Evolving Nonthermal Electron Distributions in Black Hole Accretion Simulations

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arXiv:1704.05092
Work with Ramesh Narayan and Aleksander Sądowski
Imaging a Black Hole with the EHT

Left Image Credit: NRAO (Top Left), Hada et al. 2016 (Bottom Left), Avery Broderick & Kazu Akiyama (Right)

Right Image Credit: Michael Johnson. APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin
Other work: Imaging for EHT 2017

Chael et al. 2016
(arXiv 1704.05092)
VLBI imaging software at https://github.com/achael/eht-imaging
GRMHD Simulations as models for EHT sources

Movie Credit: Hotaka Shiokawa
GRMHD Simulations model EHT sources - Polarization

M87: Moscibrodzka et al. 2017 arXiv 1703.02390

Sgr A*: Gold et al. 2016 arXiv 1601.05550
GRMHD Simulations

- Collisions bring the plasma as a single ideal fluid in local thermodynamic equilibrium.

- **Ideal MHD**: high conductivity cancels electric field in the rest frame – Lorentz force on a particle vanishes.

\[ \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \]
ADAFs

- **Advection Dominated Accretion Flow.**
- Most viscous energy is advected to smaller radii instead of being radiated.
- Flows are:
  - Hot
  - Low luminosity
  - Low accretion rate
  - Optically thin
  - Geometrically thick
Two-Temperature Simulations

• Low densities in hot flows $\rightarrow$ inefficient Coulomb coupling between ions and electrons.

• Generally expect ions to be hotter than electrons:
  • Electrons lose energy through radiation much more efficiently than ions.
  • Relativistic electrons store more energy with a smaller increase in temperature than non-relativistic ions.

\[ nk_B T = (\Gamma - 1) u \]
Two-Temperature Simulations

Ressler et al. 2015 (arXiv 1509.04717)
2017 (arXiv 1611.09365)

Sadowski et al. 2017 (arXiv 1605.03184)
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  - Howes (2010) puts almost all energy into electrons in high magnetization regions
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Adjust from 5/3 $\rightarrow$ 4/3 self consistently with T
Two-Temperature GRRMHD Simulations

- Total fluid quantities are evolved as in single-temperature GRRMHD
- Electron and ion energy densities are evolved via the 1st law of thermodynamics:

\[
T_e (n_e s_e u^\mu)_{;\mu} = \delta_e q^v + q^C + \hat{G}^0
\]
\[
T_i (n_i s_i u^\mu)_{;\mu} = (1 - \delta_e)q^v - q^C
\]
Two-Temperature ADAF simulation (Sądowski et al. 16)

\[ \frac{T_e}{T_i} \quad \rho \]
Sgr A* SED: Nonthermal Electrons are important!

Image Credit: Genzel et al. (2010)
Yuan et al. (2003)
Nonthermal distributions contribute to Sgr A* variability!

Ball et al. 2016 arXiv 1602.05968
Goals:

1. Self-consistently evolve a spectrum $n(\gamma)$ of nonthermal electrons in global GRRMHD simulations including interactions with all other quantities (thermal gas, radiation, magnetic field . . .).

2. Include the resulting nonthermal population in radiative transfer to produce images & spectra.

3. Compare to data and constrain the bulk properties and microphysics of the accretion flow.
Non-Thermal Population: Assumptions

• Track the spectrum $n(\gamma)$ sampled in different “bins” in Lorentz factor space.

• We assume the non-thermal distribution is isotropic in the fluid frame.

• We also assume the non-thermal population is highly relativistic and optically thin (neglect absorption).
Evolution Equation

\[
\frac{\partial n(\gamma)}{\partial t} - \nabla \cdot (\vec{v} n(\gamma)) = \text{Advection}
\]
Evolution Equation

\[
\frac{\partial n(\gamma)}{\partial t} - \nabla \cdot (\vec{v} n(\gamma)) = -\frac{\partial}{\partial \gamma} (\dot{\gamma}_{\text{adiab}} n(\gamma))
\]

