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# Outer Wind Evolution of Instability-Generated Clumped Structure in Hot-Star Winds

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**Abstract.**
The line-driven instability of hot-star winds is understood to lead to extensive clumped structure in the near-star acceleration portion of the wind. In this paper, we summarize our recent efforts to simulate the evolution of this structure far from the stellar surface. We first present direct simulations of structure to about $r = 40R_*$, and then model the further hydrodynamical evolution to 160 $R_*$ through a quasi-periodic approach. Finally we outline a novel, pseudo-planar method designed to simulate the evolution of such structure to very large radial distances of $1000R_*$ or more.

## 1. Introduction

The line-driving of hot-star winds is understood to be highly unstable (see, e.g. review by Feldmeier, these proceedings, and references therein), resulting in a highly structured flow with a non-monotonic velocity field, strong compressive shocks, and extensive clumping in density. The implications of this structure for interpreting observational diagnostics formed at distances ranging from near the surface (e.g. H$\alpha$ emission) to quite large radii (i.e. $r > 100R_*$ for radio emission) depends on how such structure evolves and decays. But with only a few exceptions (e.g. Feldmeier et al. 1997), most previous simulation models have focussed on only the formation of structure in the wind acceleration region near the star. In this paper, we summarize recent efforts to study the outer evolution of wind structure through various extensions to previous models.

## 2. Direct Simulation to Moderate Distances of a few 10 $R_*$

A key challenge in direct simulations of the line-driven instability is the computation of the line-force, which requires numerical evaluation of nonlocal escape integrals, with a spatial grid fine enough to adequately resolve the strongest instability growth at scales near and below the Sobolev length, $L \equiv v_{th}/(dv/dr) \sim 0.005R_*$. So far most simulations have been restricted to 1D radial outflow (see, however, Owocki 1998), using the relatively simple "Smooth Source Function" (SSF) approach to computing the line-force (Owocki and Puls 1996, 1999), and focusing mostly on the initial development of structure in the inner wind, i.e.

