Relativistic Jet Simulations and Modeling on Horizon Scale

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Collaborators:

Cruz-Osorio, Fromm, YM et al. (2022), Nature Astronomy
Fromm, Cruz-Osorio, YM et al. (2022), A&A

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Relativistic Jets

- Outflow of highly collimated plasma
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity $\sim c$
  - Generic systems: Compact object (Neutron Star, Black Hole) + accretion flows
  - Jets are common in the universe

- Key Issues of Relativistic Jets
  - Acceleration & Collimation
  - Propagation & Stability
  - Origin of high energy particle (particle acceleration)
Motivation

- Black holes and relativistic jets are the perfect laboratories to study:
  - Plasma physics
  - Gravitational physics
  - Particle physics

- Observations with recent & future instruments (from radio to $\gamma$-ray + multi-messenger):
  - EAVN, VLBA, GMVA, EHT, ngVLA, ngEHT
  - HST, SWIFT
  - Chandra, NuSTAR, IXPE, Athena, eXTP
  - Fermi
  - HESS, MAGIC, VERITAS, LHAASO, CTA
  - Ice Cube, …

$\Rightarrow$ need tools & methods to interpret the observations & test theoretical models
M87 multi-frequency observations

How good are the models at different frequencies?

non-thermal synchrotron (VLBA spectral index map)

thermal synchrotron (EHT 2019, paper V)

Image Credit: The EHT Multipurpose Working Group, the EHT Collaboration, ALMA/ESO/NASA/NAOJ, the EVN, the Erudit Corporation, VLBA/NAOJ, the GMVA, the Hubble Space Telescope, the NASA Galaxy Swift Observatory, the Chandra X-ray Observatory, the NuSTAR Collaboration, the Fermi-LAT Collaboration, the H.E.S.S Collaboration, the MAGIC Collaboration, the VERITAS Collaboration, NASA and ESO, Composition by J. C. Adams
M87 multi-frequency observations

Compare with 86GHz Global Millimetre VLBI observations and board band SED

**VLBI @ 86GHz (jet structure)**

- wide opening angle
- edge brightening

**broad band spectrum**

- flat spectrum ($\nu < 10^{12}$ Hz)
- power-law decay spectrum ($\nu > 10^{12}$ Hz)

GMVA: Kim et al. 2018
Numerical modeling

GRMHD (BHAC):
- spacetime
- Disk evolution
- Magnetic field
- Jet launching & propagation

Observations:
- Data comparison
- Model prediction

GRRT (BHOSS):
- Mass & distance
- microphysics
- Emission model
  post-process

Theoretical prediction (GENA):
- Synthetic data (VLBI observation)
- Image generation

BHAC: Porth et al. (17), Olivares et al. (19)
BHOSS: Younsi et al. (21)
GENA: Fromm et al. (19)
MAD vs SANE (GRMHD Simulations)

RIAF model, two extreme situation
Magnetically Arrested Disk (MAD)
Standard And Normal Evolution (SANE)

3D GRMHD simulations with $a=0.94$

Kerr BH $a=0.9375$

- density
- plasma beta
- magnetisation

side view

SANE     MAD

top view
MAD vs SANE

RIAF model, two extreme situation
Magnetically Arrested Disk (MAD)
Standard And Normal Evolution (SANE)

3D GRMHD simulations with a=0.94

- Magnetization
- Plasma beta
- Temperature
- Lorentz factor

- Time & azimuthal averaged distribution

- Mass accretion rate
- Magnetic flux rate

Kerr BH a=0.9375
GRRT calculation

• Compute the emission structure: BHOSS (Younsi et al. 2021)
• Scale to source: black hole mass, distance, accretion rate, electron distribution function (eDF) & emission process

1) get eDF + emission

\[ \frac{dN}{d\gamma} \propto \frac{1}{\Theta_e} \exp\left(-\gamma/\Theta_e\right) \]

⇒ thermal synchrotron
⇒ electron temp., \( \Theta_e \) unknown

2) connect to GRMHD

\[ \frac{T_i}{T_e} = R_{\text{high}} \frac{\beta_p^2}{1 + \beta_p^2} + \frac{1}{1 + \beta_p^2} \]

Moscibrodzka et al. (16)

3) get geodesics + radiation transfer

\[ a_* = 0.9374 \]

⇒ emission+absorp. coeffs.
GRRT Jet Modeling for M87

Parameter space:

