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MHD Jet Propogation - Case of DG Tau.

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ABSTRACT

The aim of the work is to perform numerical simulations of stellar jets in propagation region with consistent nozzle conditions from launching simulations. This novel approach provides a global picture of jet and highlight the launching as well as its interaction with the ambient medium. The flow parameters observed at a distance of few AU from the protostellar jet DG Tau have been eventually used to settle the jet inflow conditions values whereas the profiles of different quantities are obtained from steady state launching simulation, and a new simulation has been run on typical stellar jets time and length scales. We also investigate the effects of cooling in these jets. We find evidence of density knots in our adiabatic simulations whereas the cooling flow have much lesser and weaker knots.

1. Introduction

Jets and outflows are seen ubiquitously in most of the astrophysical objects ranging from low mass stars to AGN. They a play vital role in form of different feedback processes in nearby environments. The extended nature of the jet drives turbulence in ISM on large scales, where at smaller scales these outflows are efficient carrier of angular momentum allowing the matter from the disk to accrete on to the central object.

Outflows from protostellar objects have been discussed extensively in the literature. Outflows ejected from underlying accretion disks are believed to be launched by magneto-centrifugal process Blandford & Payne (1982). According to this picture, the matter from the accretion disk is loaded onto the field lines and is magneto-centrifugally accelerated along the field lines. Numerical work for studying launching of disk winds have been carried out with disk in domain and also treating the disk as boundary. Vaidya et al (in prep) have carried out numerical simulations of launching disk winds treating the disk as a boundary condition. The magnetic field profiles were chosen to be force free and similar to Ouyed & Pudritz (1997) setup. The final steady state jet velocity obtained is shown in Fig. 1

The propagation of jet and its interaction with ambient medium is likewise studied extensively. (e.g. Lind et al. (1989), Appl & Camenzind (1992), Frank et al. (1998), Stone & Hardee (2000), Nakamura & Meier (2004), de Colle & Raga (2006)). Most of the simulations of jet in propagation have a top hat velocity profile at the nozzle and pressure there is estimated using a radial force balance between thermal pressure gradient and toroidal magnetic tension. Stone & Hardee (2000) investigated the effect of varying magnetic fields on structure of such jets. Jets with varying field strength showed very little internal structure in case when no time varying perturbation was included. However, in runs with a sinusoidal temporal perturbation to the top hat velocity profile produced density blobs at regular intervals. Also, most of these previous simulations do not prescribe jet rotation at the nozzle of the flow.

The initial conditions used in most of the simulations are disjoint from the launching simulations. Frank et al. (1998), also attempted to have self similar solutions of Blandford-Payne model at the base of the flow. Ideally, one would like to self consistently study the jet from launching base to a very large distance and investigate different aspects of launching, collimation and interaction of the jet. However, this study is as of now expensive computationally due to the presence of different velocity scales involved in the ideal setup. We in this work examine the interaction of jet as it propagates in the ambient medium. However, to have more self consistent approach we prescribe values of jet quantities at the nozzle as obtained from steady state launching simulation. (See Fig. 1)

1.1. DG Tau Jet Features

Proto-stellar jets have been studied observationally in great details with the advent of state of art telescopes. Usually jets are observed in forbidden emission lines like SII, OII etc. One of the jet studied in great details is the DG Tau jet. (Lavalley-Fouquet et al. (2000), Dougados et al. (2000), Bacciotti et al. (2002), Pyo et al. (2003),Cerqueira & de Gouveia Dal Pino (2004))

DG Tau jet is believed to have onion shaped structure as it comprises of inner High

Velocity Component (HVC) and outer Low Velocity Component(LVC). Bacciotti et al. (2002) observed rotations in this jet via measuring the asymmetries in the line profile. The typical rotational velocity measured was of the order of 10 km/s. The HVC velocity is estimated to be around 300-400 km/s whereas the LVC is propagating at 150-200 km/s. The typical outflow mass rate is observed to be $\sim 10^{-8} M_{\odot} yr^{-1}$. Güdel et al. (2008) has also found evidence of X-ray emission using Chandra. This implies that there are regions in the jet where temperature is close to 10^6 K.

