DYNAMICS OF RELATIVISTIC JET FORMATION: A CASE STUDY OF GRB 090510

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ABSTRACT

We employ General Relativistic Magnetohydrodynamic (GRMHD) simulations to investigate the properties of GRB 090510, a short gamma-ray burst detected by the Fermi observatory. This study aims to quantify key parameters such as the energetics, jet structure, variability, and opening angle of the burst to understand its underlying physical conditions. Additionally, we perform a suite of models to study short GRB jet dynamics in general. Our results align closely with observations, validating our simulation methodology. This alignment enhances our theoretical models, improving their fidelity in replicating observed phenomena.

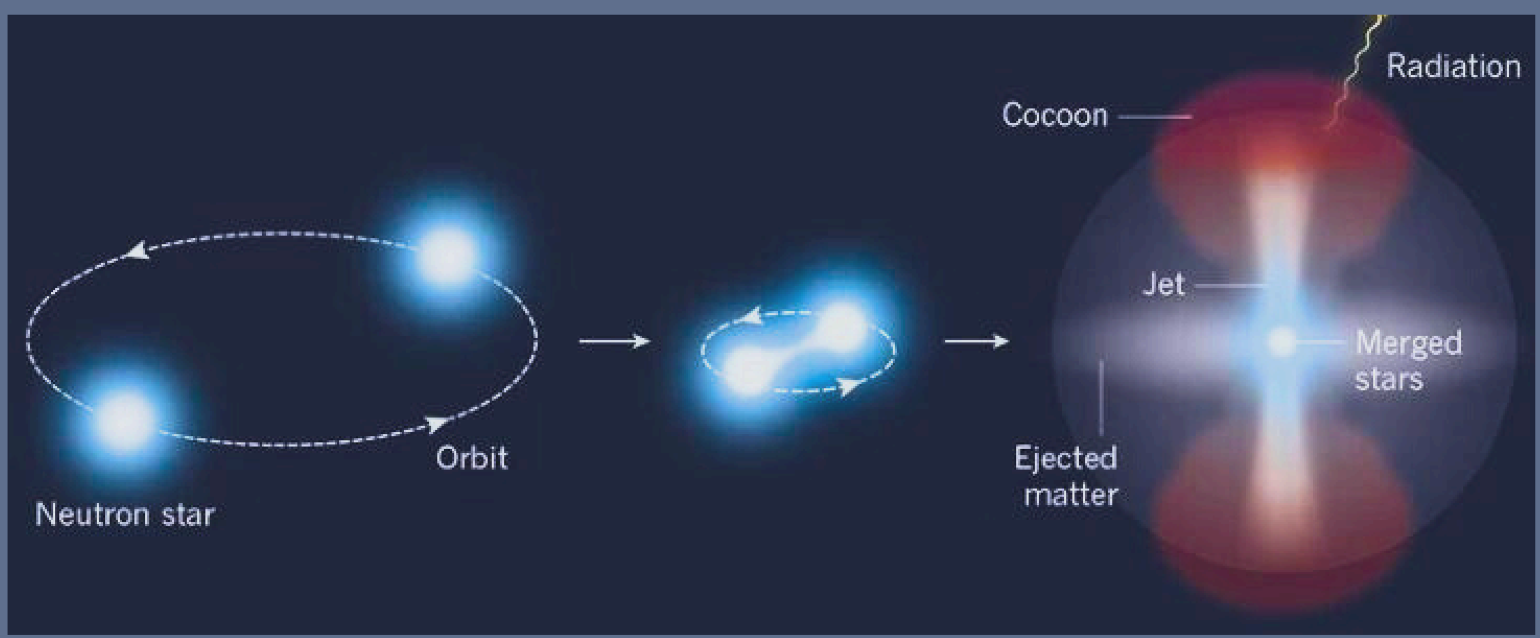
Gamma Ray Bursts (GRB)

- A brief introduction

- Short but intense flashes of high energy radiation detected in gamma rays
- Lasts from milliseconds to hundreds of seconds.
- Typical Radiation energy: $10^{49} - 10^{54}$ ergs

Progenitors;

- Short GRB: Originates from the merger of compact objects
- Long GRB: Progenitors are identified to be massive stars based on their association with a core-collapse supernova.



A schematic showing short GRB formation and resulting jet structure from two neutron star mergers (Image credit: Nature 554, 178-179 (2018))

Modeling GRBs using GRMHD Simulations

Using numerical simulations, we model relativistic jets from an accreting system around a Kerr-black hole.