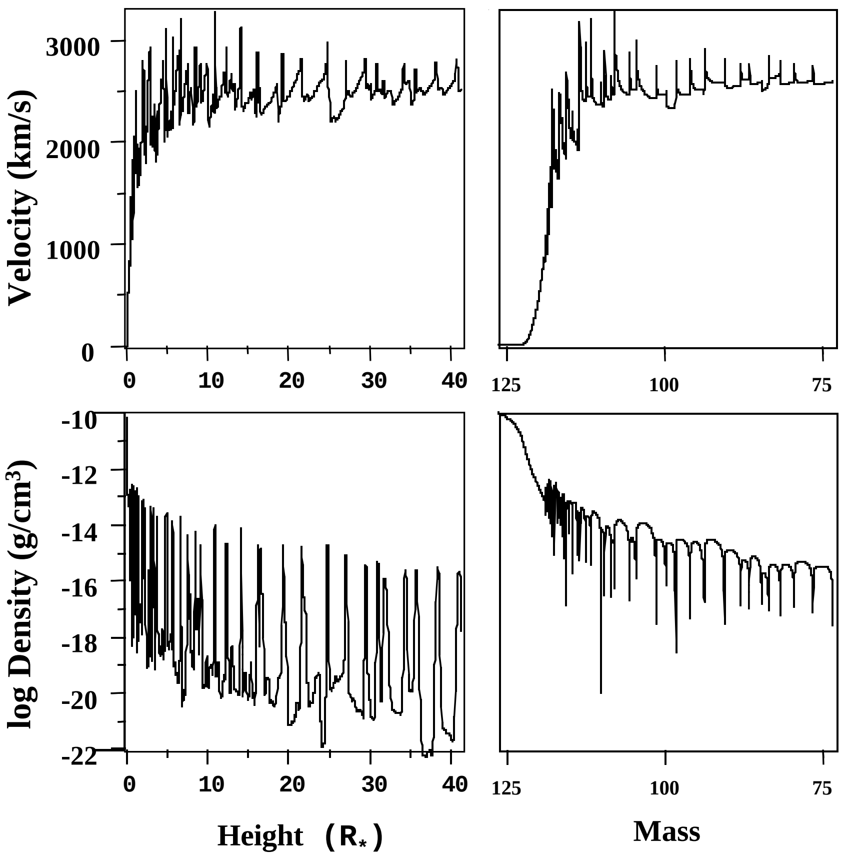


Figure 1. Snapshot of the velocity (upper panels) and density (lower panels) structure in self-excited instability model, plotted vs. radius (left) and vs. mass (right).

$R_* \le r \le R_{max} \lesssim 5R_*$. For a fixed, uniform grid resolution, the overall computational cost scales as $N_r^2 \sim R_{max}^2$, reflecting the longer evolution time needed to relax a larger scale model. To avoid this quadratic scaling for extending simulations to larger radii, a common approach (e.g. Feldmeier et al. 1997) is to set radial zone sizes to increase linearly outward, $dr \sim r$. Since the total number of zones then increases only logarithmically with radius, the overall compational cost scales almost linearly with radial extent, i.e. as $R_{max} \log(R_{max})$. The tradeoff is, of course, severe reduction in spatial resolution for the outer flow structure.

As a compromise approach here, we relax an initial direct simulation model using $N_r = 3000$ radial grid points, with highest resolution ($dr/r = 0.002$) near the strongly stratified wind base, then increasing as $dr \sim r$ for $r \le 10R_*$ and $r \ge 31R_*$, but kept fixed at $dr = 0.02R_*$ for the interval in-between. Figure 1 shows a snapshot of the velocity and density structure at an instant about twice a characteristic flow time $R_{max}/v_\infty \sim 250$ ksec after the initial condition, which

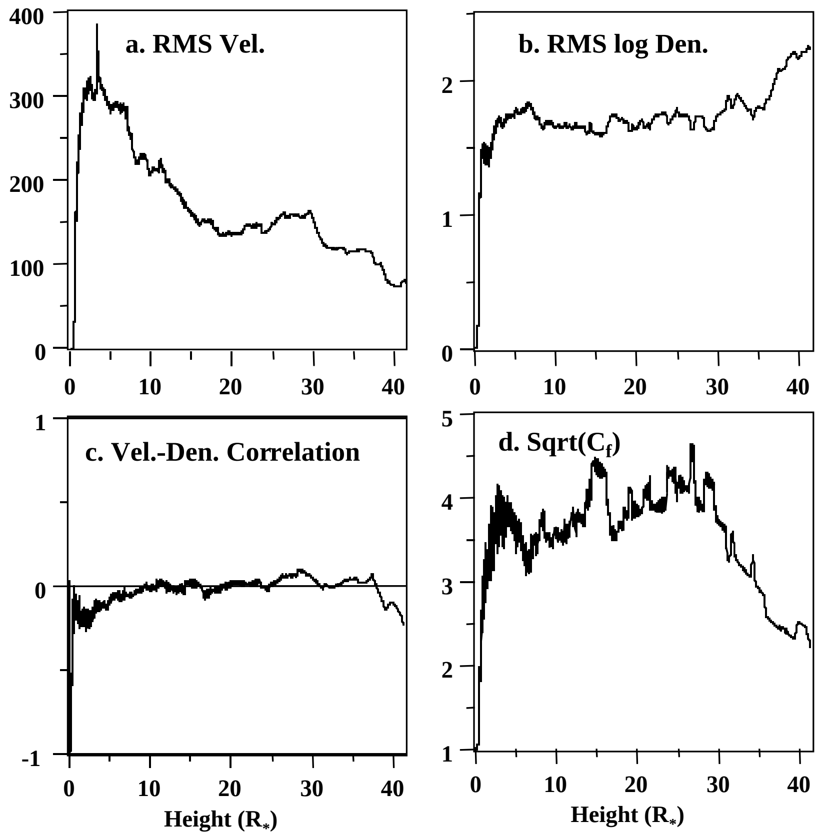


Figure 2. Radial evolution of key statistical properties of the flow structure show in figure 1, including the rms variations in (a) velocity and (b) log(density); (c) the velocity-density correlation coefficient; and (d) the root of the clumping factor, $C_f \equiv \langle \rho^2 \rangle \, / \, \langle \rho \rangle^2$.

