Turbulent Entrainment Model of Molecular Outflows

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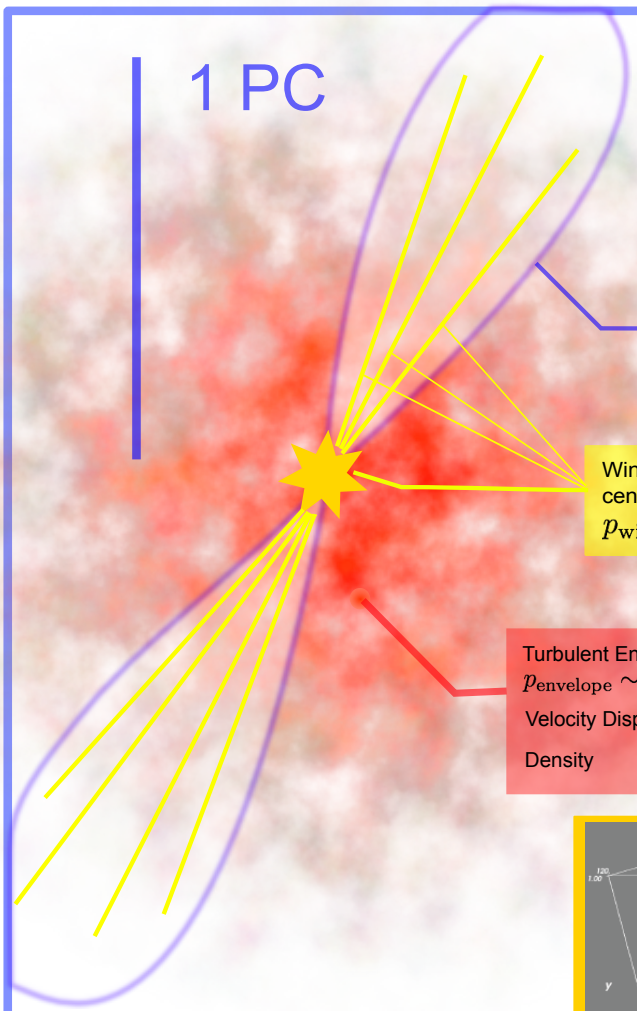


Motivations:

* Explain the kinematic structure of wide-angled outflow
* Understand the interaction between wind and *turbulent* ambient gas

The outflow layer

Outflow: Mixing Layer between the wind and the envelope

Mixing Efficiency: α

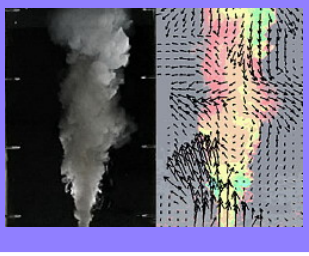
The wind contributes momentum
The envelope contributes mass

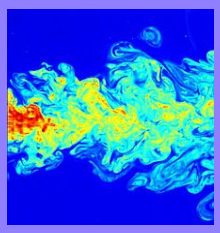
$$\dot{P}_{\rm wind} \sim \rho_{\rm wind} v_{\rm wind}^2 {\rm d}s \sim \rho \sigma^2 {\rm d}s$$
$$\dot{M}_{\rm envelope} \sim \alpha \rho \sigma {\rm d}s$$

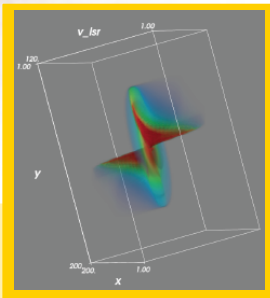
Outflow Velocity

$$v_{\rm outflow} = \frac{\dot{P}_{\rm wind}}{\dot{M}_{\rm envelope}} \sim \frac{\sigma}{\alpha} \sim 3 \times \sigma$$

Some Examples of Turbulence Mixing:







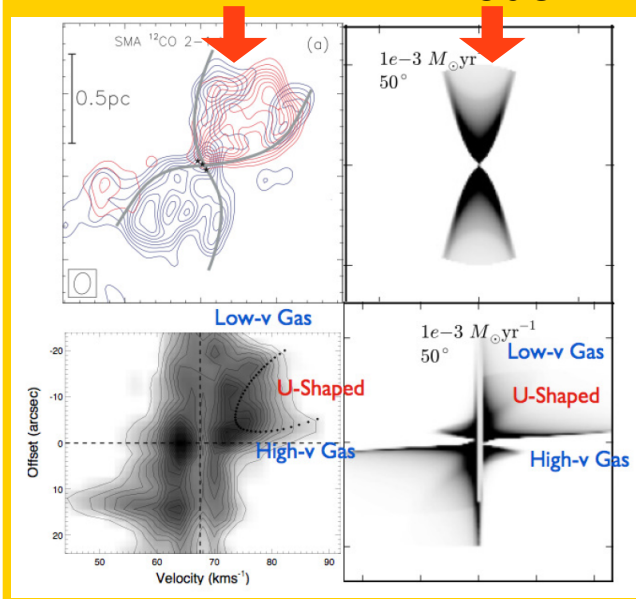
3D Rendering of a CO(3-2) data cube from our model

Results:

* Explain the velocity structure of wide-angled outflows
  -- both the low-v gas and the high-v gas

* The outflow velocity is always several times of the velocity dispersion of the ambient gas
  -- a natural result of turbulent mixing

Observation v.s. Model



G240.31+0.07, observations are from Qiu et al. (2009)

Turbulent Entrainment Origin of Protostellar Outflows

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ABSTRACT

Protostellar outflow is a prominent process accompanying the formation of stars. It is generally agreed that wide-angled protostellar outflows come from the interaction between the wind from a forming star and the ambient gas. However, how the interaction takes place is unclear. In this work, we theoretically investigate the possibility that the outflow results from interaction between the wind and the ambient gas in the form of turbulent entrainment. Unlike previous models, turbulent motion of the ambient gas around the protostar is taken into account. In our model, the ram-pressure of the wind balances the turbulent ram-pressure of the ambient gas, and the outflow consists of the ambient gas entrained by the wind. The calculated outflow from our modelling exhibits a conical shape. The total mass of the outflow is determined by the turbulent velocity of the envelope as well as the outflow age, and the velocity of the outflow is several times larger than the velocity dispersion of the ambient gas. The outflow opening angle increases with the strength of the wind and decreases with the increasing ambient gas turbulence. The outflow exhibits a broad line width at every position. We propose that the turbulent entrainment process, which happens ubiquitously in nature, plays a universal role in shaping protostellar outflows.

Key words. Stars: winds, outflows–Stars: massive–ISM: kinematics and dynamics–ISM: jets and outflows – Turbulence–Line: profiles