**GRMHD:**
- Accretion model: SANE & MAD
- Spin: a=-0.94, -0.5, 0, 0.5, 0.94

**GRRT:**
- eDF: thermal & non-thermal (kappa)
- $R_{\text{low}}$: 1
- $R_{\text{high}}$: 1, 10, 20, 40, 80, 160
- $\sigma_{\text{cut}}$: 1, 3, 5, 10

**Setup & Analysis:**
- M87 mass & distance: $M_{\text{BH}}=6.5 \pm 0.7 \times 10^9 M_\odot \ & 16.8 \text{ Kpc}$
- Inclination angle of 160 deg
- Iterate mass accretion rate to obtain 1.0 Jy at 230 GHz
- Use 200 GRMHD snapshots across 2000 M interval (~ 2 years of observation)
- Compare average spectrum to observed one
- Compute jet width (and opening angle) and compare with data
kappa distribution function

\[
\frac{dn_e}{d\gamma} = N\gamma\sqrt{\gamma^2 - 1} \left(1 + \frac{\gamma - 1}{\kappa w}\right)^{-(\kappa+1)}
\]

kappa eDF = thermal core + non-thermal tail

- thermal core at low values of the Lorentz factor, asymptotically turns into a power-law
- power-law index, \( p = \kappa - 1 \)
- In the limit of \( \kappa \rightarrow \infty \), the \( \kappa \)-distribution becomes the Maxwell–Jüttner DF
- \( \kappa (\beta, \sigma) \) ← subgrid model from PIC simulation

Energy content

\[
w = \frac{\kappa - 3}{\kappa} \Theta_e + \tilde{\varepsilon} \frac{\kappa - 3}{6\kappa} m_p \sigma.
\]

electron temp., \( \Theta_e \): R-beta parameterised prescription

\[
\frac{T_i}{T_e} = R_{\text{high}} \frac{\beta_p^2}{1 + \beta_p^2} + \frac{1}{1 + \beta_p^2}
\]

→ connect to GRMHD
GRRT Jet Modeling of M87

thermal vs kappa eDF

• Thermal eDF can not reproduce broad band SED
• Kappa eDF produces more extended jet emission

Fromm et al. (2022)
GRRT Jet

Modeling of M87

MAD vs SANE

• Both MAD & SANE models can reproduce broadband SED of M87 (using kappa-eDF)

• MAD can make wide jet morphology but SANE can not make wide jet structure

• Lower BH spin case can not make bright extended jet

Fromm et al. (22)
Best Fitting Model

- 3D GRMHD simulations of MAD accretion flows + GRRT calculations (thermal + non-thermal eDF)
- MAD (a=0.94) fits SED & jet morphology at 86GHz
- Still not good to reproduce edge-brightening

Cruz-Osorio et al. (22)
Magnetic Reconnection in Jets

- Looking for magnetic reconnection site (opposite field topology) in helically twisted jets by CD kink instability
- Calculate reconnection rate, $<v_{\text{rec}}> \sim 0.05$
- In agreement with relativistic turbulent reconnection simulation (Takamoto+ 15)

![Magnetic reconnection rate](image1)

Kadowaki et al. (21)
Particle Acceleration in Jets via CD Kink Instability

- Local magnetic reconnection in jets will heat the plasma and accelerates particles.
- Particle is accelerated via stochastic Fermi-like acceleration in turbulent fields developed by CD kink instability in relativistic jets
- Spectrum becomes flatter tail

Medina-Torrejon et al. (21)
Particle Acceleration at Jet Shear Region

- Simulation: 3DRMHD Jet propagation with magnetic field
- Excite KH Instability at jet shear region with external medium \( \Rightarrow \) make turbulence at jet spine and sheath
- Jet shear region is potential particle acceleration site

![Image of jet shear region with magnetic field](image1)

**Spectrum of turbulent (velocity & B-field)**

![Image of Kolmogolov spectrum](image2)

Wang et al. (22)
∑ Improved numerical modeling of relativistic jets
∑ Direct fitting of observational data with GRMHD/GRRT models
∑ Reproducing broadband spectrum emission & jet morphology (jet width, edge-brightening) of M87 jet
∑ Constrained model parameters (high BH spin is favored)

- Explore more electron temperature models (using two-temperature GRMHD model: YM et al. 21)
- Need more micro-physics such as cooling process (GRMHD + radiative cooling: Dihinghia et al. 22)
- Extend the GRMHD simulations to a larger distance (e.g., 43GHz)
- Compute high-energy emissions (X-ray & gamma-ray)
- Connection to polarimetry