was set by the steady-state CAK model (Castor, Abbott, and Klein 1975). In addition to variations vs. the standard Eulerian height, the plots vs. Lagrangian mass coordinate (Owocki and Puls 1999) show how much material has a given velocity or density. Since we introduce no explicit base perturbations, the extensive flow structure is entirely "self-excited" by back-scattering from wind flow structure to provide the initial seeds to instabilities near the wind base.

Figure 2 plots the radial variation of key statistical properties of this flow structure. The rms velocity variation is highly supersonic, some 300 km/s in the inner wind, decaying slowly to about 100 km/s at the outer radius $R_{max} \approx 42 R_*$. The associated density shows typically a factor 50 variation. The velocity and density begin with a strong anti-correlation, but the mutual interaction of structure quickly leads to no correlation. Finally, the clumping factor characterizes the enhancement expected from density-squared diagnostics, implying roughly

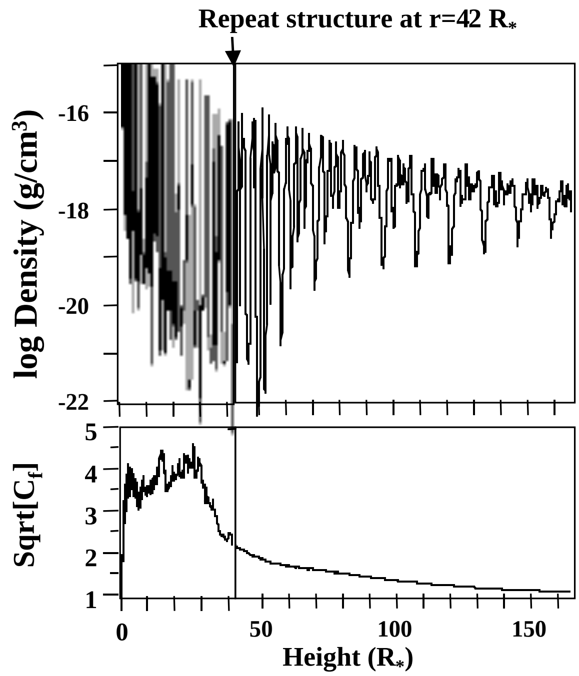


Figure 3. Quasi-periodic extension of the direct instability simulation from $r = 42R_*$ to an outer radius of $R_{out} = 160R_*$. The upper panel shows the radial variation of log(density), while the lower panel plot the associated evolution for the root of the clumping factor.

a factor 3-4 overestimate in mass loss rate for emission diagnostics originating over the broad range from 1.5-30 $R_*$.

## 3. Quasi-Periodic Extension to Distances of Order 100 $R_*$

The inverse-square radial decline in radiative flux suggests that radiative force should have limited dynamical effect in the outer wind. In following the distant evolution of flow structure, it thus seems reasonable to convert to a pure gas dynamical simulation that simply omits the costly calculation of the line-driving force. In this approach, the outer boundary variations in flow variables at $R_{max}$ of a full, line-driven instability simulation provide the inflow boundary conditions to the separate, pure-gas-dynamical simulation, for which the overall lower computational cost allows use of a fixed resolution grid extending to a larger outer radius, $R_{out}$. Moreover, to avoid having to run the instability simulation for the extended time needed for structure to reach this outer radius, we may simply repeat the structure over a fixed “quasi-period” that is much longer than the short time-scale variations associated with the structure we wish to follow.

