GRB jet structure and variability studies with 3D simulations of magnetically arrested disks

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MOTIVATION

Gamma-ray bursts (GRB) are transient phenomena observed in the high energy sky at cosmological distances. Based on their duration, they can generally be classified into two: short and long GRBs. The short GRBs typically last <2s and originate from the merger of two compact objects. The long GRBs last longer, upto a few hundreds of seconds, and originate from the collapse of massive stars. Both of these scenarios can result in an accretion disk around a central compact object, which will act as their central engine. GRBs are observed as relativistic jets pointing towards our line of sight. The properties of the accretion inflow can affect the properties of the observed GRB jets. The formation of magnetically arrested disk (MAD) has recently been invoked to explain the properties of jets from accreting black hole sources. We numerically model the evolution of the accretion disk around a Kerr black hole with 3D general relativistic magnetohydrodynamic (GRMHD) simulations and study the formation and evolution of the MAD state and its effect on the properties of the observed GRB jets.

NUMERICAL SETUP AND MODELS

We use the GRMHD code `HARM`, a conservative and shock capturing scheme, to evolve the equations of magnetohydrodynamics in a fixed Kerr metric [1]. The initial state is prescribed according to a pressure equilibrium disk embedded in a poloidal magnetic field (e.g. Fig. 1). We use two analytical hydrodynamical models of accretion disk, based on the Fishbone-Moncrief [2] (FM76) and Chakrabarti [3] (Ch85) solutions, as our initial states for the models of collapsar disk and the remnant after a binary neutron star merger, respectively. Our models have a black hole spin characterized by the Kerr parameter a = 0.9. The simulations are run at a resolution of 288x256x128 in the r, θ and ϕ directions respectively. We use a γ-law equation of state with γ=4/3.

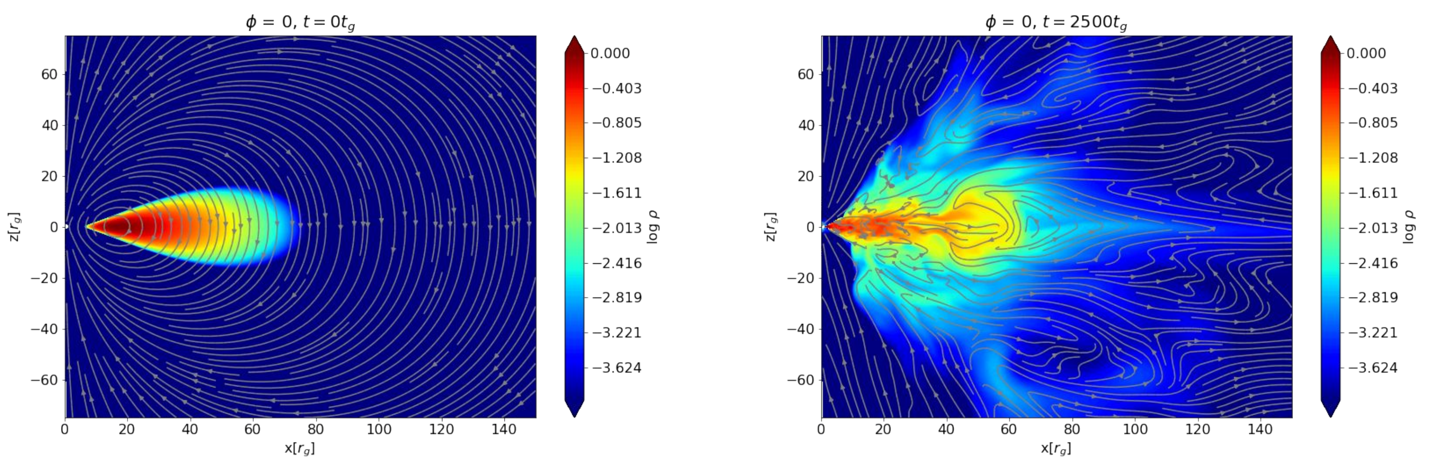

Fig. 1: Initial and evolved states of the disk density structure overplotted with the magnetic field lines for Ch85 model.

