Effect of Instability-Generated Clumping on Wind Compressed Disk Inhibition

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1. Introduction

A longstanding problem in the study of Be stars is the origin of their circumstellar disk. Much recent attention has focused on the very appealing "Wind Compressed Disk" (WCD) paradigm proposed by Bjorkman & Cassinelli (1993; hereafter BC), by which disks form naturally around a rapidly rotating B-star from the equatorward deflection of the star's radiatively driven stellar wind. Dynamical simulations have shown, however, that the formation of such WCDs depends crucially on the radial vs. non-radial nature of the driving of the stellar wind. Inital simulations (Owocki, Cranmer, and Blondin 1994) that generally substantiated the WCD formation model were based on an assumption, posited in BC's original WCD analysis, that all forces were strictly radial. But subsequent models (Owocki, Cranmer, and Gayley 1996) showed that including the finite non-radial components of the line-driving force (Cranmer and Owocki 1995) can effectively *inhibit* the formation of any WCD.

A key limitation of all these previous dynamical models, however, is that they are based on local, CAK models that suppress the strong line-driven instability (Owocki, Castor, Rybicki 1988; Feldmeier 1995; Owocki and Puls 1999). The goal of this presentation is to examine the robustness of the WCD inhibition when instability-generated clump structure is included.

2. Origin of Poleward Driving that Inhibits Wind Compression

Within a multidimensional extension of the usual CAK formalism, the vector line-force $\mathbf{g}^{\rm rad}$ at wind position $\mathbf{r}$ is obtained by numerical integration over solid angle Ω_* of the stellar core intensity I, weighted by the line-of-sight velocity gradient,

$$\mathbf{g}^{\rm rad}(\mathbf{r}) \sim \int_\Omega d\Omega \, \mathbf{n} \, I(\mathbf{n},\mathbf{r}) \left(\frac{dv_n}{dn}\right)^\alpha . \qquad (1)$$

where α is the usual CAK exponent. From this it is clear that one way to get a finite nonradial force component is through asymmetries in the projected velocity gradient, dv_n/dn. For example, even in an azimuthally symmetric rotating wind, the stronger velocity gradient along retrograde directions to the star yields a net azimuthal line-torque, causing a modest (20-40%) spindown of the wind angular momentum (Gayley and Owocki 1999). Because formation of an equatorial WCD depends on wind rotation, this spindown by itself already implies some weakening of any WCD.

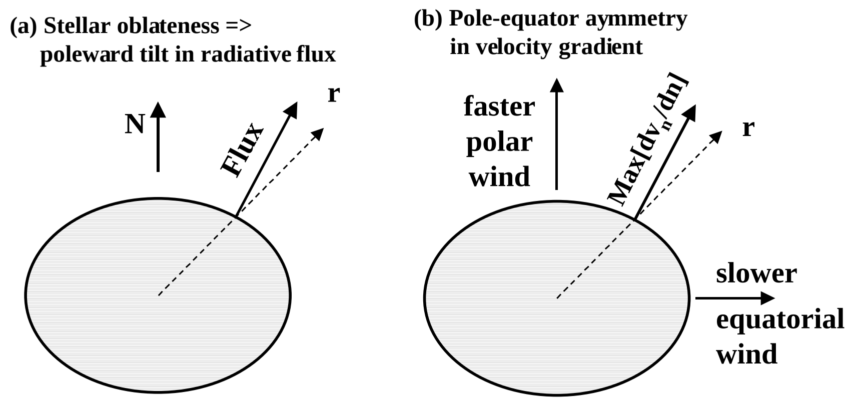

Figure 1. Schematic to illustrate the two main causes of the poleward component to the line-force, namely: a. poleward tilt of radiative flux from oblate stellar surface; and b. poleward bias of velocity gradient from global trend of increasing velocity at higher latitudes.

But the major factor in the full WCD inhibition is a poleward tilt in the *latitudinal* component of the line-force, which acts to stop (Owocki, Cranmer, and Gayley 1997), and indeed reverse, the equatorward flow that is crucial to WCD formation. Fig. 1 illustrates that this poleward tilt of wind driving is the result of two distinct effects. First, much as in the case of the azimuthal spindown line-torque, asymmetries in the global velocity field, now between the relatively fast wind above the poles and the slower outflow from near the equator, lead to an overall poleward bias of the velocity-gradient weighting in eqn. (1). But a second, more robust effect is the geometrical flattening – oblateness – of the rotating stellar surface, which gives the radiative flux itself a poleward bias.

