Models of Inefficient Accretion onto a Black Hole and Pair Production in Jets

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Radiatively Inefficient Accretion Flows (RIAFs)

• RIAF in theory
  • $\dot{m} < m_{\text{crit}} = \text{few} \times 10^{-7}$ ($\dot{m} = \dot{M}_{\text{acc}}/\dot{M}_{\text{Edd}}$, $\dot{M}_{\text{Edd}} = 10\% \, L_{\text{Edd}} \, c^2$
    $L_{\text{Edd}} = 4\pi GM_{\text{bh}} m_\text{p}/\sigma_T$)
  • $t_{\text{rad}} \gg t_{\text{dyn}}$, weak radiative cooling, energy advection (ADAF, Narayan & Yi 1994)
  • Accretion flow $\rightarrow$ geometrically thick and optically thin $+$
    accretion flow dynamics decoupled from radiation
  • collisionless plasma $\rightarrow$ $T_p/T_e \neq 1$

• RIAF in practice, BH systems with $L \ll L_{\text{Edd}}$
  • quiescent GN: Sgr A* ($L/L_{\text{Edd}}=10^{-9}$)
  • BLLac/FRI: M87 ($L/L_{\text{Edd}}=10^{-5.5}$)
  • many nearby galactic nuclei, BHB in quiescent state
Outline

• Numerical realization of RIAF models (GRMHD simulations)

• Radiative properties of RIAFs from Monte Carlo simulations
  • application to Sgr A*

• Non-equilibrium electron-positron pair production in the jet (magnetized funnel)
  • \( \gamma + \gamma \rightarrow e^+ + e^- \)
  • pair production is balanced by pair escape rather than pair annihilation

Goals

• Understand physics of accretion in underluminous X-ray sources such as Sgr A*

• Understand composition of jets and conditions to produce jets
  • during RIAF phase
  • during transition from RIAF to efficient accretion mode
  • Selfconsistent model of accretion disk and jet
Accretion disk model - initial setup

- Equilibrium torus (Fishbone & Moncrief 1976, Abramowicz et al. 1978) + weak magnetic field
- MHD equations solved with HARM (2D Gammie et al. 2003, 3D Noble et al. 2006, 2009), conservative, shock capturing scheme to solve GRMHD eq,
- radial range = \( r_h - 40 \, R_g \) (Kerr-Schild coordinates-no singularity at \( r_h \))
• All simulations show a similar, statistically steady final state
• We assume that the inner parts of this torus are the inner parts of large RIAF
• Scaling depends on $M_{bh}$ and $\dot{M}_{acc}$
Model comparison to observation - radiative transfer

- Monte Carlo technique for radiative transfer:
  - Generate photon $E=\hbar \nu$ and $\vec{p}$ based on the emissivity of the physical radiative process
  - trace individual photons to the observer

- Important emission processes in RIAF:
  - synchrotron radiation (relativistic thermal distribution of electrons)
  - Compton scattering
  - Absorption

- All relativistic effects are included: photons move on geodesics, Doppler boosting, gravitational redshift etc. (Dolence et al. 2010)
Observations of Sgr A* ( $M_{bh}=4 \times 10^6 \, M_{\odot}$ )

- Quiescent emission (radio, sub-mm, NIR, X-rays) + flares (NIR and X-rays)
- VLBI size of emission at 1.3 mm FWHM=37 $\mu$as, apparent size of horizon 55$\mu$as

VLBI, 230 Ghz
Doeleman et al. 2009

Keck, NIR,
UCLA group

- model free parameters: $m$, $a^*$, $T_p/T_e$, $i$
- fit model SED to sub-mm obs., do not overproduce limits at high energies + fit the size from VLBI
Emission from turbulent disk from Monte Carlo radiative transfer

Origin of photons at different frequencies, Moscibrodzka et al. 2009

← Spectral energy distribution (SED)
"Best-bet" model for Sgr A* gives $a=0.94$, $T_p/T_e=3$, $i \approx 90$ deg, $\dot{m}=10^{-7}$.