Simulation Tool: GRMHD code HARM [1,2]

HARM --> Simulates fluid flow evolution by solving continuity, energy-momentum conservation, and induction equations in the GRMHD scheme.

Jet Mechanism: Jets are Poynting-dominated, magnetized plasma, launched via the Blandford-Znajek (BZ) [3] mechanism utilizing the rotational energy of the black hole.

We use two quantities μ and σ to quantify the jet produced via the BZ mechanism.

$$\mu = -\frac{T^r_t}{\rho u^r}$$

μ --> **Jet energetics parameter;** Ratio of total energy flux to mass flux, used in methodologies involving the calculation of jet opening angle, Lorentz factor, and minimum timescale variability [4].

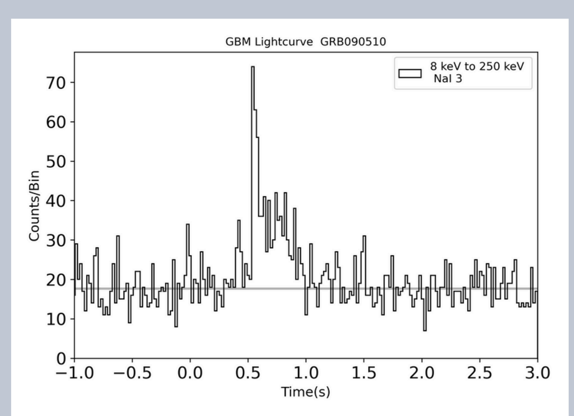
$$\sigma = \frac{(T_{\rm EM})^r_t}{(T_{\rm gas})^r_t}$$

σ --> **Jet magnetisation parameter**; The ratio of the electromagnetic energy flux to the gas energy flux.

[T^r_t is the radial component of the energy-momentum tensor, representing the energy flux in the radial direction, ρ is the rest-mass density, and u^r is the radial component of the four-velocity.]

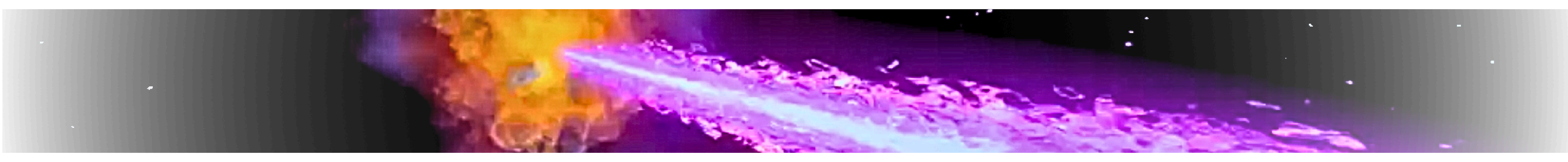
Combining Observations with simulations

- Exploring jet properties like opening angle, variability, Lorentz factor & Energetics is crucial for uncovering emission mechanisms
- However detailed multi-wavelength observational limitations pose significant challenges.
- Integrating simulations with observations enhances our ability to model GRB jets more accurately, improving predictions for both observed and unobserved bursts.
- In this work, We focus on a short GRB with multi-wavelength observation; GRB 090510; using GRMHD short GRB simulations to explain the observed properties of 090510.



Prompt emission lightcurve of GRB090510 (8-250 KeV)

GRB 090510 [5]
T90 - 0.6s; Redshift: 0.903
Total bolometric Luminosity: 4×10^{53} ergs/s
Total isotropic energy, Eiso : 10^{53} ergs
Opening angle from observation: 10.04^{o}



Simulation setup

2D & 3D simulations with multiple accretion disk and magnetic field properties.
Disk: Fishbone & Moncrief (FM) Solution [6]

Magnetic field - Poloidal wire field
(non-vanishing component of magnetic vector potential is given by $A_\phi(r,\theta)$; E and K are complete elliptic functions. The radius of the circular wire is taken to be the r_{max} of the FM torus

$$A_\phi(r,\theta) = A_0 \frac{(2-k^2)K(k^2) - 2E(k^2)}{k\sqrt{4Rr\sin\theta}} \quad ; \quad k = \sqrt{\frac{4Rr\sin\theta}{R^2 + r^2 + 2Rr\sin\theta}}$$