Also, in the case of DG Tau jet large number of internal features are seen and the most prominent ones are the axial density knots at regular intervals. The origin and evolution of these knots is still unknown. In this work, we investigate numerically the propagation of DG Tau jet and see how the formation and evolution of these density knots is altered with consistent profiles of different quantities at the nozzle of the flow. Since the cooling time in these jets are much shorter than dynamical time scale, the effects of cooling on the flow should also be considered. We also investigate the effect of cooling on the internal structure in jets.

2. Numerical Setup

The present study is to simulate propagation of winds that are launched from underlying accretion disks from young stellar object. We setup a static isothermal ambient medium in which the jet which is ejected from the nozzle at the base of the domain. Cylindrical coordinates (r,ϕ, z) are used for this 2.5 dimensional axisymmetric simulation of jet propagation. The radial extent of the domain is of 240 AU with a uniform resolution of δr = 0.468 AU while the extend in vertical direction is from 150 AU to 800 AU with resolution of δz = 0.634 AU.

The ambient medium with constant density ρ_a and sound speed $c_{s,a}$ has no magnetic fields initially. The magnetic fields are dragged in medium by the magnetized jet. The medium is considered to be isothermal and hence the pressure is constant and given by $P_a = \rho_a c_{s,a}^2$. The jet is introduced in this medium via a nozzle at the base of the domain. The density and the velocity of the jet is parametrized by two dimensionless numbers viz. density contrast between jet and medium

$$\eta = \frac{\rho_{jet}}{\rho_a}$$

and initial sonic Mach Number

$$M = \frac{V_{jet}}{c_{s,a}}$$

The boundary conditions at the top and right of the domain are chosen to be outflow in which gradients of all physical quantities are set to be zero. The axisymmetric boundary is along the axis of the flow. At the base of the domain, physical quantities of the jet flow obtained from steady state of launching simulations are prescribed at the nozzle of width equal to radius of jet (R_{jet}), where as the remaining part of the lower boundary ($r > R_{jet}$) has values of quantities equal to the initial ambient medium.

The non-relativistic MHD module of the PLUTO code (Mignone et al. 2007) is used to study the propagation of these jets in the ambient medium. We perform simulations in the ideal MHD limit and also consider adiabatic jets (no explicit cooling) and radiative jets (with explicit cooling). The related equations are listed below.

$$\frac{\partial \rho}{\partial t} + (\mathbf{v}.\nabla)\rho + \rho\nabla.\mathbf{v} = 0 \tag{1}$$

$$\rho(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v}) = -\nabla\mathbf{P} + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \mathrm{E}) + \nabla. \left[(\rho \mathrm{E})\mathbf{v} + (\mathbf{P} + \frac{B^2}{8\pi})\mathbf{v}\right] - \mathbf{B}(\mathbf{v}.\mathbf{B}) = -n^2\Lambda(T) \tag{3}$$

$$\mathrm{E} = \epsilon + \frac{v^2}{2} + \frac{B^2}{8\pi\rho} \tag{4}$$

$$\rho\epsilon = \frac{\mathbf{P}}{\gamma - 1} \tag{5}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \tag{6}$$

where, ρ is gas density , $\mathbf{v}$ velocity vector with components as v_r, v_z and v_ϕ , $\mathbf{P}$ is the gas pressure, $\mathbf{B}$ is the magnetic field vector whose magnitude is B. Total energy of the flow E comprises contribution from internal energy (ϵ), mechanical energy and magnetic energy and γ is the adiabatic index. $\Lambda(T)$ is a cooling function which is dependent on temperature and n is the number density. Since the jets are considered in propagation region much above the escape surface, we neglect the effects of gravitational forces in our calculations.

In case of jets with explicit cooling, the cooling term is also taken into to account for the conservation of total energy (Eq. 3). The cooling function $\Lambda(T)$ is calculated using a non-equilibrium cooling prescription in the code. In this prescription the cooling is mainly due to recombination of ionized hydrogen. The fraction of neutral (f_n) is evolved consistently at each advection time step in this prescription.

$$\frac{\partial f_n}{\partial t} + \mathbf{v}.\nabla f_n = n_e \left[-(c_r + c_i) f_n + c_r \right] \tag{7}$$

where n_e is the electron density and c_r, c_i are recombination and ionization rate of hydrogen respectively. These rates solely depend on the temperature of the flow. The cooling function which appears as a source function in the energy conservation equation is calculated at each advection time step of the flow based on the fraction of neutrals and temperature of the flow.