From the current perspective of examining the robustness of WCD inhibition, the distinction between these two effects is quite significant. The former, velocity-gradient effect can be expected to become substantially disrupted in a wind with extensive, small-scale, clumped structure. But the latter, flux tilting effect should give a poleward bias to any kind of radiative force, even from continuum scattering (Cranmer and Owocki 1995). Since this effect is thus essentially independent of the details of the wind velocity and density structure, we can expect that it would lead to some poleward force even in a highly clumped wind.

As a simple test of the relative importance of these two effects in the WCD inhibition, fig. 2 compares 2D CAK simulations for the standard "S-350" model (cf. OCB) of B-star rotating at 350 km/s. Case a shows the equatorward flow and WCD formation that results when one ignores nonradial line-forces. Case b shows how inclusion of nonradial line-forces reverses this equatorward flow, inhibiting the WCD formation. Case c shows that even when these nonradial line-forces are computed without taking into account any latitudinal velocity gradients (i.e. setting $\partial v/\partial\theta$ in eqn. (1)), they are still strong enough to reverse

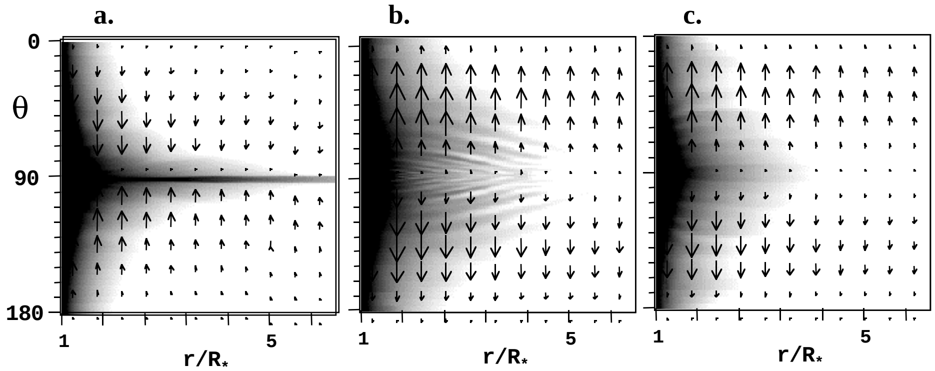

Figure 2. Greyscale of log(density) vs. radius and latitude. The superposed vectors show sense and magnitude of latitudinal velocity, with maximum length corresponding to a speed of 100 km/s. The three cases represent models with nonradial line-forces (a) ignored; (b) fully included; (c) computed without latitudinal velocity gradients ($\partial \mathbf{v}/\partial\theta = 0$).

the equatorward flow and thus effectively inhibit WCD formation. The implication of this is that the WCD formation is likely to be remain inhibited, even in a highly structured wind where small-scale variations dominate over large-scale equator-to-pole trends in the overall wind velocty.

3. 2D (r, θ) Non-Local Line-Driven-Instability Simulations

We have also made initial attempts to directly incorporate instability-generated clumping within 2D simulations of rotating winds. A key challenge is to develop an approach for efficient evaluation of the line-driving force, which in such instability simulations requires computation of nonlocal escape integrals over a suitable collection of directional rays. Owocki (1998) introduced a simplified 3-ray integration method and applied this to study the effect of instabilities on large-scale, co-rotating stream structures in the equatorial plane of a 2D (r, ϕ) model of a rotating stellar wind. For the WCD analysis here, we have adapted this method to 2D meridional models with variations in radius and co-latitude (r, θ), assuming azimuthal symmetry $(\partial/\partial\phi = 0)$. Unfortunately, a key, still unsolved problem regards the lower boundary "staircasing" of grid points along the star's rotationally oblate surface. At certain edges along this staircase, there arise artificial, strong, persistent stream structures that severely compromise the physical interpretation of how clumping might affect nonradial line-forces and the WCD inhibition. Nonetheless, typical simulation results (fig. 3) thus far do not show the necessary equatorward flow to form a WCD. This is generally consistent with the above notion that, even without large-scale velocity gradient asymmetries, the WCD effect is already effectively inhibited by just the oblateness-induced poleward component of the radiative driving flux.

