# GRMHD simulations of disk/jet systems: Application to collapsars (astro-ph/0502225)

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## Introduction

We have performed 2-D and 3-D General Relativistic Magneto-Hydrodynamical (GRMHD) simulations of a collapsar (Woosley 1993). Typical mass for a black hole in a collapsar is $M_{\rm BH} = 3M_\odot$ and for the initial torus $M_{\rm torus} = 0.3M_\odot$. The density in the torus is around $10^{11} - 10^{12}{\rm g/cm}^3$. In our simulations we place a weakly magnetized initial torus (the magneto-rotational instability (MRI, Balbus & Hawley 1998) generates turbulent transport of angular momentum, transforming the initial torus into an accretion disk) around a black hole with an infalling dust background which accounts for infall from the outer layers of the star. The outer layers of the star are not part of the simulation. In this sense we are simulating the interior of a collapsar.
The collapsar is thought to provide the inner engine for Gamma Ray Bursts (GRBs) once energetic axial jets escape from the star. Shocks in the jet accelerate electrons, and gamma radiation is synchrotron radiation produced by these accelerated electrons.

## Theory

The three equations of GRMHD are (e.g. De Villiers & Hawley 2003)

- The law of baryon conservation:

$$\nabla_\mu(\rho U^\mu) = 0$$

- The conservation of stress-energy

$$\nabla_\mu T^{\mu\nu} = 0$$

- Maxwell's equations

$$\nabla_\mu {}^*F^{\mu\nu} = 0$$

Where $\rho$ is the density, $U^\mu$ is the 4-velocity, $T^{\mu\nu}$ is the energy-momentum tensor for the fluid, and $F^{\mu\nu}$ is the electromagnetic field strength tensor.
The Kerr metric contributes a fixed background, which, in Boyer-Lindquist coordinates reads:

$$ds^2 = g_{tt}dt^2 + 2g_{t\phi}dtd\phi + g_{rr}dr^2 + g_{\theta\theta}d\theta^2 + g_{\phi\phi}d\phi^2$$

The GRMHD code evolves the above equations in this fixed background.

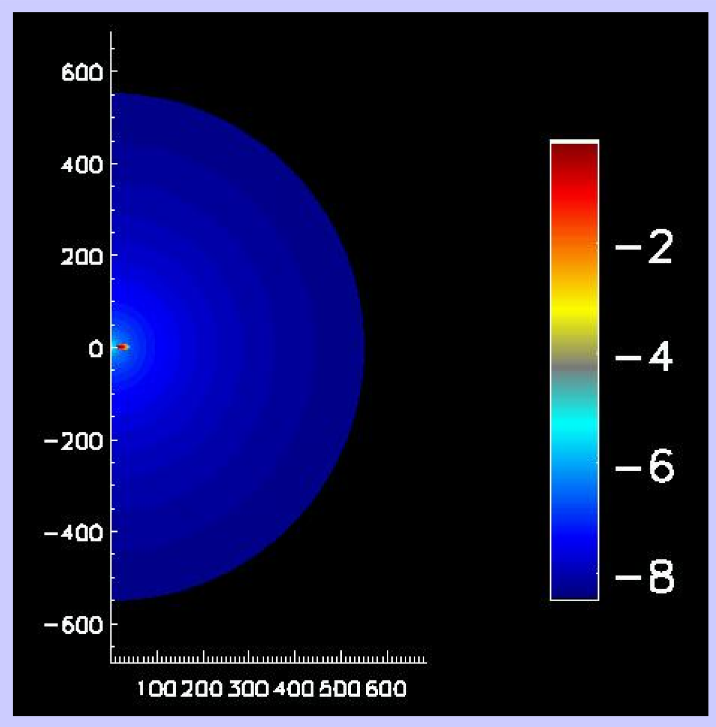

*Fig 1: The initial density in the 2-D simulations. The red "dot" is the initial torus. The scale is relative to the density maximum. The black hole is located at the origin. The distance scale is in units of black hole mass M.*

## Simulation details

- We performed six $512 \times 512$ zones 2-D simulations. The six simulations were with or without an external magnetic field, and with three different spin parameters for the black hole, a non-rotating ($a/M = 0$) black hole, a rapidly rotating black hole ($a/M = 0.9$), and an extreme rotating black hole ($a/M = 0.995$). The outer boundary was set at $r_{\rm max} = 700M$ ($3 \times 10^8$ cm with typical collapsar parameters). The inner boundary depends on the spin, is just outside the horizon.
- In addition we performed one full 3-D $192^3$ zones simulation of the rapidly rotating black hole model with an external magnetic field. The outer boundary was set at $r_{\rm max} = 120M$ ($5.3 \times 10^7$ cm).
- We use an ideal gas equation with $\Gamma = 4/3$.
- Outside the initial torus, we place a radially infalling dust with density six orders of magnitude less than the maximum in the disk.
- The initial torus has its inner edge at $9.1M$ for all three cases. The outer edge is at $31M$ for the non-rotating case, $36M$ for the rapid rotating black hole and at $38M$ for the extreme rotating black hole (see Fig. 1).
- Simulations were run until an accretion flow was established, at which point data collection began and continued for several orbits of the main disk.

