High-Energy Gamma-Ray Emission from Isolated Stellar-Mass Black Hole Magnetospheres

(Kin et al. submitted)

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Formation of BH Magnetospheres

<Plasma injection>
Theory:
primary source
= annihilations of disk MeV photons
\( \gamma + \gamma \rightarrow e^+ + e^- \)

<Flux transportation>
Theory:
gas bring magnetic flux
\( \rightarrow \) magnetized gas disk around BHs
(Magnetically Arrested Disks, MADs)

EHT's M87 observations:
highly-magnetized, poloidal B
(consistent w/ MAD GRMHD simus)
Current Structure • Charge Distribution in BH Magnetosphere

- **sufficient plasma** → steady EM structure, $E \cdot B = 0$ (e.g. Blandford & Znajek 77)

- Extraction of BH rotation energy
- $v \sim c$ plasma flow
- Maintain poloidal current
  (Blandford-Znajek process)

- **far zone**: $(-)$ outflow (connected to the jet)

- **near horizon**: $(+)$ inflow
  (due to gravity, rapid rotation)

- Charge & flow separation at $r_{null} \sim 2r_g$
Formation of Spark Gap in Charge-Starved Magnetosphere

charge-starved → time-dependent E-field

charge-starved due to low MeV photon injection

(Levinson & Rieger 11; Levinson & Segev 17; Hirotani & Pu 16 etc...)

→ local charge deficiency in magnetosphere

\[ n < n_{GJ} = \left| \rho_{GJ} \right|/e \]

→ displacement current develops

\[ \partial_t(E_p) \approx -4\pi(j^r - J_0/r^2) \]

local intermittent E-field region (spark gap)
Formation of Spark Gap in Charge-Starved Magnetosphere

© charge-starved $\rightarrow$ time-dependent E-field

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local intermittent E-field region (spark gap)

efficient acceleration, gamma-ray emission secondary pair creation
Motivation: Detecting Isolated stellar-mass Black Holes via Gamma-Rays?

◎ $10^{7-8}$ undetected IBHs in our Galaxy

\[ SFR \times V_{gal} \times t_{galaxy} \]

$\sim 10^{-14} \text{pc}^{-3}\text{yr}^{-1} \sim 10^{11} \text{pc}^3 \sim 10\text{Gyr}$

for $10M_\odot$

→ possible interactions w/ Galactic gas clouds

→ MAD around IBHs even for weakly-magnetized gas accretion

(e.g. Ioka et al.17; Kimura et al. 21)

Can we detect gamma rays from IBH "spark gap"?

● implications to massive star evolution theory

● Galactic cosmic ray origin? (c.f. Ioka et al.17)

● BH spin, B-field strength → confirming BH jet theory

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Motivation: Detecting Isolated stellar-mass Black Holes via Gamma-Rays?

© \(10^7 - 8\) undetected IBHs in the Galaxy

\[ SFR \times V_{gal} \times t_{galaxy} \quad (e.g. \text{Sartore & Treves 10; Caputo et al. 17; Abrams & Takada 20}) \]

\(\sim 10^{-14}\) pc\(^3\) yr\(^{-1}\) \(\sim 10^{11}\) pc\(^3\) \(\sim 10\) Gyr

→ possible interactions w/ Galactic gas clouds
→ MAD around IBHs even for weakly-magnetized gas accretion

(e.g. Ioka et al.17; Kimura et al. 21)

Can we detect gamma rays from IBH "spark gap"?

● YES for nearby IBHs
● BH spin, B-field strength → confirming BH jet theory
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Simulation Setting

**1D · GRPIC simulation code**

(Levinson & Cerutti18; Kisaka et al.20;22)

\[
\frac{du_{\pm}}{dt} = -\sqrt{g_{rr}} \gamma_{\pm} \partial_r(\alpha) + \alpha \left( \frac{q_+ E_r}{m_e} - \frac{p}{m_e v_{\pm}} \right) : e_{\pm} \quad \text{EoM}
\]

\[
\frac{dr}{dt} = -\sqrt{g_{rr}} p^t \partial_r(\alpha) : \text{IC photon trajectory}
\]

\[
\partial_t(\sqrt{A} E_r) = -4\pi (\Sigma j^r - J_0) : \text{Ampere’s law}
\]

\[
\partial_r(\sqrt{A} E_r) = 4\pi \Sigma (j^t - \rho_{GJ}) : \text{Gauss’ law}
\]

**IC · secondary pair creation by Monte-Carlo**

(NOT ’primary’ injection via MeV photon annihilation)

