GRMHD Positron Applications from the Present and Primordial Universe

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“Observing” JAB Systems

1. Start with general relativistic magnetohydrodynamic (GRMHD) simulation or semi-analytic model of jet (or outflow)/accretion flow/black hole (JAB) system
2. Convert GRMHD variables to radiation prescriptions for emission, absorption, polarization, particle acceleration and/or dissipation to emulate sources
3. Add “observer” viewing sources, e.g., Event Horizon Telescope (EHT) targets:
   I. Sgr A*  
   II. M87  
   III. 3C 279
Application I. Positron Modeling of M87*
Zooming towards M87’s Jet and Central Black Hole
Courtesy of European Southern Observatory (ESO)
Radiative Transfer

- Radiative transfer links source properties such as emissivity $j_\nu$ to observed radiation:

$$\frac{dl_\nu}{ds} = j_\nu \Rightarrow I_\nu = \int_0^s j_\nu ds'$$

- Polarized radiative transfer equations w./absorption and Faraday effects (Dexter 2016):

$$\frac{d}{ds} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} j_\nu \\ j_Q \\ j_U \\ j_V \end{bmatrix} - \begin{bmatrix} \chi_t & \chi_q & \chi_u & \chi_v \\ \chi_q & \chi_t & \rho_v & \rho_u \\ \chi_u & -\rho_v & \chi_t & \rho_q \\ \chi_v & -\rho_u & -\rho_q & \chi_t \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

For synchrotron radiation:

$$j_\nu \sim P_e F(\vec{B}, \nu), \quad P_e \sim \int \gamma N(\gamma) d\gamma$$

- Emitting particle distribution functions $N(\gamma)$:
  - Thermal
    $$N(\gamma) \sim \exp(-\gamma/\theta_e)$$
  - Power law
    $$N(\gamma) \sim \gamma^{-p}$$
Polarized M87 Observations

- M87 polarization has been observed by ALMA, VLBA and EHT
EHT M87 Simulation Library

- Turbulent heating physics (Howes 2010): Relativistic electrons preferentially heated at low $\beta = \frac{P_g}{P_B}$; protons and other ions at high $\beta$, relativistically cold plasma
- R-Beta Model (EHTC Papers I-VIII)

$$ R = \frac{T_i}{T_e} = \frac{1}{1 + \beta^2} R_{\text{low}} + \frac{\beta^2}{1 + \beta^2} R_{\text{high}} $$

- Using the R-Beta Model (w./$R_{\text{low}} = 1$) and SANE and MAD simulations (w./ $\frac{a}{M} = -0.94, 0, 0.94$):
  - Increasing spin magnitude increases asymmetry
  - MAD has mostly spiral EVPA/vertical implied B-field
  - SANE has mostly radial EVPA/toroidal implied B-field

EHTC Paper VIII
Emission Prescriptions with Magnetic Energy Conversion

- Constant Electron Beta ($\beta_e$) Model – Magnetic-to-Particle Energy Conversion:

$$\beta_e = \frac{p_e}{P_B} = \frac{(\gamma_e - 1)u_e}{B^2/2} \Rightarrow u_e = \rho T_e = \frac{1}{(\gamma_e - 1)} \beta_e \frac{B^2}{2}$$

- Magnetic Bias Model

$$p_e = K_n \left( \frac{b}{\sqrt{2}} \right)^{2n}, \quad K_n = K_1 \frac{\left\langle \frac{b^2}{2} \right\rangle}{\left\langle \frac{b}{\sqrt{2}} \right\rangle^{2n}}, K_1 = 1$$
M87 Simulation Assumptions and Fluid Equations

- Start with a HARM GRMHD simulation assuming:
  - Geometrically thick disk
  - Magnetically arrested disk
  - Jet power derived from flux threading black hole of mass $M$ and spin $a/M=0.92$
- Mass conservation
- Energy-momentum conservation

\[ \nabla_{\mu} (\rho u^{\mu}) = 0 \]

\[ \nabla_{\mu} T^{\mu\nu} = 0 \]

\[ T^{\mu}_{\nu} = (\rho + u_g + P_g + b^2)u^{\mu}u_{\nu} + (P_g+b^2/2)\delta^{\mu}_{\nu} - b^{\mu}b_{\nu} \]

- Assume power law coefficients for radiative transfer in jet models
Connecting with Observations: M87 43 GHz Radio Map Time Series vs. Current Density Model

- Current density \( (j) \) model based on having particles accelerated at current layers

\[
j_v \propto \tilde{P}_e \propto j^2
\]