2.1. Physical Values

In our simulations of jet propagation, the unique feature is to consistently provide the conditions of the jet flow at the nozzle. The physical quantities for the jet at the nozzle is obtained from the steady state jet launching simulations.(See §2). The radial variation of different non dimensional jet quantities from the steady state of launching simulations are scaled to the physical values consistent with observations of DG Tau jet and are prescribed at the nozzle to study its evolution. The advantage of using these profiles ensures initial force balance at the nozzle and also provide more consistent study of the jet as it propagates into the ambient medium.

In order to scale the non-dimensional radial profiles from jet launching simulations, we need to prescribe three scaling parameters viz. length scale (L_o), velocity scale (V_o) and the density scale (ρ_o). In our attempt to study the DG Tau jet in more details we consider observational values of these quantities and scale accordingly. The values used for the present study are listed below in Table 1.

The radial profiles of different quantities are shown in Fig. 2. The physical quantities for the ambient medium are prescribed with the help of dimensionless parameters, η and M,

Table 1: The physical quantities used to scale the non-dimensional steady state profiles of the jet. m_H is the mass of atomic hydrogen

Quantity	Scaling Parameter	Physical Values (See Fig. 2)
Number density	$n_o = \frac{\rho_o}{m_H}$	$2.5 \times 10^4 \mathrm{cm}^{-3}$
Jet Velocity	V_o	200 km/s
Jet Radius	L_o	20.0 AU

defined previously. In all our simulations we choose $\eta = 10$ and $M = 20$. For the density contrast we choose maximum value of jet density at the nozzle and use the average velocity at the nozzle for the Mach number. With this choice the number density in the ambient medium is 250 cm^{-3} and sound speed is evaluated as 7.5 km/s corresponding to temperature in ambient medium to be $\sim 10^3$K

3. Results & Discussion

The study of numerics of jet in the propagation region explores the subject of interaction of the jet with ambient medium and the instabilities that are caused due to this interaction. There are two main drivers of instabilities in these MHD jets. The pressure driven Kelvin Helmholtz instability is caused to shear between the jet material in the back flow and the cocoon. The sausage and the kink instability are mainly driven due to presence of poloidal current in the jet. In case of axisymmetric jets, the main instability due to current is the sausage instability (i.e.due to m = 0 mode). Physically, this type of instability is caused due to perturbation in the radius of the flux loop. The linear stability analysis of m = 0 mode with simplified magnetic field profiles have been derived by Begelman (1998)

In this section we compare the adiabatic and cooling jet simulations with same set of initial parameters. Fig. 3 shows logarithmic density at certain time step for adiabatic and cooling jet simulation. It can be seen that there are large number of differences between these two jets. The main differences are can be listed as follows -

- The cocoon of the adiabatic jet is much broader than the one in jet with radiative cooling.

- The radiative jet has higher density at the tip of the bow shock

- Kelvin Helmholtz instability is more pronounced in case of radiative jet

- The radiative jets form less number of clumpy knots as compared to the adiabatic jets particularly at the axis of the jet

The above differences in the two sets of simulations are mainly due to the loss of thermal pressure in radiative simulations. Initially, the radiative jet behaves in the same manner as the adiabatic jet, however after one cooling time, the differences start to appear. The shocked ambient material at the tip of the bow show will loose it thermal pressure support due to cooling and collapses on the bow head which leads to density enhancement at the tip of the bow show. The pressure ratio between the jet and ambient medium also plays a important role in governing the formation of knots due to internal shocks. In case of radiative jets where the thermal pressure is reduced the magnetic pressure begins to play a crucial role.