Goals --> Produce GRB with an opening angle ~10 degrees
--> Total jet energy: 1.5×10^{52} ergs (source frame, 10 % radiative efficiency)
--> Minimum variability timescales ~4.5 ms (wavelet analysis on lightcurves)
--> Stable jet for a duration of ~0.6s (T90 of GRB 090510)

Dynamic Ejecta:

- Origin: Ejecta stripped off from the neutron stars (NSs) during the merger; contributes to the jet collimation
- Density distribution: We adopt a density profile that includes both radial and angular distributions, inspired by the work of Gottlieb et al., 2022 [7],

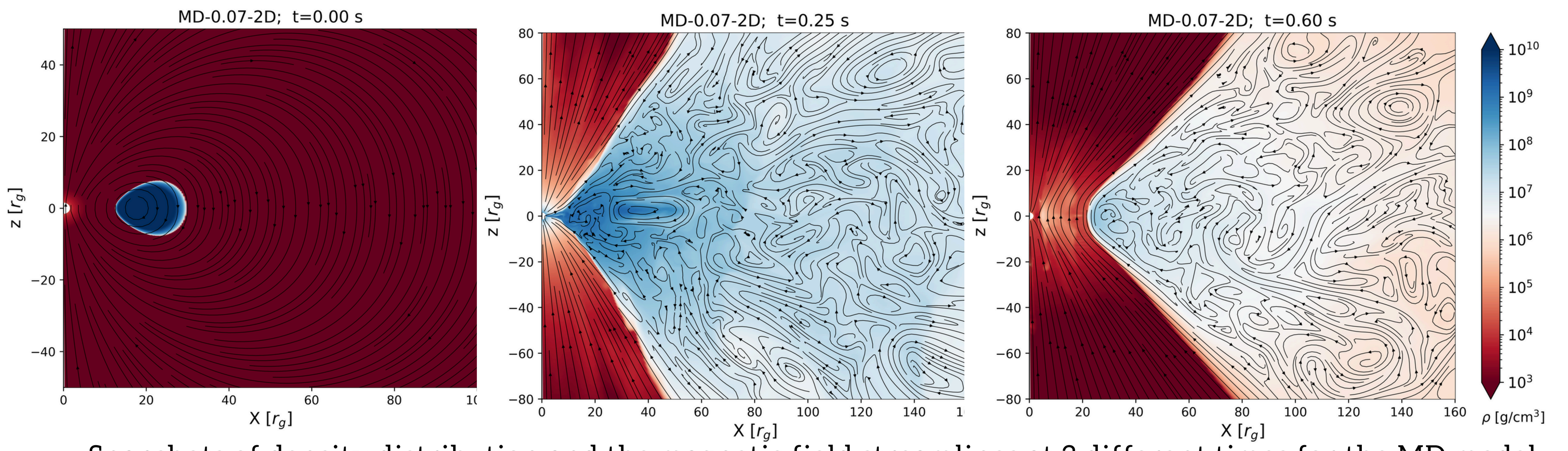
$$\rho(R_{\rm min} < r < R_{\rm max}, \theta) = \rho_0 r^{-\alpha}(0.1 + \sin^2\theta)^\delta$$

- Ejecta --> unmagnetized & Mass = *0.006 & 0.012 Msun*, expands homologously with v = *0.15c*