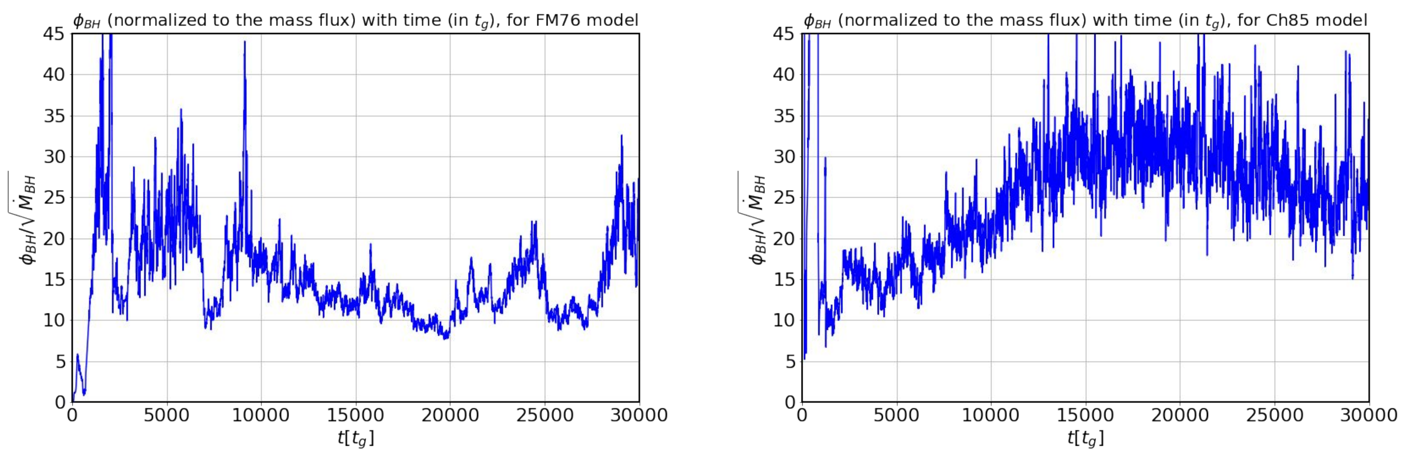

Fig. 2: Magnetic flux on the black hole horizon with time for FM76 model (left) and Ch85 model (right).