In Fig. 4, the radial pressure profiles from different components are shown for adiabatic and radiative simulations. The cut it made at the place where density knot is formed in the adiabatic simulation ($z \sim 380$ AU), however radiative simulation does not show any prominent knot feature. The reason could be comprehended from Fig. 4. In radiative jet, the polo dial magnetic pressure becomes important at the axis due to the loss of thermal pressure. The dominant magnetic pressure smears apart the formation of density accumulation by accelerating the material as it converges to axis. Thus , the material will find it difficult to collapse against the polo dial magnetic pressure and not form a density knot as seen in adiabatic simulation. Also the strength of the internal shock is weak in case of radiative jet.

This implies that the formation of density knots with internal shocks are highly dependent on pressure ratio and in general when physical cooling is effective the dominant polodial magnetic pressure hinders the formation of knots at the axis. This could suggest that the density knots observed at regular intervals in the astrophysical jets could be an effect caused due to the perturbation at the accretion disk. We are currently trying to produce synthetic emission maps for these simulations so as to directly compare with observations done for DG Tau jet.

Fig. 1.— Steady state MHD jet velocity obtained from the launching simulation. The values in of the velocity are in code units. The *yellow* lines depict the fieldlines. The different critical surfaces [slow magnetosonic (*dashed white*), escape (*black*), Alfven (*red*), fast magnetosonic (*blue*)] are also shown

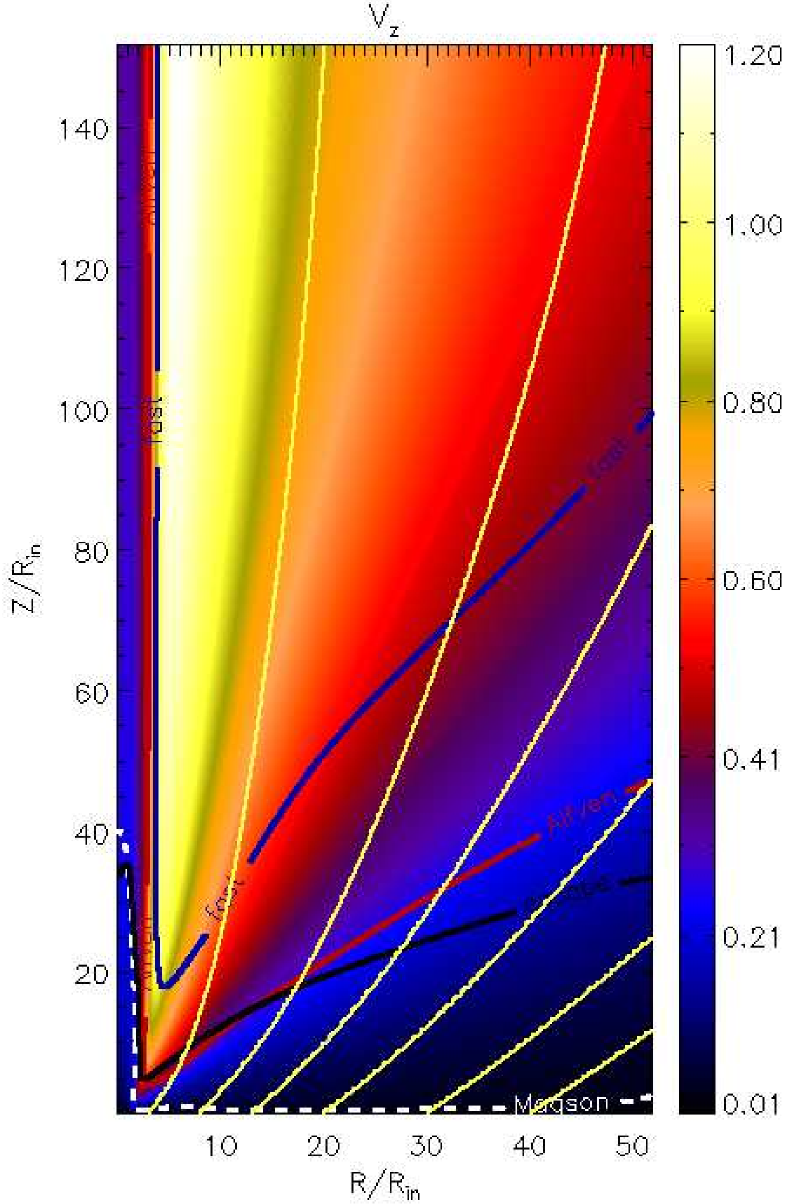


Fig. 2.— Values of different jet quantities prescribed at the nozzle. These values are scaled to physical units using the scale factor as given in Table 1. The *dashed* lines show azimuthal components and *solid* line denote the vertical component for the velocity and polodial component for the magnetic field.