\((\theta_{\text{Obs}}, \Phi_{\text{Obs}}) = (20^\circ, 0^\circ), T_{\text{Obs}} = 2000M, 2056M, \ldots, 2560M\)

Emissivity: Current Density Model
Disk subtraction: \(|z| > 35M\)

\(L_{J_{\text{Sq}}} = 1e4 \text{ M}\)

M87 43GHz (7mm) VLA maps
21-Day frame rate, Epochs A,B,D-L

Amati, Blandford and Chekhovskoy [2018] Galaxies, 6, 31

VLA 3C274 EpochA 43GHz

(Courtesy of Craig Walker [NAO], Chun Ly, UCAT), Bill junior Las Acornas, and Phil Hardee (U. Alabama)
Stationary Axisymmetric Self-Similar Semi-Analytic Jet Model

- Assume stationary (d/dt=0), axisymmetric (d/d\phi =0) parabolic jet with self-similarity parameter \( \xi = s^2/z \)
- Use force-free jet region of a HARM simulation
- Relate GRMHD variables to fieldline angular speed \( \Omega_B(\xi) \) and flux \( \Phi_B(\xi) \) connected to horizon

\[
I = -2\Omega_B \xi \Phi' \\
\begin{pmatrix} B_1 \\ B_2 \\ \Omega_B \end{pmatrix} = \begin{pmatrix} -\frac{1}{2\pi s} & 0 & \frac{1}{2\pi s} \\ \frac{1}{2\pi s} & 0 & \frac{1}{2\pi s} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} v_2 \\ v_3 \\ \Omega_B \end{pmatrix} = \begin{pmatrix} v_2^0 \frac{1}{2} & \frac{1}{2} & 0 \\ s\Omega_B (1-v_2) & 0 & 0 \end{pmatrix} \\
\vec{E} = \vec{B} \times (\hat{\Omega}_B \times \vec{r})
\]

and at z=50M, derive fitting forms for flux threading the horizon

\( \Phi_B(\xi) = \tanh[-0.3\xi] \)

and fieldline angular speed

\( \Omega_B(\xi) = 0.15 \exp[-0.3\xi^2] \)
Semi-Analytic Jet Model

- Assume stationary (d/dt=0), axisymmetric (d/d\(\phi\) =0) parabolic jet with self-similarity based on force-free region of HARM jet simulation.
- Use self-similarity to obtain GRMHD flow on different scales.

\[ \rho E + j \times B = 0 \]

**B\text{Poloidal}** (arrows) & **B\text{Toroidal}** (colors) at various jet segments.
Positrons can be created in AGN jet/accretion flow/black hole (JAB) systems via:

- Photon-photon interactions: $\gamma \gamma \rightarrow e^- e^+$ (Breit-Wheeler Pair Production):
  - Electrons in Compton clouds of disk photons may scatter soft photons to MeV energies, which photons undergo photon-photon interactions resulting in $e^- e^+$ pairs (Laurent & Titarchuk 2018) in jet funnel walls
  - Funnel wall positron number densities predicted for Sgr A* ($n_\pm = 10^{-8} \text{ cm}^{-3}$) and M87 ($n_\pm = 10 \text{ cm}^{-3}$) walls (Moscibrodzka et al. 2011)

- Spark gap processes
  - Jets in AGN generically host a spark gap in which plasma moves away from the black hole beyond the outer light cylinder but must fall toward the central black hole within a stagnation surface at smaller radii from the hole (Levinson & Segev 2017)

Positron effects can be included by in GRMHD postprocessors by generalizing:

- Particle number density $n = n_i + n_{e+} + n_{e-}$ (Anantua et al. 2020a) and:
In the $\beta_0 = 10^{-8}$ Constant Electron Beta model ($j_\nu \propto P_e P_B^{1+\alpha} \nu^{-\alpha} \propto \beta_0 P_B^{2+\alpha} \nu^{-\alpha}$) with positrons, at 86 GHz, as ion content increases from 0% to 100% of positive charge carriers (or $n_{e+}/n$ goes from 0.5->0), the intensity map

- Becomes inwardly core shifted
- Remains bilaterally asymmetric

Our fiducial $\gamma_{\text{min}} = 10$ and $\gamma_{\text{max}} = \infty$
Degree of Circular Polarization

For the parameter space $86\text{GHz} \leq \nu \leq 230\text{GHz}$, $0 \leq n_{e^+/n} \leq 0.5$, $10^{-10} \leq \beta_{e0} \leq 10^{-6}$, circular polarization degree V/I

