High-Energy Radiation From Accretion Disks and Jets Near Rotating Black Holes

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O’ Riordan, Pe’er, & McKinney, 2017b, in prep.
Motivation - Astrophysical Jets

- Jets are observed in a wide range of accreting black hole systems
- XRBs $\Rightarrow M \sim 10 \, M_\odot$
- AGN $\Rightarrow M \sim 10^6 - 10^9 \, M_\odot$
- Jet launching mechanism?
- Emission location?
- Mass loading of funnel?

Centaurus A (ESO/WFI)
Motivation - Jet Power vs Spin

- Correlation between 5GHz emission and spin $P_{\text{jet}} \sim a^2$
  (Narayan & McClintock 2012)

- $P_{\text{jet}} \sim a^2 \Rightarrow$ jets powered by rotational energy of black holes $\rightarrow$ BZ mechanism?
  (Blandford & Znajek 1977)

- Spin dependence of high-energy emission?

(Narayan & McClintock 2012)
Global 3D GRMHD simulations with HARM
(Gammie, McKinney, & Tóth 2003)

Efficient jet launching by BZ mechanism in MADs
(Tchekhovskoy et al. 2011; McKinney et al. 2012)

Density floors where $b^2/\rho \gtrsim 10 \Rightarrow$ mass uncertain in BZ funnel
Radiative Transport

- GR radiative transport code based on grmonty
  (Dolence, Gammie, Mościbrodzka, & Leung 2009)

- Ray tracing in Kerr spacetime

- Synchrotron emission, absorption, and Compton scattering

- Thermal distribution of relativistic electrons

- Vary $\mathcal{T} = T_p / T_e$ independently in disk and jet

- Disk $\Rightarrow \beta_p > 0.2$, jet $\Rightarrow \beta_p \leq 0.2$
1) Effects of Spin on Observed Signal

- Luminosity increases with spin by \( \sim 2 \) orders of magnitude
- Synchrotron peak shifts from optical \( \rightarrow \) X-rays
- X-rays and \( \gamma \)-rays vary with spin, while NIR constant
- Luminosity increases with viewing angle

\[(O'\text{ Riordan}, \ Pe'er, \ & \ McKinney, 2016b)\]
1) Total Radiated Power vs Spin

- Strong dependence on spin and viewing angle
- $P \propto a^2$
- Max for observers perpendicular to spin axis

\[ P \sim a^2 \]
1) Comoving Synchrotron Emission

- $\nu j_\nu \sim nB^2\Theta^2$
- Dominated by near-horizon region
- Horizon radius decreases with spin $r_H = 1 + \sqrt{1 - a^2}$
- Emitted power vs observed power $\Rightarrow$ redshift effects
1) Gravitational Redshift

\[ \mathcal{R} = \frac{E'_{\infty}}{E} = \frac{p_t}{u^\mu p_\mu} \]

- Redshift profiles depend strongly on spin and viewing angle
- Observers with \( \theta = \pi/2 \) see closer to the horizon
1) Spin Signature

- X-rays from near horizon
- NIR emission from further out in disk/jet
- $P_X / P_{\text{NIR}}$ observational signature of spin

![Graph](image)

![Graph](image)
1) Retrograde Spin

- Power depends on $r_H$ instead of $r_{\text{ISCO}}$
- $r_{\text{ISCO}}$ monotonic in $a$, $r_H$ symmetric about $a = 0$
- Power increases with retrograde spin $\Rightarrow$ not due to $r_{\text{ISCO}}$
- Degeneracy between $+a$ and $-a$
2) Variability of Near-Horizon Emission

- \(a = 0.99\) model
- \(M = 10^8 M_\odot\) since timescales too short in XRBs
- PDS consistent with blazars
- Strong disk-jet couplign?
- Implications for rapid variability in 3C 279

(O’ Riordan, Pe’er, & McKinney, 2017a)
3) Jet Signatures

- Geometrically thick \( H/R \sim 1 \)
- High spin \( a = 0.94 \)
- Overlapping jet and disk components
- Break at \( \nu \approx 10^{16} \) Hz
- \( \gamma \)-ray bump \( \nu \approx 10^{23} \) Hz

\[ T_d = T_j = 10 \]

(O’ Riordan, Pe’er, & McKinney, 2016a)
3) Jet Signatures

- Vary $T_d$ and $T_j$
- Change disk/jet contributions
- $T_d = 10$
  - $T_j = 3$ (top)
  - $T_j = 30$ (bottom)
- UV break and $\gamma$-ray bump

(O’ Riordan, Pe’er, & McKinney, 2016a)
4) Jet Mass Loading

- Observations of jets show structure on large scales → knots/blobs
- These features often propagate with apparent superluminal velocities
- Mass-loading of funnel close to black hole and subsequent acceleration?

3C279 jet (NRAO/AUI)
4) Jet Mass Loading

- Funnel region dominated by numerical floors
  \[ b^2/\rho > 10 \]

- Previously considered empty funnel with
  \[ \rho_f = U_f = 0 \]

- Compare empty funnel with prescribed \( \rho_f \) and \( U_f \)

- \( T_d = 30, T_j = 3 \)
  \( \text{MAD with } H/R \approx 0.2 \)

\( \rho_f \) and \( U_f \) const in \( \theta \)

(O’ Riordan, Pe’er, & McKinney, 2017b, in prep.)
4) Mass Loading in XRBs - Low Spin

- Models with $a = 0.1$ and $a = 0.5$
- Funnel emission $\Rightarrow$ enhanced hard UV/soft X-rays
- Optical and below unaffected by funnel matter
4) Mass Loading in XRBs - High Spin

- Models with $a = 0.9$ and $a = 0.99$
- Significant funnel contribution to X-rays and $\gamma$-rays
- $\nu \lesssim 10^{16}$ Hz $\Rightarrow$ insensitive to funnel filling
4) Mass Loading in Sgr A* - Low Spin

- Models with $a = 0.1$ and $a = 0.5$
- $a = 0.1$ model ⇒ both empty and filled funnel fit data
- $a = 0.5$ model ⇒ better fit to IR limits with empty funnel
4) Mass Loading in Sgr A* - High Spin

- Models with $a = 0.9$ and $a = 0.99$
- $a = 0.99$ model doesn’t fit unless $T_p/T_e \gtrsim 300$ near horizon
- IR and X-ray limits disfavour strong funnel emission
Summary

  - X-ray and γ-ray power increase with spin and inclination
  - $P_X / P_{\text{NIR}} \Rightarrow$ observational signature of spin in low/hard state

  - Power spectrum consistent with observations of blazars

  - Break at $\nu \approx 10^{16}$ Hz, and γ-ray bump at $\nu \approx 10^{23}$ Hz

- **Funnel mass loading** (O’ Riordan, Pe’er, & McKinney, 2017, in prep.)
  - Enhanced UV and X-rays in the case of XRBs
  - Sgr A* data favours empty funnel in high-spin models
Gravitational Redshift (ZAMO)

\[
\mathcal{R} \equiv \alpha - \Omega \sqrt{g_{\phi\phi}} P_{\phi'}
\]

\[
P_{\phi} = \frac{p_{\phi}}{p_t} \quad -1 \leq P_{\phi'} \leq +1
\]

(By Bardeen et al. 1972)

- Photons emitted in the $+\phi$ direction suffer little redshift
GRMHD Models

\( a = 0.99 \) (Tchekhovskoy et al. 2011)

\( a = 0.94 \) (McKinney et al. 2012)