- $a < 0.94$ and $T_p/T_e=1$ give poor fit to sub-mm observations.
- $a > 0.94$ overestimate X-rays observations.
- $T_p/T_e > 3$ wrong sub-mm slope, overestimate NIR and X-rays + produce too large images.

SED calculated with Monte Carlo code, Moscibrodzka et al. 2009.

230 GHz image of the model (Moscibrodzka et al. 2009) calculated with ray-tracing code (Noble et al. 2007).
What are the physical conditions in the funnel?

- In the funnel matter free to fall out
  - numerically → floor density
- What is real density in the funnel?
- In nature funnel density in LLGN determined by $\gamma\gamma$ pair production (Phinney 1983)
- What is the actual pair production?
Electron-positron jets - how many pairs do we expect?

- We do not expect much of pairs to be created at all (compactness parameter, or optical depth to pair production, is small $l = L \sigma_{th}/R m_e c^3 \approx 10^{-5} \ll 1$)

- Estimate of pair plasma density

- Pair production balanced by escape

  - $Sgr\ A^*: n_{+/\pm}=10^{-4}$ cm$^{-3}$
  - $M87: n_{+/\pm}=10^4$ cm$^{-3}$

With Monte Carlo radiative transfer we can do better job!
**e+/− pair production—Monte Carlo method**

- Monte Carlo techniques allow to follow collisions between individual photons (photon packets) everywhere.
- Pair production opacity assumed small.
- We need to store information about the radiation field above 1 MeV (in the center-of-momentum frame).

$h\nu > 1$ MeV photon trajectories in the jet, Gammie 2009, private com.
$e^+/e^-$ pair production rates in RIAF

- Disk turbulent but at a given time radiation field is smooth, pair prod. distribution is smooth

- Individual rays is Monte Carlo noise

- Beaming effects $\rightarrow$ most of pairs created in the disk plane, $\mu = \cos(\theta)$

$$\dot{n}_\pm (r, \mu) \sim r^{-6} e^{-\mu^2/0.4}$$

10-20% created in the magnetically dominated funnel
e$^+/-$ pair production - dependence on observables and model parameter

Observable parameters: $L_X, \alpha_X, M_{bh}$

$$\dot{N}_\pm \sim L_X^2 e^{9.26\alpha_X} M_{BH}^{-1}$$

Model parameters: $\dot{m}, M_{bh}, r_{ISCO}$

$$\dot{N}_\pm \sim \left(\frac{2.044}{r_{isco}}\right)^{26} \dot{m}^7 M_{BH}^2$$
$e^+/-$ pair production - dependence on model parameters

Mass accretion rate vs. time at later times of simulation
e\(^{+/-}\) pair production - observational consequences

• Can we see emission from pairs? To calculate SED:
  • need pair density and distribution of pair kinetic energy
  • so need to solve dynamical equations of the pair plasma (in preparation)

Sgr A*
  • During quiescence - small number of pairs
  • During strong X-ray flare (\(L_X = 10^{35} \text{ergs/s}\)) → arising compact pair jet?
  • activity in the past \(L_X = 10^{39} \text{ergs/s}\) - might have produced stronger pair jet in the past

M87
  • number of pairs slightly larger than observed one: \(n_{+/\pm} = 100 \text{ cm}^{-3}\)
  • need to couple dynamics with radiative transfer (in preparation)
  • pair production suppressed by cooling
Summary

- We model inefficient accretion onto spinning black holes using GRMHD simulations, we model multiwavelength (radio-gamma rays) radiative properties of GRMHD simulations using GR Monte Carlo techniques.

- We have models of Sgr A* quiescent emission (Moscibrodzka et al. 2009) and variability (Dolence et al. 2010, in press), $a^*=0.94$, $T_p/T_e \sim 1$, $i=90^{\text{deg}}$.

- For the first time we compute non-equilibrium electron-positron pair production rates by $\gamma \gamma$ from turbulent accretion disk around spinning black hole.

- Production of pairs sensitive to X-ray luminosity, very sensitive to mass accretion rate and spin of the BH.

- More to be done in near future!
END
Test of pair production code

- 3D Cartesian space, 2 point sources of high energy radiation