- Tends to increase for ionic plasma at lower frequencies and higher $\beta_{e0}$
- Ranges from 0 to $O(10^{-3})$
- Is maximized near the black hole and along the jet axis, as seen for $\beta_{e0} = 10^{-8}$, except for the most leptonic plasma
- Symmetric $e^-e^+$ plasma virtually destroys V/I, despite minor Faraday conversion

$\beta_{e0} = 10^{-6}$
Near-Horizon Jet Model Stokes Maps: M87

Constant Electron Beta Model \( \left( j_\nu \propto P_e \frac{B}{P_B}^{1+\alpha} \right) \), \( \nu = 230 \text{ GHz} \)

\( (P_e)_{\text{Beta}} = \beta_{e0} P_B \),
\( \beta_{e0} = 10^{-4}, 10^{-2}, \ldots \)

\( 0 \leq f_{\text{Pos}} = \frac{n_{e+}}{n_{e-}} \leq 1 \)

\( \beta_{e0} = 10^{-2}, f_{\text{Pos}} = 0 \)

\( \beta_{e0} = 10^{-3}, f_{\text{Pos}} = 1 \)

Emami, Anantua, Chael & Loeb 2021
ArXiv: 2101.05327
Near-Horizon Jet Model Polarized Spectra: M87

- Constant Electron Beta Model polarized spectral decomposition
  - I insensitive to $f_{\text{pos}}$
  - P sensitive to $f_{\text{pos}}$ at low $\nu$
  - V sensitive to $f_{\text{pos}}$ since $j_V, \rho_V \propto (1 - f_{\text{Pos}}), \rho_Q, U \propto (1 + f_{\text{Pos}})$
Using a HARM GRMHD simulation and adding e+/e- pairs so $n = n_p + (n_{e^-})_0 + n_{\text{pairs}}$ in ray tracing at 230 GHz results in

Magnetically Arrested Disk (MAD) simulations with decreasing V/I with increasing $n_{e^+} = \frac{n_{\text{pairs}}}{2}$ due to positrons cancelling intrinsic circular polarization.

MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation.

MAD $R_{\text{high}} = 20$, $a/M = -0.5$

SANE $R_{\text{high}} = 20$, $a/M = -0.5$
Positron Effects on “Observing” GRMHD Simulations: Critical Beta Model

- Using a HARM GRMHD simulation and adding e+/e- pairs so
- Magnetically Arrested Disk (MAD) simulations with decreasing V/I with increasing $n_{e+} = \frac{n_{pairs}}{2}$ due to positrons cancelling intrinsic circular polarization
- MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation

$$MAD \ f = 0.5, \ \beta_{\text{crit}} = 1, \ a/M = 0.5$$

**MAD Observationally Preferred!**

| $m_{\text{obs}}$ (f$_{\text{min}}$,f$_{\text{max}}$) | $<|m|>$ | R-Beta | SANE R-Beta Jet | (a = -0.5) Crit. Beta | R-Beta Jet | (a = -0.5) Crit. Beta | MAD R-Beta Jet | (a = -0.5) Crit. Beta | R-Beta Jet | (a = -0.5) Crit. Beta |
|-----------------------------------------------|---------|---------|------------------|----------------------|---------|----------------------|-----------------|----------------------|---------|----------------------|
| $m_{\text{obs}}$ (f$_{\text{min}}$,f$_{\text{max}}$) | $<|m|>$ | R-Beta | SANE R-Beta Jet | (a = -0.5) Crit. Beta | R-Beta Jet | (a = -0.5) Crit. Beta | MAD R-Beta Jet | (a = -0.5) Crit. Beta | R-Beta Jet | (a = -0.5) Crit. Beta |
| $m_{\text{obs}}$ (f$_{\text{min}}$,f$_{\text{max}}$) | $<|m|>$ | R-Beta | SANE R-Beta Jet | (a = -0.5) Crit. Beta | R-Beta Jet | (a = -0.5) Crit. Beta | MAD R-Beta Jet | (a = -0.5) Crit. Beta | R-Beta Jet | (a = -0.5) Crit. Beta |

**Table 3.** Linear polarization $|m_{\text{obs}}|$ and $<|m|>$ for fiducial models at $T = 25,000 M$. The observational constraints from EHT M87 Paper VII take the form of the polarization ranges $0.01 < |m_{\text{obs}}| < 0.037 \text{ and } 0.057 < |m| > 0.107$. Note that the bold values refer to fiducial models which satisfy the net linear polarization constraints.
Positron Effects on “Observing” GRMHD Simulations: Hybrid Models

