3D Line Driven Winds - Clumpy Outflows

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Abstract

- We perform the first 3D hydrodynamic (HD) simulations of line driven disc winds.
- We find that non-axisymmetric density features, so called clumps, form primarily at the base of the wind. These clumps are
  - a factor of 3 more/less dense than the background
  - super-Sobolev in length
  - have velocity dispersion much greater than the sound speed

Introduction

- Line driving is a possible mechanism for launching outflows from massive stars, cataclysmic variables (CVs), X-ray binaries (XRBs) and active galactic nuclei (AGN).
- Observations suggest these outflows are clumpy, necessitating 3D simulations.

Hydrodynamics - Basic Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \qquad \text{(Continuity)}$$

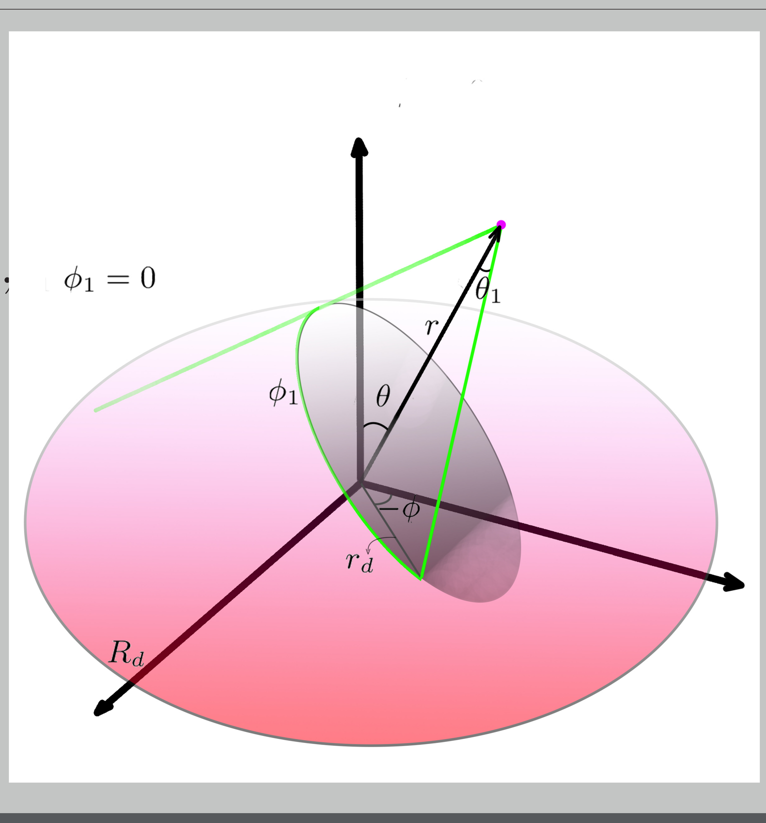
$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{vv} + \mathbf{P}) = \underbrace{-\rho \nabla \Phi}_{\text{gravity}} + \underbrace{\rho \mathbf{F}^{\text{rad}}}_{\text{radiation}}, \qquad \text{(Momentum)}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E+P)\mathbf{v}) = -\rho \mathbf{v} \cdot \nabla \Phi + \rho \mathbf{v} \cdot \mathbf{F}^{\text{rad}}, \qquad \text{(Energy)}$$

$$\mathbf{F}^{\text{rad}} = \underbrace{\mathbf{F}^{\text{rad}}_{e}}_{\text{electron scattering}} + \underbrace{\mathbf{F}^{\text{rad}}_{L}}_{\text{line driving}},$$