## Results

### Jets

Jets, unbound outflows in the funnel region (between the centrifugal barrier and the rotational axis), arise self-consistently from the MRI-driven accretion flow. The jet has two components: a hot, fast, tenuous outflow in the funnel proper, and a slower, colder, massive jet along the funnel wall (see Fig. 2).
We find that high temperature knot-like regions in the jet can reach Lorentz factors of at least 50. These high Lorentz factors are only seen at large radial distances from the black hole (see Fig. 2); this is evidence of an extended acceleration zone where the jets are accelerated by the Lorentz force (De Villiers et al. 2005).

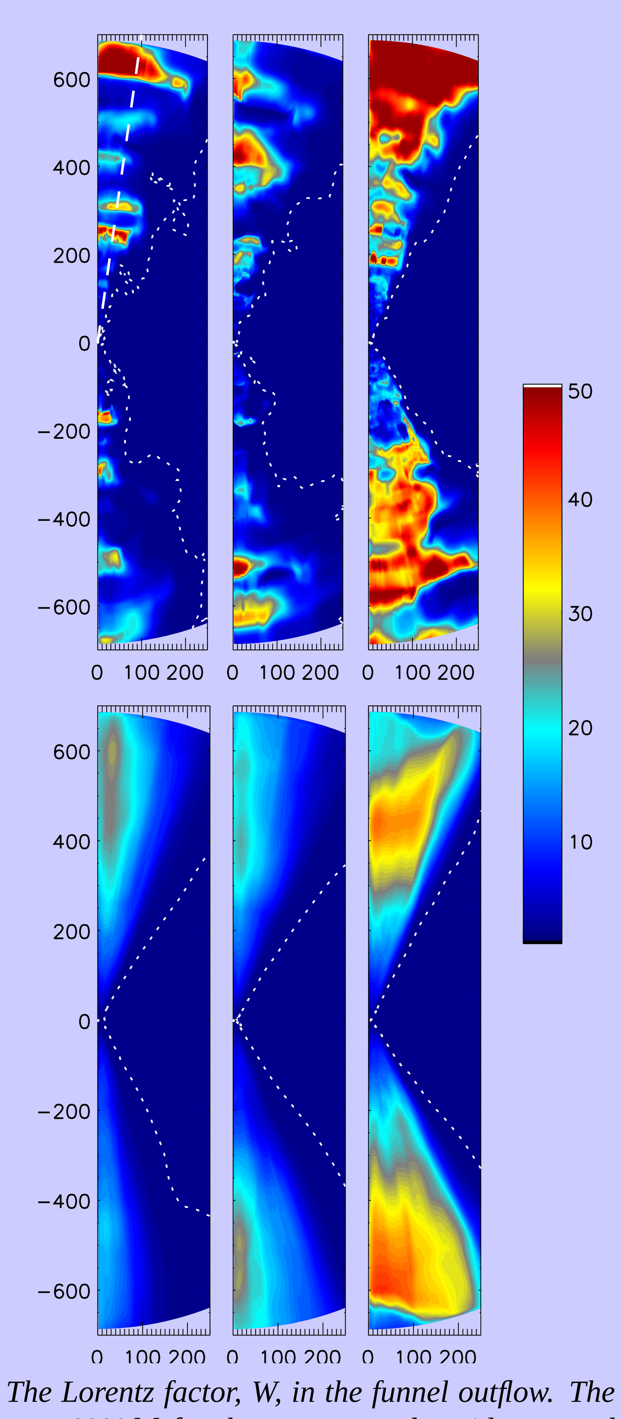

*Fig. 2: The Lorentz factor, W, in the funnel outflow. The top panel shows (left to right) snap shots at $t = 2000M$ for the extreme and rapid case and at $t = 3200M$ for the non-rotating case, all models are with the external vertical field. The bottom panel shows time averaged values for $1200M < t < 2000M$ for the extreme and rapid case, and for $2400M < t < 3200M$ for the non-rotating case, also with vertical field. These plots show evidence of an extended acceleration zone. High Lorentz factors are only seen at large radii ($r > 200M$). The dashed marks the boundary of the jets.*