- Using a HARM GRMHD simulation and adding e+/e- pairs so in ray tracing at 230 GHz

- Hybrid models can be constructed with different emission in the high $\sigma$ (electromagnetic-to-particle flux density ratio) jet funnel by setting $P_e = \beta_e P_B$ between a disk-jet transition sigma and a sigma cut above which the simulation becomes numerically unstable.

$$n = n_p + (n_e^0) + n_{\text{pairs}}$$

$SANE R_{\text{high}} = 20$, $a/M = -0.5$

$\beta_e = 10^{-2}$ for $\sigma_{\text{trans}} < \sigma < \sigma_{\text{cut}}$
Application II.

Positronium Accretion of Primordial Black Holes
The Primordial Universe: First 14 Seconds

  - For \( t_{\text{Uni}} \gtrsim 10^{-2} \text{s} \), \( T_{\text{Uni}} \lesssim 10^{11} K \), energetic photons regularly created particle-antiparticle pairs.
  - For \( 10^{-2} \text{s} \lesssim t_{\text{Uni}} \lesssim 14 \text{s} \) there were around \( 10^9 \) electron-positron pairs for every proton.

  - Primordial black hole (PBH) accretion of positronium plasma under magnetorotational instability (MRI) can result in:
    - A PBH population with masses \( 10^{15} \text{g} \lesssim M \lesssim 10^{17} \text{g} \) contributing to dark matter.
    - Hawking radiation PBH supplying the present gamma ray background.

- Curd, Fowler and Anantua (in prep)
  - General Relativistic Magnetohydrodynamic (GRMHD) simulations with PBH accretion of positronium.
Under Bondi (spherical) accretion around 1s after the Big Bang, primordial black holes grow rapidly accreting the ambient medium around the horizon.

Under Bondi accretion,

\[
\frac{M}{t} \approx \frac{dM}{dt} \approx 4\pi R_g^2 v \rho_{Amb}, \quad v \approx c \text{ near horizon}
\]

Using ambient density

The black hole mass after 1s is

\[
M_{PBH, Bondi} \approx 4 \cdot 10^{39} \text{g}
\]
PBH Accretion Under MRI

- Magnetorotational instability -

- Our model including MRI in the primordial plasma slowly accretes from a long range $R_0$:

\[
\frac{dM}{dt} \approx \frac{M}{t} \approx 4\pi R_0^2 \rho_{\text{Amb}} C^* v_k, \quad v_k = \sqrt{\frac{GM}{R_0}}
\]

\[
R_0 = \frac{0.02 \left( \frac{\text{cm}^3}{\text{g}} \right)^{1/3}}{\left( \frac{\xi}{R} \right)^{4/3}} M(t)^{1/3} t^{2/3} \propto M(t)^{1/3} t^{2/3}, \quad \text{Accretion Radius – Time Relation}
\]

\[
\frac{M}{t} \approx 4\pi \frac{10^5}{t^2} \frac{s^2}{\text{cm}^3} \frac{g}{\text{cm}^3} \sqrt{G} C^* \left( \frac{0.02 \left( \frac{\text{cm}^3}{\text{g}} \right)^{1/3}}{\left( \frac{\xi}{R} \right)^{4/3}} \right)^{3/2} \frac{M}{t}
\]

Leading to identity (in our model, $t$ determines $R_0$)

\[
\left( \frac{\xi}{R} \right)_{\text{MRI}} \approx 0.01
\]
In KORAL simulations in Curd et al. (in prep), the inflow velocity and magnetic field under magnetorotational instability yield percent-level PBH contributions to current dark matter density.
Conclusions

- Observing Jet/Accretion Flow/Black Hole (JAB) Systems is a methodology that links intuitive e-/e+ emission models of phenomenological processes such as turbulent heating and conversion of magnetic to particle energy with discrete near-horizon AGN observations.

- M87
  - Using polarized emission modeling between 43 GHz and 230 GHz
  - Observations favor Blandford-Znajek jet sourced by dynamically strong, spiral magnetic fields on the ring surrounding the black hole.
  - GRMHD simulations accentuate MAD/SANE dichotomy by positron effects, e.g., rotating EVPA, altered V/I.

- The accretion of positronium under magnetorotational instability may result in $10^{15} \text{g} \lesssim M \lesssim 10^{17} \text{g}$ primordial black holes associated with percent-level present dark matter contributions and a gamma ray background.