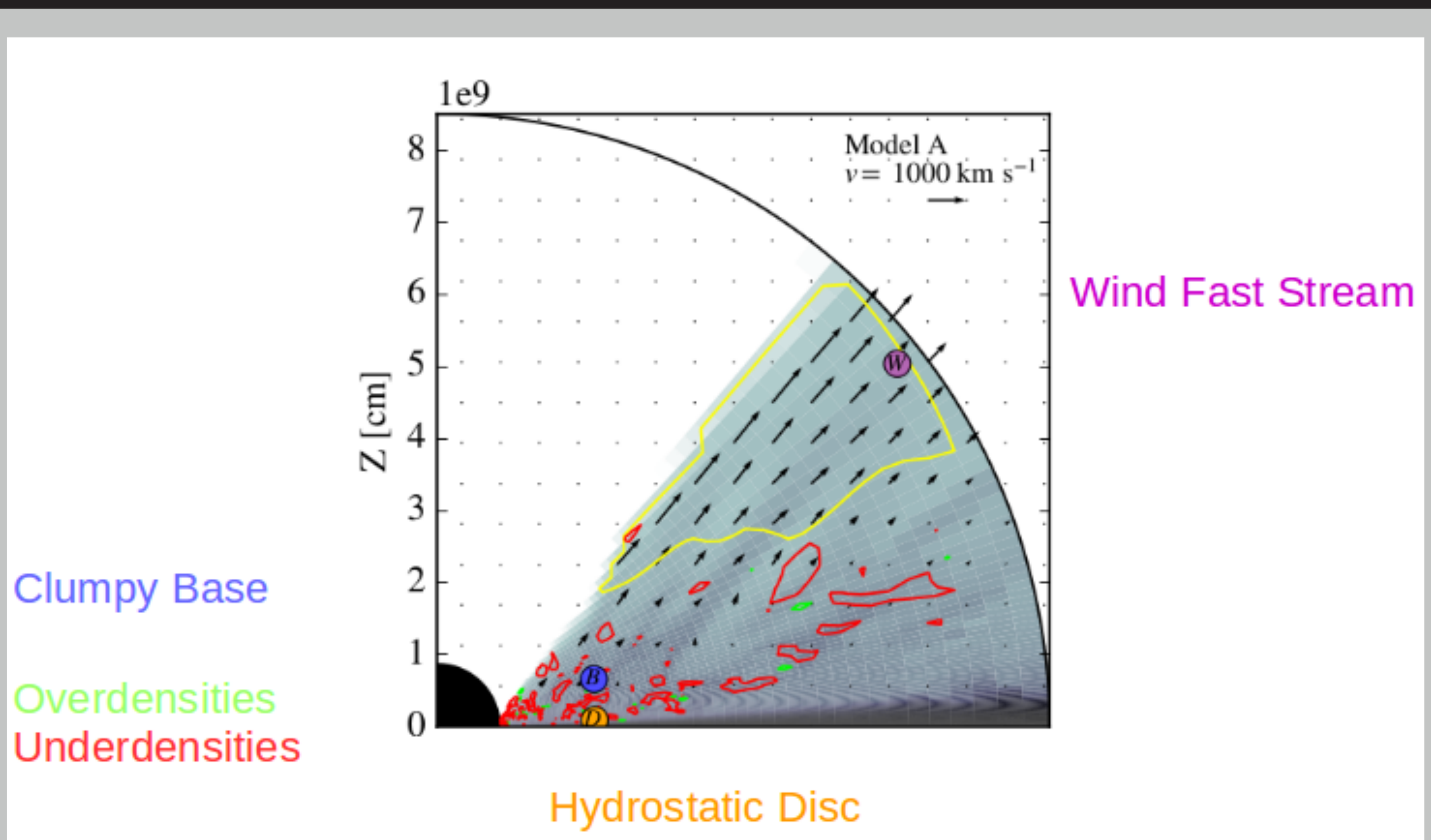
$$= \oint (1 + M(t)) \left(\mathbf{n} \frac{\sigma_e I d\Omega}{c} \right)$$

↑ Force Multiplier



- Force multiplier is
  - the effective number of optically thick lines
  - a function of optical depth parameter t

Disc Wind Anatomy



- Global properties determined by total system luminosity
  - Higher luminosity → larger mass flux
  - Higher luminosity → faster velocity
- Geometry of outflow determined by relative stellar & disc luminosity
  - Higher stellar luminosity → radial flow
  - Higher disc luminosity → vertical flow
- Non-axisymmetries primarily at the base of the wind

Clump Density

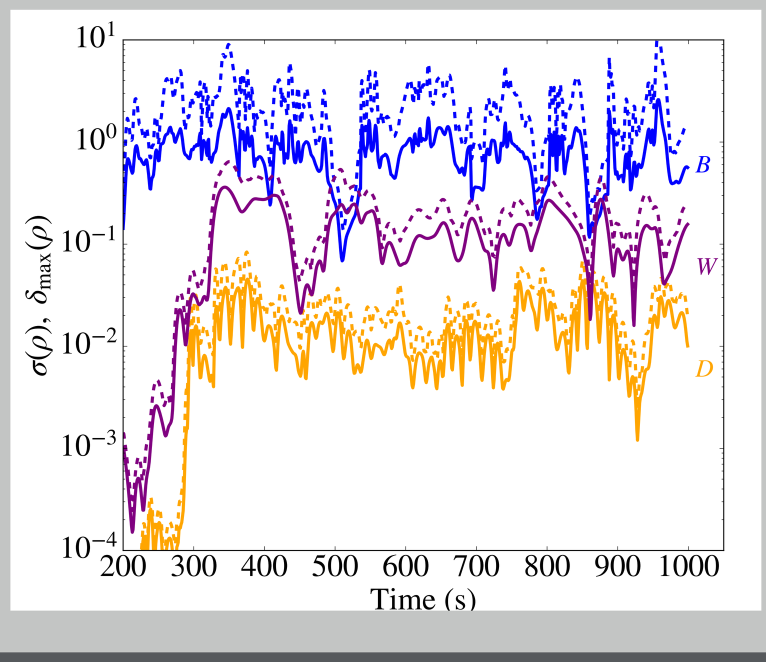
- Relative Standard Deviation

$$\sigma(\rho) = \frac{1}{\bar{\rho}} \sqrt{\sum_{k=0}^{N_\phi} (\rho_k - \bar{\rho})^2}.$$