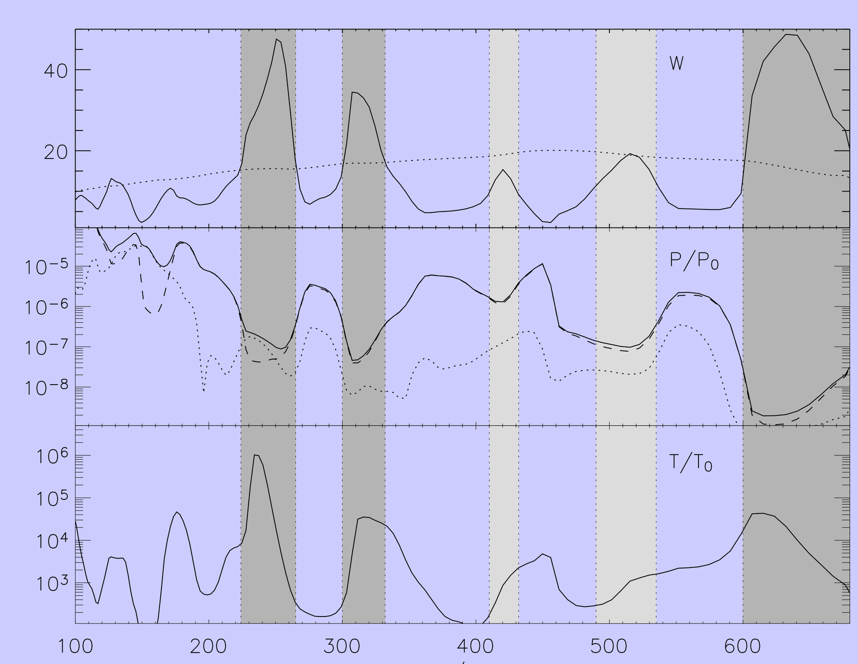


*Fig. 3: Radial cut through the upper funnel at $t = 2000M$ for the extreme rotation model. The top panel shows the Lorentz factor at $t = 2000M$ (solid line), and the time averaged (dotted line). Regions with Lorentz factor above 20 are shaded in dark grey. Regions with $10 < W < 20$ are shaded in light grey. The second panel shows total pressure (solid line), gas pressure (dashed line) and magnetic pressure (dotted line), scaled to the initial pressure maximum in the torus. The bottom panel shows temperature, scaled to the initial temperature in the torus. It can be seen that the high Lorentz factor regions exists in "pressure troughs", and also in high temperature regions.*

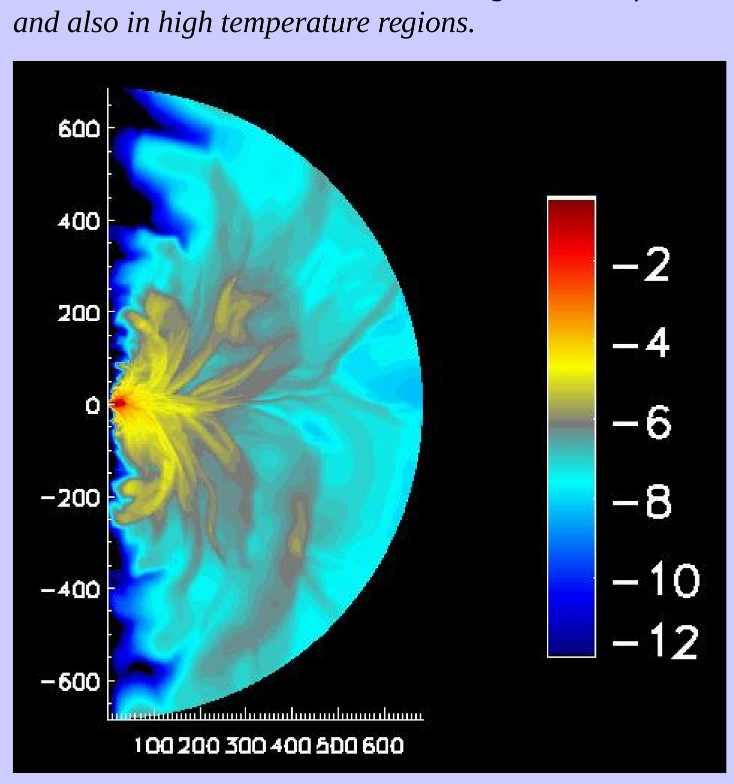

*Fig. 4: Snapshot of the density at $t = 1800M$ for the rapid rotating case. Notice the evacuated funnel along the rotation axis, and the complex structure in the corona, where a low-velocity unbound outflow is found. The density is scaled to the initial density maximum in the torus.*

### Coronal wind

An extensive unbound wind occupies the corona, the space between the main accretion disk and the funnel outflow (see Fig. 4). This wind is non-relativistic, but carries a good deal of energy and momentum (see Table 1), and should displace any remnant (outer) shell of the star.