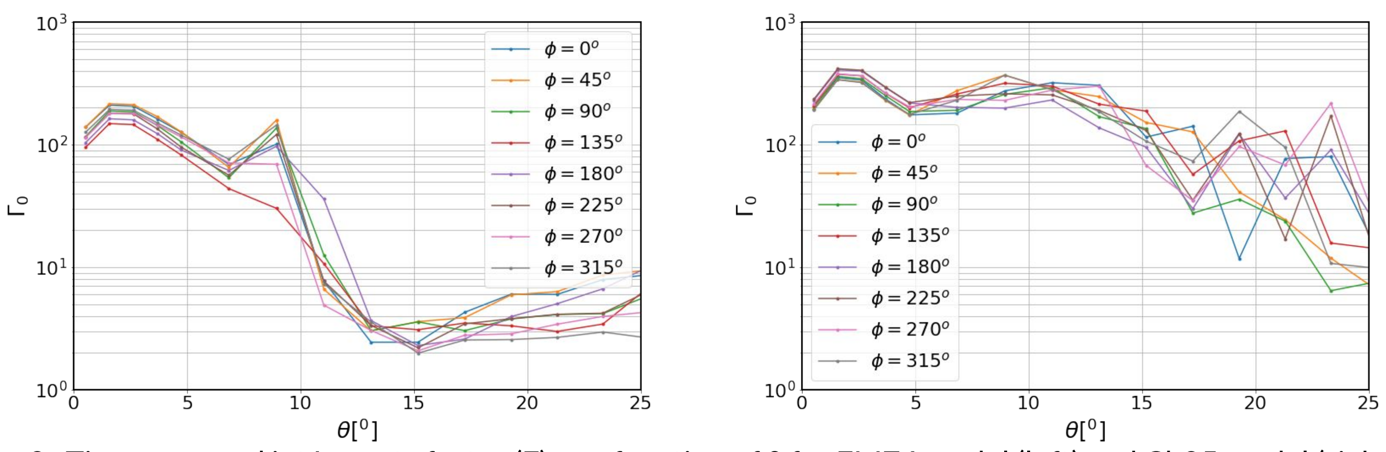

Fig. 3: Time averaged jet Lorentz factor (Γ) as a function of θ for FM76 model (left) and Ch85 model (right).

RESULTS AND APPLICATIONS TO GRB CENTRAL ENGINES

The magnetic field imposed on the initial density structure results in the development of the magnetorotational instability (MRI) and helps to start the accretion. The accreting plasma drags along with it more magnetic flux to the black hole. This results in the development of a considerable amount of poloidal magnetic flux near the horizon which can impede with the accretion (Fig. 2). Thus the smooth flow of matter along the equatorial plane is halted and further accretion proceeds mainly in short episodes due to the interchange instability developed in the plasma. Such a state of the accreting torus is termed as a MAD, which we observe in our models.

We use the jet energetics parameter (μ) to estimate the Lorentz factor at infinity, assuming all energy is transformed to the baryon bulk kinetic, as shown by [4]. It is defined as:

$$\mu = T^r_{\ t}/\rho u^r \qquad (1)$$

Here, $T^r_{\ t}$ is the energy component of the energy-momentum tensor which comprises matter and electromagnetic parts, ρ is the gas density and u^r is the radial velocity. So it is the total plasma energy flux normalized to the mass flux.

TIME VARIABILITY:

We choose 2 different locations along the jet direction at $r = 150r_g$, θ = 5° (Loc.1) and θ = 10° (Loc.2) and compute μ there to study the time variability of the jet. The values we estimate are averaged over ϕ. We estimate the Lorentz factor (Γ) as the time average of μ from these locations. We also estimate the minimum variability timescale (MTS) of the jet emission by taking the average peak width at their half maximum, over the time series. The estimated values from our models are given in the Table. The estimated MTS values for our short and long GRB models are in agreement with the values from observed samples [5] [6]. We also computed the power density spectra (PDS) of the μ time series data and fitted it with a power law. The slopes of the PDS are given in the Table. They are consistent with the observations but are in their lower limit [7] [8] [9].

Model	Lorentz factor (Γ)			MTS estimated (in t_g)			Slope of the PDS	
	Loc. 1	Loc. 2	Average	Loc. 1	Loc. 2	Average	Loc. 1	Loc. 2
FM76	105.96	89.45	97.71	178.63	269.80	224.21	-0.8253	-1.4899
Ch85	61.33	202.36	131.85	147.01	147.72	147.37	-0.8016	-1.1310

JET PROFILE:

The jets produced in our models are highly structured and non-axisymmetric. The higher values of Γ are reached at the outer region of the jet farther from the axis. This can be observed in the time snapshots of the 3D μ contours (e.g. Fig. 4). We also compute the time averaged profile of the jet with the polar angle θ, at a large distance of ~ $2000r_g$, to further understand the average jet structure qualitatively (Fig. 3). For our long GRB (FM76) model, the most energetic parts of the jet are confined to an angle of θ~11° and highest Γ are reached around θ~9°. This is in the lower bound of the observed values estimated by 248 observed long GRB samples [10]. The jet produced in our short GRB model (Ch85) is broader and has an opening angle of θ~25°. This is in the upper range of the observed values in [10].

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Our models produce **structured jets** with **opening angles** of **~25° for short GRBs** and **~11° for long GRBs.**

The **MTS** values are **2.18 ms for the short GRB** model and **13.26 ms for the long GRB** model.