- Maximum Deviation

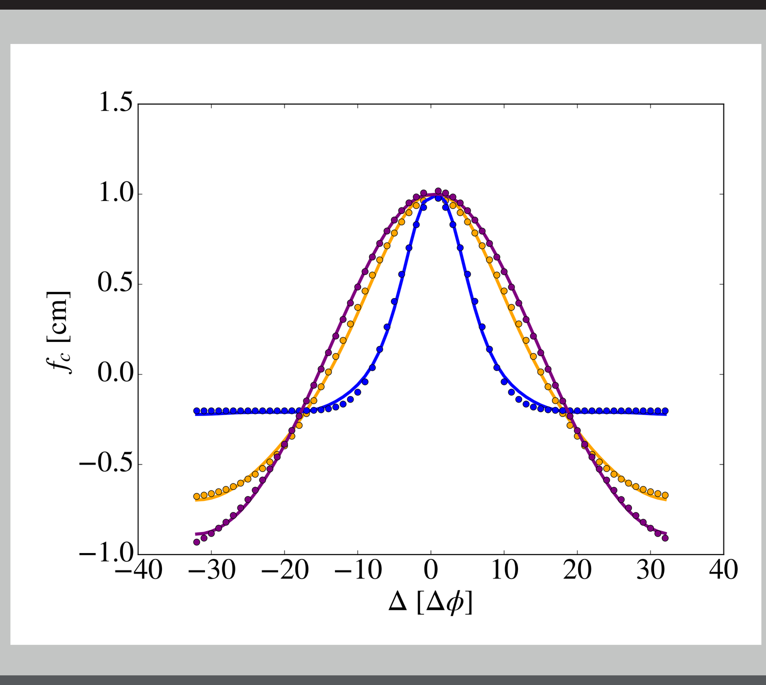
$$\delta_{\max}(\rho) = \frac{1}{\bar{\rho}} \max \left| \rho_k - \bar{\rho} \right|.$$

- Clumps ∼ a few times background density



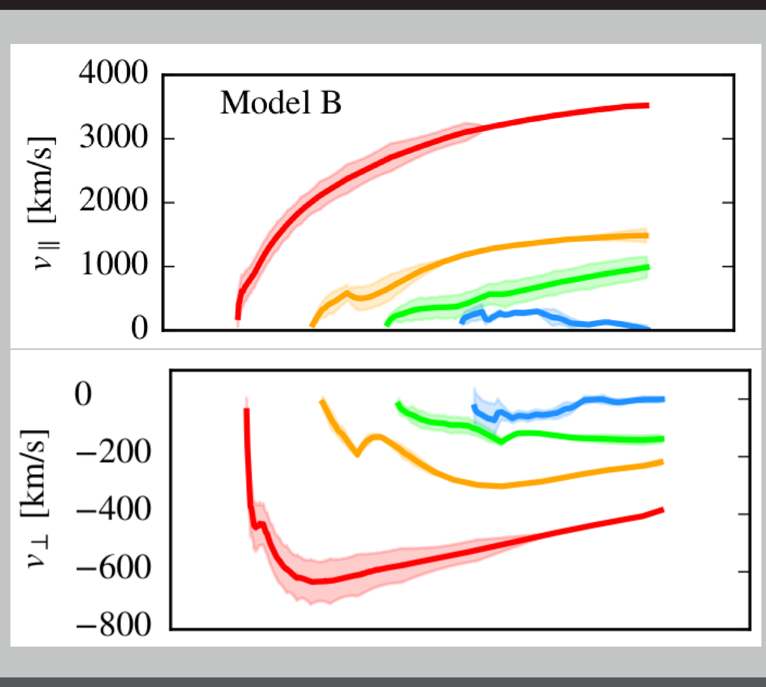
Clump Size

- Characterize size using width of density auto-correlation
- Clumps restricted to base of wind
- Super-Sobolev in length $l \sim 10^8 \text{cm} \gg l_{\text{Sob}} \sim 10^7$ cm



Velocity Dispersion

- Time-averaged streamlines most stationary in fast stream.
- Velocity dispersion comparable to wind velocity at base
- Velocity dispersion large compared to sound speed.



Observational Prospects

- Emission spectra $\sim \rho^2$
- Absorption spectra $\sim \rho$
- Line broadening due to velocity dispersion

Future Work

- Can clumps grow further via thermal instability?
- Can self-shielding enhance/suppress the wind by changing ionization state of gas?
- Are outflows sensitive to the driving spectral energy distribution?

References

[1] Dyda, S., Proga, D., 2018, MNRAS, 475, 3786D, arXiv:1710.07882

[2] Dyda, S., Proga, D., 2018, MNRAS, 478, 5006D, arXiv:1802.03670

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