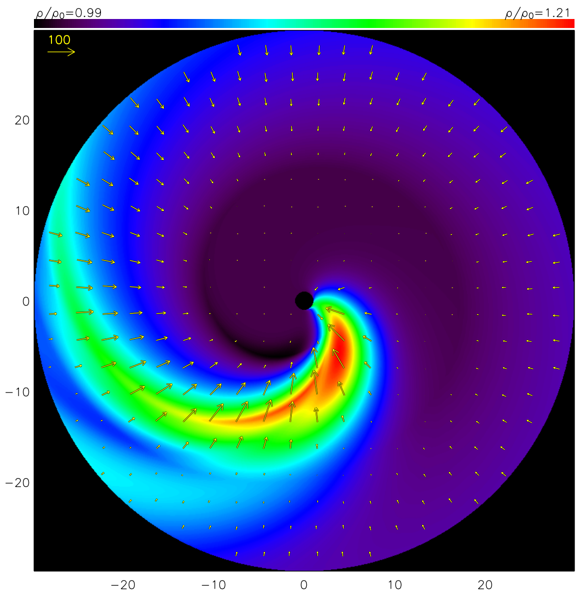

Figure 1: The colour scale presents the density contrast of the CIR with respect to the smooth wind. The velocity vectors plotted show the differences with respect a smooth wind. The model parameters are: $A_{\rm sp} = 0.1$, $\Phi_{\rm sp} = 50^o$, $v_{\rm sp} = v_{\rm rot}/2.5$.

The effect of a spot on the hydrodynamics of the wind is easiest to understand if there is no rotation. In that case, there is a sector above the spot with a different wind (i.e. a different mass-loss rate and terminal velocity) compared to the smooth wind around it. When the star rotates, these different winds collide and a spiral-shaped density enhancement is formed (see Fig. 1). Trailing this density

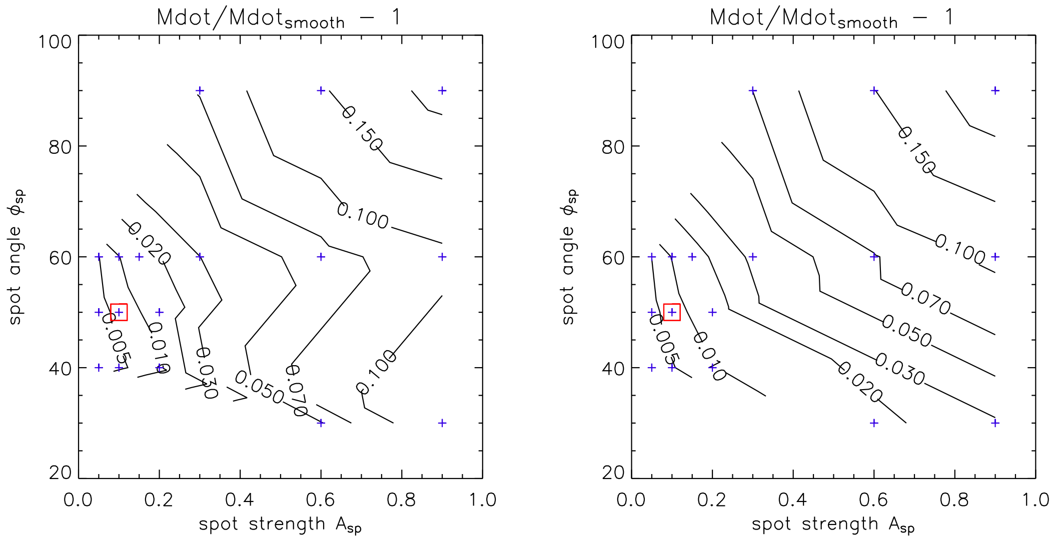

Figure 2: Contour lines of the effect of a CIR on the mass-loss rate as a function of spot brightness and angle. The plusses indicate the models we calculated. The best-fit model is shown with a red square. The left panel shows the values measured from the hydrodynamical models, the right panel the results from the approximation in Eq. 2.

wave is a region with a velocity plateau, which is mainly responsible for the formation of the DAC (Lobel 2007). One should also note that the CIR is not a stream of material particles, but is a pattern in the wind. If we follow trace particles, we see that they can cross the whole width of the CIR as they move out almost radially.

We constructed a large grid of hydrodynamical models, from which the DACs were then calculated using the Wind3D code. The best fit to the Si IV $\lambda\,1395$ line of HD 64760 was then determined (see Lobel 2007). The hydrodynamical model of this best fit is shown in Fig. 1.

The total mass-loss rate of the structured wind ($\dot{M}_{\rm struct}$) is easy to calculate if we assume the star to be non-rotating:

$$\dot{M}_{\rm struct} = \frac{\Omega}{4\pi} \dot{M}_{\rm spot} + \left(1 - \frac{\Omega}{4\pi}\right) \dot{M}_{\rm smooth}, \qquad (1)$$

where Ω is the solid angle of the spot, $\dot{M}_{\rm smooth}$ is the mass-loss rate in the smooth wind and $\dot{M}_{\rm spot}$ that above the spot. Using the approximate relation that $\dot{M} \propto L^{1/\alpha}$, we can rewrite this as:

$$\frac{\dot{M}_{\rm struct}}{\dot{M}_{\rm smooth}} \approx \frac{\Omega}{4\pi} \left(1 + A_{\rm sp}\right)^{1/\alpha} + \left(1 - \frac{\Omega}{4\pi}\right). \qquad (2)$$

A rotating star will have a structure that is quite different from the non-rotating model, but close to the stellar surface the differences will be small. We can therefore use the density and velocity measured near the surface to determine the mass-loss rate. The results for a series of models are presented in Fig. 2. Our best-fit model for the HD 64760 DAC corresponds to an additional mass loss of only 0.6 %.