**Kerr spacetime**

**steady, split-monopole B-field**

**Parameters**

\[
M = 10M_\odot, \ a_* = 0.9, \ B_H = 2\pi \times 10^7 \text{G}
\]

\[
\theta = 30^\circ, \ 1.5r_g \lesssim r \lesssim 4.3r_g
\]

\[
(r_g = \frac{GM}{c^2} \sim 1.5 \times 10^6 M_\odot \text{cm})
\]
Simulation Result: Overall Evolution

(time step=6220000 t = 30.02r_g/c)

- particle number density
- E-field

- quasi-periodic gap (similar to Kisaka 20;22)

- $\gamma_{e-, pk} \sim 10^7$

$\rightarrow$ GeV-TeV gamma-rays
Simulation Result: Disk Photon Intensity Dependence

\[ \tau_0 \approx n_\gamma \sigma_T r_g \propto \text{disk photon intensity} \] : Thomson depth for \( r_g \) controlling secondary pair multiplicity \( (\tau_{\text{pair}} \sim 0.1 \tau_0 \times (\epsilon_{ic} \epsilon_2)^{-1}) \)

(\( \tau_0 = 175 \)) time step=33980000 t = 163.99r_g/c

\[
\frac{\Delta (\Delta_{\text{min}}) n_h}{n_{h_{\text{min}}}} \Delta_{\text{min}} = 3 \times 10^{-1} (r/r_g) \]

\[
\frac{(A/A^*)}{E_{v}/E_{H}} \]

\[
\frac{L_{\text{cur},pk}/L_{BZ}}{\tau_0} \sim 10^{-1}(\tau_0/30)^{-\alpha} \] (\( \alpha \sim 8/3 \) for \( p = 2.0, \epsilon_{\text{min}} = 10^{-6} \))

\[ L_{BZ} : \text{BZ luminosity} \]

◎ secondary pair multiplicity affects gap dynamics (period, gap size, E strength)

◎ \( L_{\text{cur},pk}/L_{BZ} \sim 10^{-1}(\tau_0/30)^{-\alpha} \) (\( \alpha \sim 8/3 \) for \( p = 2.0, \epsilon_{\text{min}} = 10^{-6} \))
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\( \gamma \)

\[ \varepsilon_{\text{ic}} \]

\[ \varepsilon_2 \]

\( \text{IC} \)

\( \gamma e \)

\( e^+ \)

\( e^- \)

- IC pair creation (disk photons)

- Secondary pair multiplicity affects gap dynamics (period, gap size, E strength)

- \( L_{\text{cur}, pk}/L_{\text{BZ}} \sim 10^{-1} (\tau_0/30)^{-\alpha} \) \( (\alpha \approx 8/3 \text{ for } p = 2.0, \varepsilon_{\text{min}} = 10^{-6}) \)

\( L_{\text{BZ}} \): BZ luminosity
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© Summary
Semi-Analytic Model of Averaged Gamma-Ray Emission from Gap

©predicting gamma-ray emissivity for wide range of BH mass, gas density

\[ \dot{M}(M_{BH}, n_{ISM}) \rightarrow \text{one-zone IBH MAD model} \] (Kimura et al. 21)

assuming Bondi accretion

solve EoM, IC photon transfer, pair creations
\[ \rightarrow \text{gap boundaries: enough pairs created (consistent w/ simu)} \]

maximum Lorentz factor \( \gamma_{pk} \)
gamma-ray peak luminosity \( L_{\text{cur, pk}} \)

\[ N_{\text{pair}}(r_{out}) = N_{\text{thre}} \]
Semi-Analytic Model of Averaged Gamma-Ray Emission from Gap

predicting gamma-ray emissivity for wide range of BH mass, gas density

\[ \dot{M}(M_{\text{BH}}, n_{\text{ISM}}) \rightarrow \text{one-zone IBH MAD model} \quad (\text{Kimura et al. 21}) \rightarrow \tau_0, \epsilon_{\text{min}}, B_H \]

solve EoM, IC photon transfer, pair creations
→ gap boundaries: enough pairs created
maximum Lorentz factor \( \gamma_{pk} \)
gamma-ray peak luminosity \( L_{\gamma \text{pk}} \)

calculate persistent gamma-ray spectra →

\[ \dot{N}(N^{89}, O); < \rightarrow \text{one-zone IBH MAD model} \quad (\text{Kimura et al. 21}) \rightarrow \tau_0, \epsilon_{\text{min}}, B_H \]

\[ M = 10M_\odot, n_{\text{ISM}} = 65 \text{ cm}^{-3} \]

\[ E\gamma F_{\gamma}, [\text{ergs}^{-1} \text{ cm}^{-2}] \]

\[ m = 3.1 \times 10^{-5} \]

\[ d_L = 1.0 \text{kpc} \]

\[ E_{\gamma} \text{ [GeV]} \]

\[ \text{gap curvature} \quad \text{gap IC scattering} \]
Semi-Analytic Model of Averaged Gamma-Ray Emission from Gap