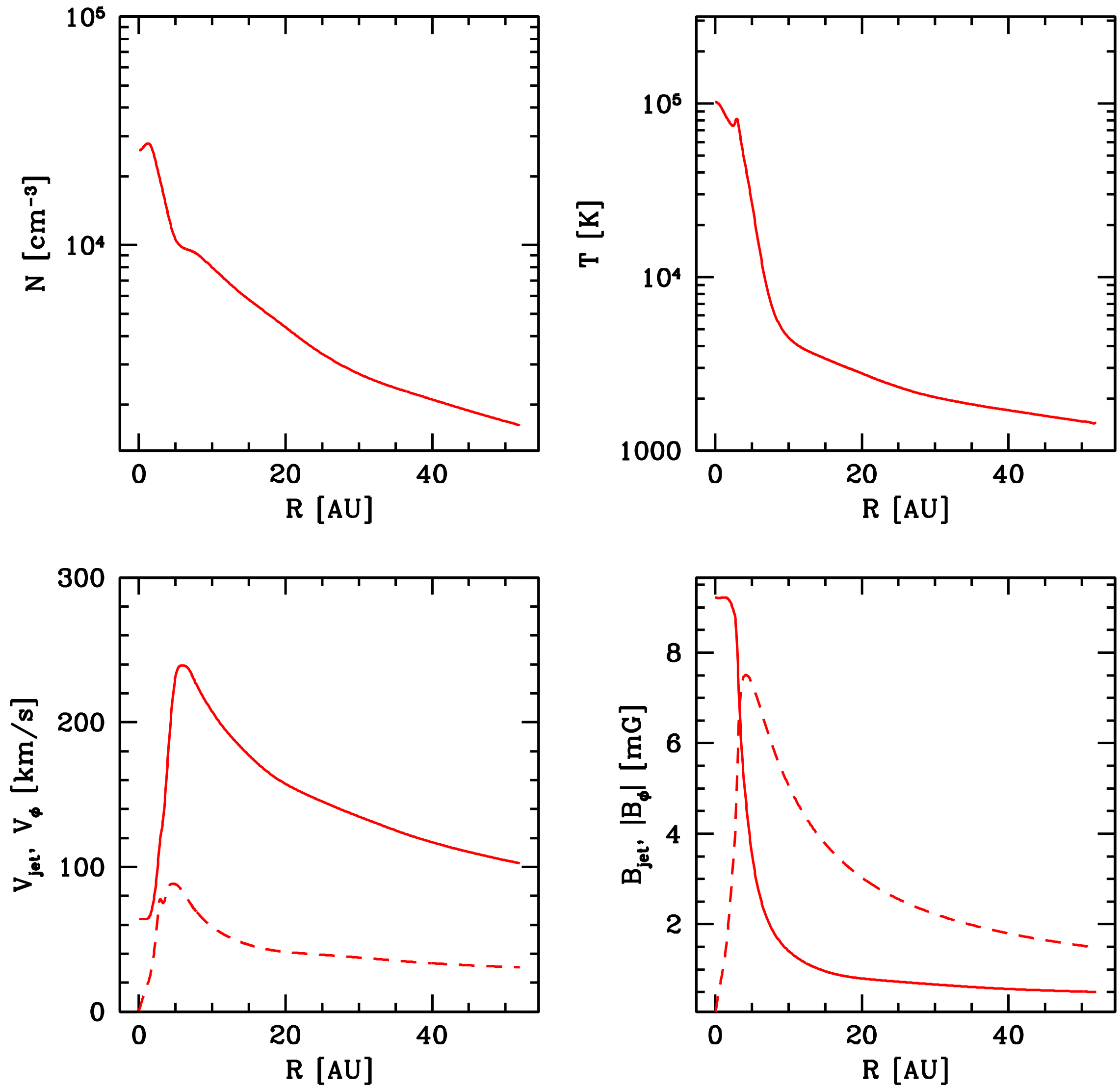


Fig. 3.— Logarithmic values of number density for the adiabatic jet (*left*) at $\tau = 900$ and for radiative jet at $\tau = 800$ (*right*)