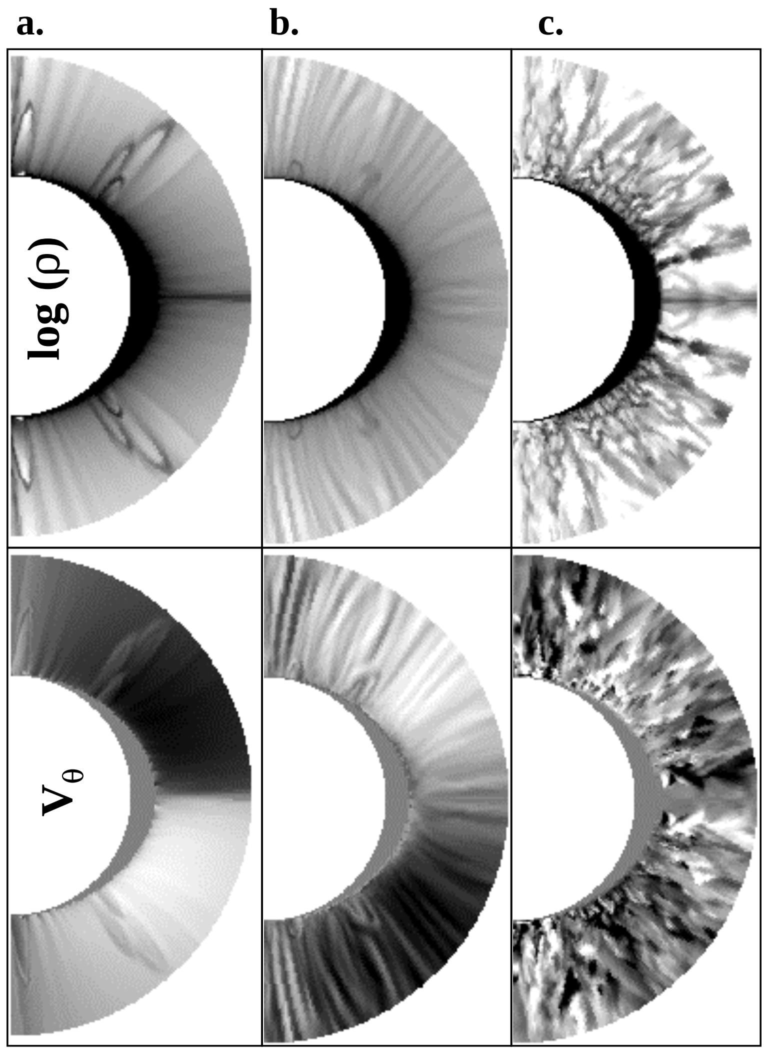

Figure 3. Grey-scale plots of log(density) (upper row) and latitudinal velocity (lower row) in models with a 3-ray spatial grid. The line-force is computed using the local CAK method in cases a and b, either ignoring or including nonradial force components. Case c uses the full *nonlocal* line-force computed from the "Smooth Source Function" (SSF; Owocki & Puls 1996) method applied to integration along the 3 rays. In the lower panels, lighter/darker shading indicates northward/southward latitudinal flow. Note that even in the case c with extensive structure, there is still not the systematic equatorward flow needed to form a WCD.

4. Conclusions

A clear goal for future work is to solve the lower boundary "staircase" problem, to control the formation of wind structure and thus allow a systematic examination of its effect on WCD inhibition. Ultimately this will likely require moving beyond the crude 3-ray treatment of the line-force, perhaps through application of less retrictive, short-characteristic methods (e.g., Folini 1998). However, in the context of WCD models for Be-star disks, the specific impetus to develop such a complex code is moderated somewhat by several observational results presented at this meeting (e.g. by Hanushik, Stefl, Baade, Rivinius, and others), which now seem quite clearly to favor a stationary, Keplerian disk over the kind of equatorially compressed outflow characteristic of WCDs. Moreover, even apart from remaining issues regarding the role of structure, the results obtained here suggest that just the poleward flux tilt arising from the oblateness of a rotating star can by itself effectively inhibit any equatorial wind compression.

Acknowledgments. We thank J. Bjorkman for emphasizing to us the possible role of clumping in the WCD inhibition, and for first suggesting the effect-separation test shown in fig. 2c. The computations presented here were carried out using computer time allocations at the San Diego Supercomputer Center.

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