As an example, the output from the above simulation model at a maximum radius $R_{max} \approx 42R_*$ is stored over a long quasi-period $\Delta t = 2^{16}$ sec, computed in $2^{14}$ uniform time steps of $dt = 4$ sec. This is then used as input for a pure hydrodynamical simulation over the radial range $r = 42 - 160R_*$, and repeated for 10 quasi-periods, long enough to allow structure to reach the outer radius $R_{out} = 160R_*$. Figure 3 shows the resulting radial evolution of the density variation, together with the outward decline in the overall clumping factor.

## 4. Pseudo-Planar Approach for Very Extended Evolution to 1000 $R_*$ and Beyond

To extend such simulation calculations to even larger radii, we have been experimenting with a new "pseudo-planar" approach. Starting at some radius $R$, we rewrite the spatial coordinate and flow speed in a frame moving with some fixed velocity $V_o$,

$$x \equiv r - R - V_o t \quad ; \quad w \equiv v - V_o$$

Then by defining flow variables that scale out the spherical wind expansion,

$$\tilde{\rho} \equiv \rho (r/R)^2 \quad ; \quad \tilde{P} \equiv P(r/R)^2 \quad ; \quad \tilde{E} \equiv E(r/R)^2,$$

we can write the equations for conservation of mass, momentum, and energy in the "pseudo-planar" form,

$$\frac{\partial \tilde{\rho}}{\partial t} + \frac{\partial (\tilde{\rho} w)}{\partial x} = 0$$

$$\frac{\partial (\tilde{\rho} w)}{\partial t} + \frac{\partial (\tilde{\rho} w^2)}{\partial x} = - \frac{\partial \tilde{P}}{\partial x} + \frac{2\tilde{P}}{r}$$

$$\frac{\partial \tilde{E}}{\partial t} + \frac{\partial (\tilde{E} w)}{\partial x} = - \tilde{P} \frac{\partial w}{\partial x} - \frac{2\tilde{P}(V_o + w)}{r}$$

wherein the two terms proportional to $1/r$ represent the only explicit sphericity corrections to the otherwise planar form. This provides a very efficient way to extend simulation of any quasi-periodic structure produced in an explicit spherical model. So far, we have only used the approach in experimental test cases, such as the periodic Sod shock tube case illustrated in figure 4. Note how the persistent reflection allows regeneration and long-term retention of flow structure.

## 5. Conclusions and Future Work

The instability simulations here suggest that strong fluctuations in velocity and pressure tend to dissipate by mutual shock interaction on scales of several times $10R_*$. In the resulting nearly isobaric, constant speed flow, the persistance of a strong density contrast thus requires a countervailing temperature contrast. Our plans for future work are to apply this pseudo-planar approach toward the distant evolution of wind structure, including also an explicit treatment of radiative heating and cooling terms in the energy equation. The eventual goal is to understand the effect of instability-generated structure on key observational

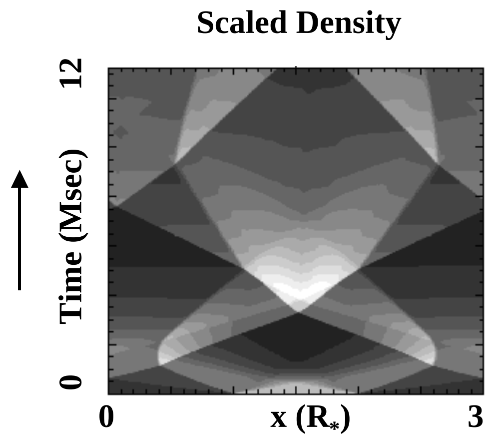


Figure 4. Application of the pseudo-planar formalism to follow the adiabatic evolution of an periodic density pulse in a spherical outflow. The total evolution time is some 4 months, corresponding to a flow-distance of some 2000 $R_*$.

diagnostics, like the X-ray emission that originates from hot-gas at a radial distance of order $10R_*$, as well as mass-loss rates inferred from free-free radio emission that originates at distances of order $100R_*$.

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