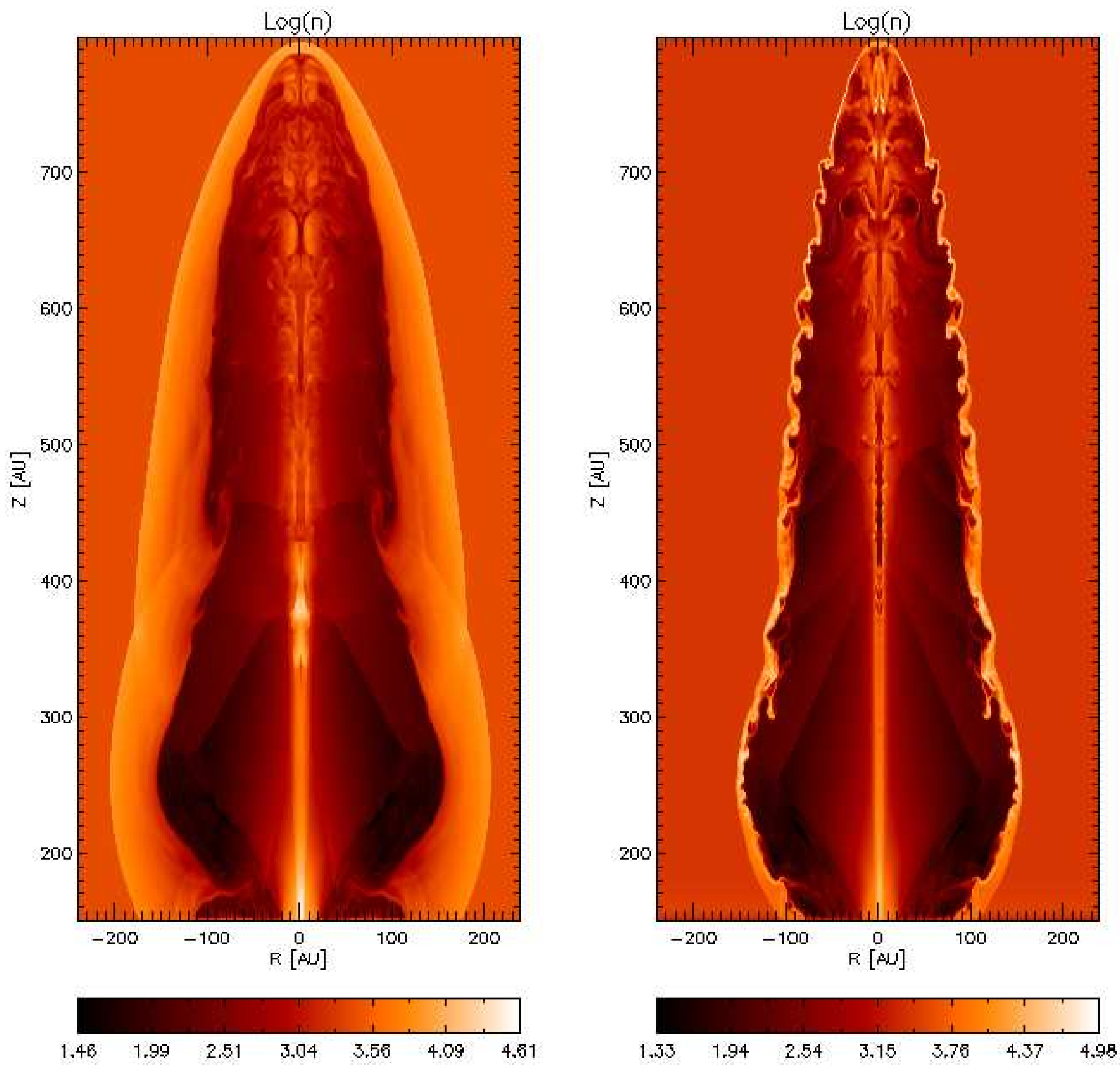
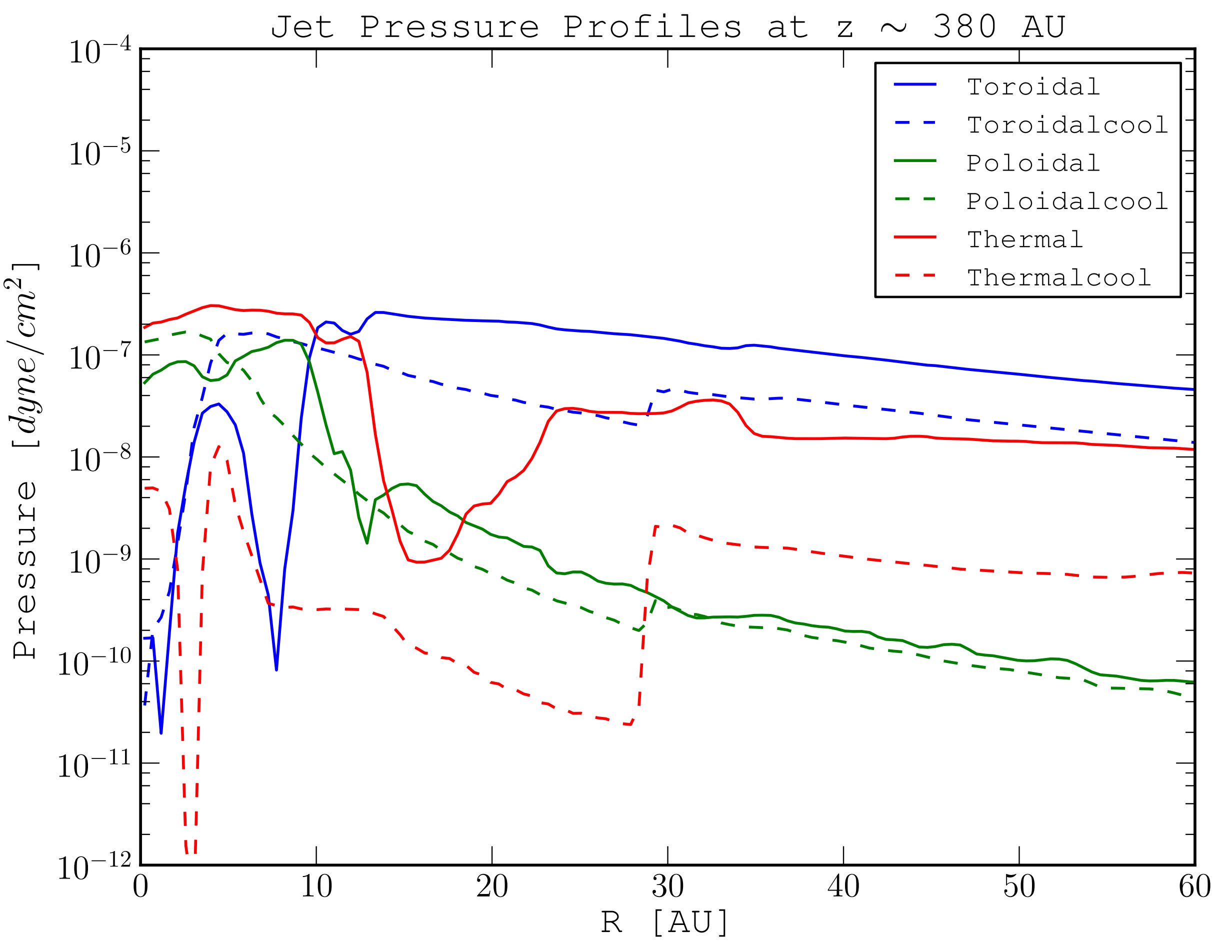


Fig. 4.— Comparison of radial profiles at z ∼ 380 AU for different components of pressure (shown with different color) in the jet. The pressure for adiabatic jets are shown as *solid line*, while radiative jets are denoted by *dashed line*



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