### Lifetime of inner engine

The funnel outflow will generate the GRB once it escapes from the outer layers of the star. The lifetime of the GRB is determined by the mass depletion rate of the accretion disk. The mass depletion rate takes into account accretion onto the black hole and mass losses through the funnel and coronal outflows. The mass depletion rate suggests a duration of the eventual GRB between one-tenth and a few seconds. The shorter bursts are generated by rapidly spinning black holes, which generate strong jets (see table below).
Table 1 shows the jet lifetime, energy of the jet and energy of the wind in the models with an external vertical field. The models without the external field have similar values. S is the non-rotating (Schwarzschild) case, R the rapid rotating and E the extreme rotating case.

Table 1: Lifetime and energetics from simulation data

| | S | R | R3D | E |
|---|---|---|---|---|
| $t_{\rm eject}$(s) | 1.380 | 0.237 | 0.316 | 0.170 |
| $E_{\rm jet}(\times 10^{48}{\rm erg})$ | 0.782 | 3.804 | 6.961 | 3.162 |
| $E_{\rm wind}(\times 10^{48}{\rm erg})$ | 0.334 | 7.400 | 5.465 | 7.626 |

### Energetics

The energy and mass flux is highly variable with sharp brief peaks followed by quiescent periods on the order of milliseconds (see Fig. 5). The energies of the outflows can be estimated from the jet lifetime. For all simulations, the energies are found to be between $10^{48}$ to $10^{49}$ ergs (see table above). We find that jets launched in the rapidly spinning black hole models are energetic, whereas those launched in a non-rotating black hole model are considerably weaker. In all simulations the power of the jet is comparable to the power of the coronal wind, reinforcing the idea that the wind can displace any remnant (outer) shell of the star.

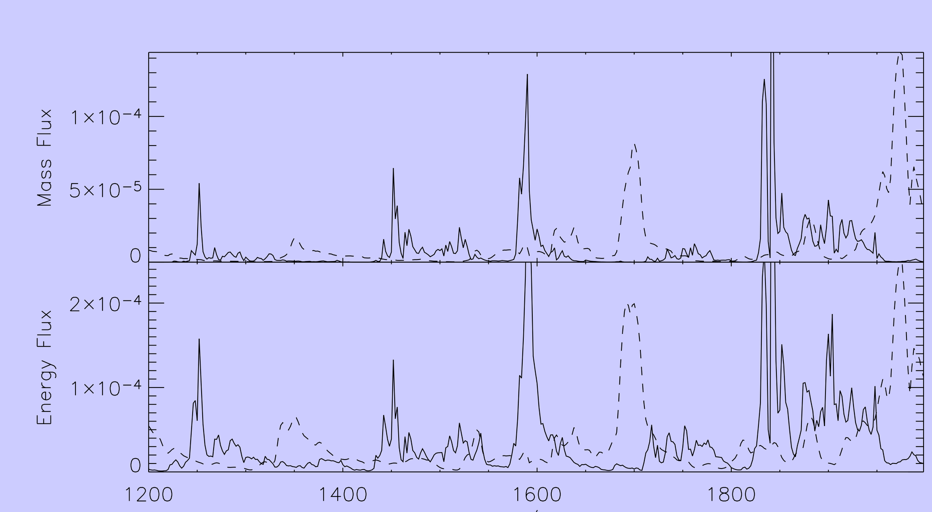


*Fig. 5: Shell-averaged mass and energy flux in the jet for $r = 15.0M$ (solid line) and $r = 100M$ (dashed line). Close to the black hole fluctuations occur at the order of $1M$ of time, and strong bursts followed by quiescent periods occur on the order of $100M$. At larger radii the rapid fluctuations have been smeared out, but bursts followed by quiescent periods persists.*

## Conclusions

- Our simulations of collapsars show that high Lorentz factors ($W \geq 50$) are found in knot-like regions in the funnel outflow.
- The jet is highly variable, with variations on the order of milliseconds.
- The lifetime of the jet is of the order of a few seconds, indicating that the collapsar model within our setup favors shorter GRBs.
- The energy in the jet is found to be of the order $10^{48}$ - $10^{49}$ergs.

See http://www.capca.ucalgary.ca for more information and animations made from the simulations.

## References

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