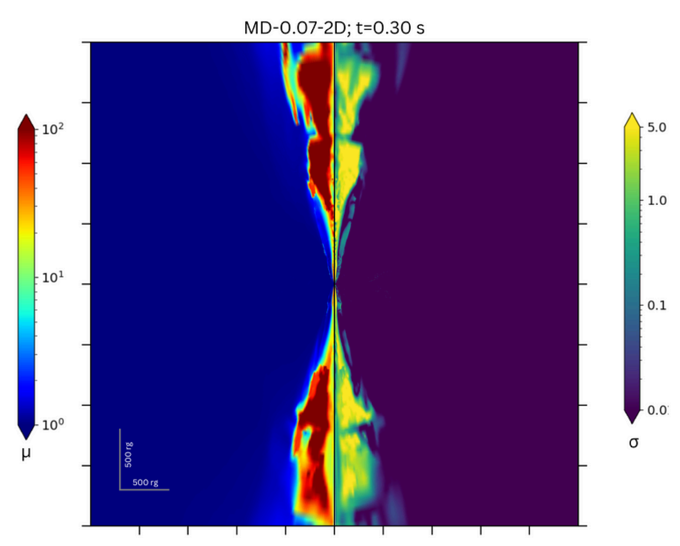
Results

Model	Disk Mass ($10^{-3} M_\odot$)	BH spin	β_{max}	E_{jet} (erg)	θ_{jet} (deg)	Resolution ($N_r \times N_\theta \times N_\phi$)	t_f (t_g)
HD-0.10-3D	105.67	0.95	200	1.10×10^{53}	18.1	256×128×64	45k
MD-0.07-2D	74.32	0.80	150	1.11×10^{52}	9.2	700×512×1	50k
DE2-0.07-2D	86.65	0.80	150	1.60×10^{52}	10.0	700×512×1	50k

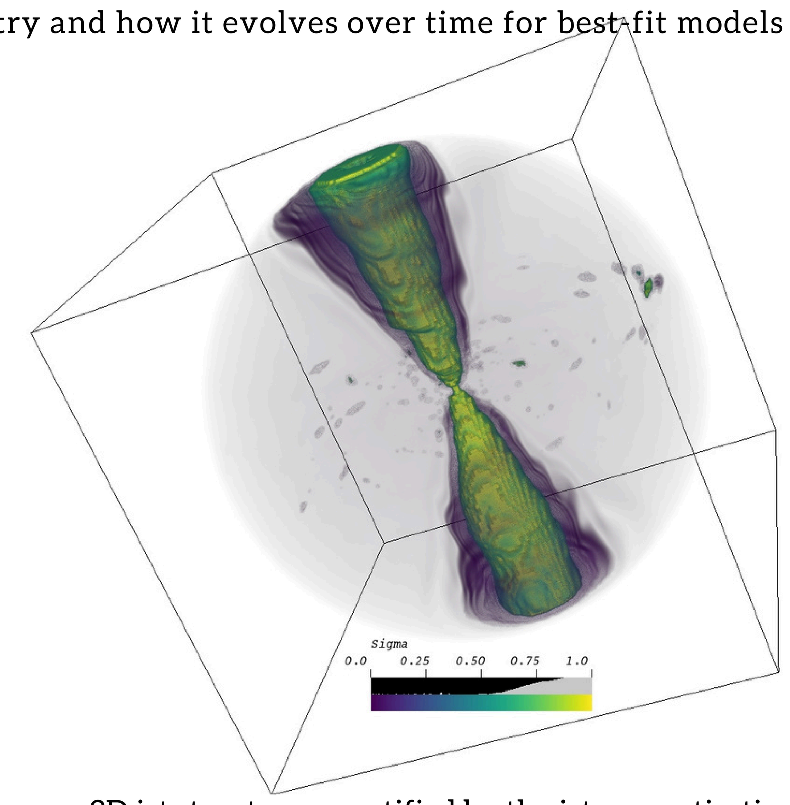
Table presents key parameters from selected models: accretion disk mass, plasma β (ratio of magnetic to gas pressure), black hole spin, Total Energy E_jet, jet opening angle, resolution and total duration of simulation runs in code units. MD & DE model represent the ones that match observations, DE is model with Dynamic ejecta. HD model is 3D



Snapshots of density distribution and the magnetic field streamlines at 3 different times for the MD model. Plot Show initial accretion disk and field geometry and how it evolves over time for best-fit models



Snapshots of jet energetics parameter (Left panel) & Jet Magnetisation (Right panel) for the MD model at 0.3 s. This plot shows jet structure for one of the best-fit models to explain 090510



3D jet structure quantified by the jet magnetisation parameter -sigma- for HD model at 0.3s. For 3D models, jets get narrower over time. Bounding box is 500 gravitational radii.

Conclusion

- Using GRMHD simulations, we effectively modelled jets with similar energetics, opening angles, and variability timescales to those observed in GRB 090510 within 1-sigma confidence levels.
- The main drive for the jet collimation in our jets is represented by disk winds, with additional contributions from BH spin & magnetic field strength.
- Introducing dynamic ejecta into our simulations, we have further studied the effect of pre-merger ejecta in jet structure & dynamics close to the jet base.
- Our comprehensive study has not only investigated targeted GRB properties but also examined a diverse array of short GRB jets through eleven models, including both 2D and 3D simulations. This dual focus enhances our understanding and sets a solid groundwork for future explorations into GRB jet dynamics

References

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