3 Rotational modulations

Encouraged by the good fit we obtained for the DAC, we also tried to fit the "rotational modulations" present in the dynamic spectrum. These are the banana-shaped, nearly-flat absorption components seen in Fig. 3. All our models fail however to reach the terminal velocity sufficiently quickly. Our failure is surprising in view of the good agreement presented by kinematical models such as those by Owocki et al. (1998) and Brown et al. (2004).

To investigate this further, we switched to using the kinematical models developed by Brown et al. We find that these models can indeed explain the observations, provided the $v_{\rm rot}/v_\infty$ ratio is small (~ 0.05). In such a case, the rotational modulation does reach the terminal velocity sufficiently quickly (dotted white line in Fig. 3). For HD 64760 however, we have that $v_{\rm rot}/v_\infty \approx 0.16$ and we obtain the solid white line in Fig. 3, which does not fit the observations. Because we consider the spot velocity as a free parameter, we can of course introduce a slower-moving spot (thereby getting a more favourable $v_{\rm sp}/v_\infty$ ratio). However, the recurrence time scale then becomes longer, stretching out the time-axis, and we again obtain a bad fit which is indistinguishable from the high $v_{\rm rot}/v_\infty$ solution (solid white line).

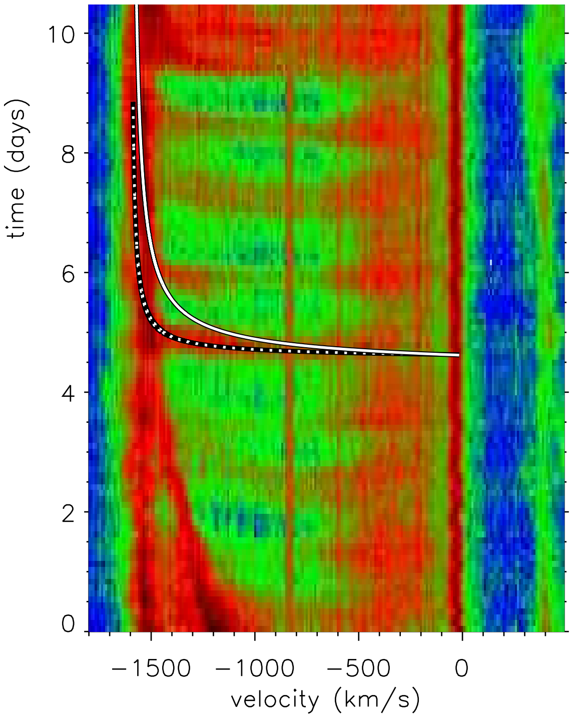

Figure 3: The dynamic spectrum of the Si IV λ 1395 line in HD 64760. One of the observed rotational modulations is fitted with a kinematical model based on Brown et al. (2004). The dashed white line has $v_{\rm rot}/v_\infty = 0.05$, the solid one has $v_{\rm rot}/v_\infty = 0.16$ and is indistinguishable from the $v_{\rm sp}/v_\infty = 0.05$ solution.

4 Conclusions

Lobel (2007) and the present paper show that the DACs of HD 64760 can be well fitted with hydrodynamical models for CIRs. The recurrence time of the HD 64760 DACs requires that the spots responsible for the CIRs rotate considerably more slowly than the stellar surface (by a factor of 2.5). The spots cannot be fixed on the surface, thereby excluding magnetic fields as a possible cause. As suggested by Kaufer et al. (2007), a beat-pattern due to non-radial pulsations seems to be the only valid explanation for the spot.

The additional mass-loss rate put into the wind is very small and no shocks are formed due to the (weak) CIR in HD 64760. The CIRs can therefore not be responsible for the clumping discussed at this workshop, nor for the X-ray emission of these stars. As Owocki (1998) showed, CIRs are sensitive to the amount of instability in the wind. Too large an amount of clumping could therefore destroy the CIRs responsible for the DACs. As the DACs are almost ubiquitous in hot-star winds, this imposes important constraints on the amount of clumping.

Finally, our failure to reproduce the rotational modulations seen in HD 64760 suggests that we still lack a key component in our understanding of these stellar winds.

We thank Asif ud-Doula for making his version of the Zeus3D code available to us.

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Hamann: Can you offer a plausible physical explanation for the nature of the "spot" at the CIR footpoint, which explains why it is running like mad counterwise to the stellar rotation?

Blomme: Kaufer et al. (2006) invoke a beat-pattern of NRPs for this. Admittedly, their value for the spot velocity is not the same as ours. We took their work to mean that we could count the spot velocity as a free parameter. Its value is then of course determined by the ratio of the recurrence time of the DAC (10.3 d) against the rotational period (4.1 d). We did not model a specific beat-pattern that could give this spot velocity.

Prinja: I would just like to echo the point made by Ronny that invoking substantial amounts of clumping must not then destroy the CIR-type structures, since the spectral signatures of the latter are so widespread in OB stars.

Owocki: The 2D SSF simulations of CIRs show that velocity plateaus and (somewhat rounded) "kinks" are not an artifact of the Sobolev approximation.