©predicting gamma-ray emissivity for wide range of BH mass, gas density

$$\dot{M}(M_{BH}, n_{ISM}) \xrightarrow{\text{one-zone IBH MAD model}} \tau_0, \epsilon_{\text{min}}, B_H$$

disk photon peak energy

gap curvature
gap IC scattering

gap curve

gap IC scattering

GeV-TeV gamma-ray emission detectable from ~kpc

[Submitted on 19 Oct 2023]

1D GRPIC Simulations of Stellar–Mass Black Hole Magnetospheres: Semi–Analytic Model of Gamma–Rays from Gaps

Koki Kin, Shota Kisaka, Kenji Toma, Shigeo S. Kimura, Amir Levinson

(Kin et al. submitted; arXiv:2310.12532)
Discussion: strategy

◎ peak in GeV-TeV → **Fermi-LAT unIDs**

- hard spectral index \( \frac{dN}{dE_{\gamma}} \propto E_{\gamma}^{-\Gamma} \), \( \Gamma \approx 2/3 \)
- spectral break
- point source, association w/ gas clouds

◎ cross-correlation w/ **MAD signals in IR~X-ray**

\( P \rangle \propto \dot{\mathcal{M}} \propto \frac{\partial}{\partial \mathcal{L}} \frac{\mathcal{L}}{m^2} \)

\( \Delta \mathcal{F} \gtrsim 10^{5} \mathcal{M}_{1} \left( \frac{v}{40 \text{ km s}^{-1}} \right)^{-3} \text{ s} \)

\[ M = 50 M_{\odot}, \quad j_{0} = -1/2 \]

\[ \begin{align*}
\text{Fermi-LAT, 10yr} & \quad \text{(l,b)=(0,0)} \\
\text{CTA-N, 50h} & \quad \text{(l,b)=(0,30)}
\end{align*} \]
Summary

◎ Research Motivation: finding undetected isolated BHs through gamma-ray observation
  gas infall → formation of BH magnetosphere, particle acceleration in spark gap?

◎ Method: analyze plasma dynamics & gamma-ray characteristics using
  
  1D GRPIC simulation + semi-analytic modeling

  GeV-TeV gamma rays from BH gap detectable from ~kpc
  ~a few in Fermi-LAT unID objects, cross-correlation w/ opt~X-ray
  luminosity variation w/ ~yr timescale?

◎ Model uncertainty: $J_0$ fluctuation timescale, lensed photons affect luminosity/lightcurve
  $\dot{M}$ calculation

◎ Future work: candidate search, multi-D simulation
Back up
Discussion: expected number of detection in certain gas phase $\mathcal{N}_{\text{det}}$

$\mathcal{N}_{\text{det}} = \text{number of IBHs in gas & sensitivity limit}$

sensitivity limit $d_{i,\text{det}}$: luminosity vs sensitivity

$$d_{i,\text{det}} = \sqrt{\frac{L_{\text{obs}}}{4\pi F_{\text{sen}}}} \sim 5 L_{\text{obs,33}}^{-1/2} F_{\text{sen,12}}^{-1/2} \text{ kpc}$$

$\therefore \mathcal{N}_{\text{det}} \sim n_0 \xi_0 \frac{1 - \gamma}{M_2^{1-\gamma} - M_1^{1-\gamma}} M^{1-\gamma} 2\pi H_{\text{ISM}} d_{i,\text{det}}^2 \approx 3.7 \left(\frac{d_{i,\text{det}}}{5 \text{kpc}}\right)^2 \left(\frac{M}{50 M_\odot}\right)^{1-\gamma}$

$$\left(\begin{array}{c}
\frac{dN}{dM} \\
\xi_0 : \text{Volume filling factor}
\end{array}\right) \propto M^{-\gamma} \ (\gamma \sim 2.6 \ \text{Abbott et al.} 21)$$

$n_0 \sim R_G W n_{\text{gal}}^{-1} H_0^{-1} \sim 2 \times 10^2 \text{kpc}^{-3} : \text{merged BH density}$
Simulation Results: higher $J_0$

$j_0 \equiv J_0/|\mathcal{V}_{BZ}|$

$$j_0 = -1/2\pi$$

higher $n$ in gap $\rightarrow E_r \propto (\gg 10^{-2}B_H) \rightarrow L_{cur} \rightarrow$, but $L_{ic} \propto |j_0|(\propto n)$