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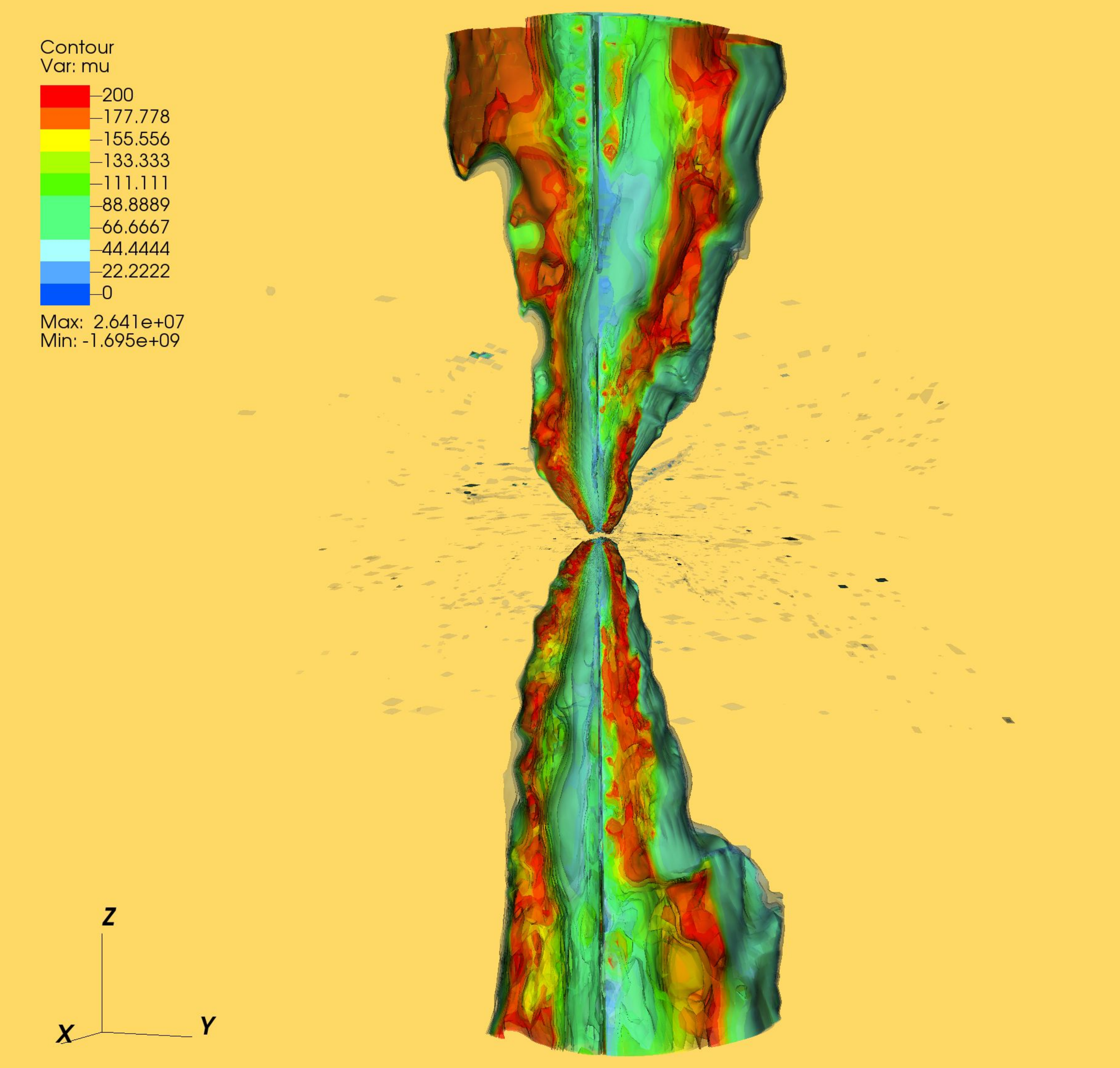

Fig. 4: 3D jet structure at time $t=5000t_g$ for FM76 model. Plot shows the contours of the energetic parameter defined as μ (see Eqn. (1)) up to a radius of $200r_g$.