- Advection
- Adiabatic Compression/Expansion
Evolution Equation

\[
\frac{\partial n(\gamma)}{\partial t} - \nabla \cdot (\vec{v} n(\gamma)) = -\frac{\partial}{\partial \gamma} (\dot{\gamma}_{\text{adiab}} n(\gamma)) - \frac{\partial}{\partial \gamma} (\dot{\gamma}_{\text{rad}} n(\gamma))
\]
Evolution Equation

\[
\frac{\partial n(\gamma)}{\partial t} - \nabla \cdot (\vec{v} n(\gamma)) = -\frac{\partial}{\partial \gamma} (\dot{\gamma}_{\text{adiab}} n(\gamma)) - \frac{\partial}{\partial \gamma} (\dot{\gamma}_{\text{rad}} n(\gamma)) + Q(\gamma)
\]

Advection
Adiabatic Compression/Expansion
Radiative Cooling
Injection/Particle Acceleration
Evolution Equation

\[
(n(\gamma)u^\alpha)_{;\alpha} = \frac{\partial}{\partial \gamma} \left[ \frac{1}{3} u^\alpha_{;\alpha} (\gamma - \gamma^{-1})n(\gamma) \right] - \frac{\partial}{\partial \gamma} (\dot{\gamma}_{\text{tot}} n(\gamma)) + Q^I(\gamma). \]

- Advection
- Adiabatic Compression/Expansion
- Injection/Particle Acceleration
- Radiative Cooling
Evolution Equation

\[ \dot{\gamma} n(\gamma) = \text{Flux in Lorentz factor space} \]

Solved with implicit upwind finite differencing. Maybe spectral method in future?
Radiative Cooling

• **Synchrotron:**
  \[ \dot{\gamma}_{\text{syn}} \sim B^2 \gamma^2 \]

• **Free-Free:**
  \[ \dot{\gamma}_{ff} \sim -n_i \gamma \log \gamma \]

• **Inverse Compton:**
  \[ \dot{\gamma}_{\text{IC}} \sim -\dot{E}_r \gamma^2 F_{KN}(\gamma) \]
Synchrotron Cooling + Particle Injection

- Constant background B-field and particle injection spectrum.

\[ \dot{\gamma}_{\text{syn}} \sim B^2 \gamma^2 \]

- Synchrotron cooling break between injection index \( p \) and \( p+1 \) propagates to lower Lorentz factor:

- Below minimum injection Lorentz factor, spectrum has universal power law of -2
Based on result from Manolakou et al 2007
- 30,000 K photon background modifies IC cooling.

\[ \dot{\gamma}_{IC} \sim -\dot{E}_r \gamma^2 F_{KN}(\gamma) \]

\[ F_{KN}(\gamma) = \left(1 + 11.2\gamma \frac{kT_r}{m_e c^2}\right)^{-3/2} \]

- At the highest Lorentz factors, Synchrotron dominates, and the spectrum is broken.
- At the lowest Lorentz factors, the KN correction is unimportant and the IC break develops normally.
Viscous Heating & Injection

• We compare the internal energy of the total fluid to the internal energy of the components evolved adiabatically.

• A fraction $\delta_e$ goes directly into both electron populations: $\delta_{nth}$ of that goes into non-thermal electrons.

• We must also specify an injection power law index and minimum Lorentz factor

• What physics determines the heating/injection rate? MHD turbulence, shocks, reconnection....
Total Fluid $T^{\mu\nu} = [\text{Ions } s_i + \text{Thermal Electron } s_e + \text{Nonthermal Electrons } n(\gamma)]$ + Photons $R^{\mu\nu}$

1.) Adiabatic Advection

2.) Viscous Heating

3.) Radiative Emission + Absorption
Sgr A* Simulation

- Initial conditions: evolved two-temperature disk with no nonthermal electrons.

- **Constant** 1.5% nonthermal energy injection fraction

- **Constant** $p=3.5$ power law.

- **Fixed** injection minimum and maximum $\rightarrow$ chosen to be above hottest thermal peak.
Magnetic Field and Electron Temperature
Nonthermal Energy Density
Comparison to simulation without nonthermal electrons
Timescales and Cooling Break

- Cooling time: time for entire injected spectrum to break assuming constant injection.

\[ t_{\text{syn}} \propto \frac{1}{B^2} \left( \frac{1}{\gamma_{\text{min}}} - \frac{1}{\gamma_{\text{max}}} \right) \]

- Accretion time:

\[ t_{\text{acc}} \equiv \frac{r}{\sqrt{v_r^2 + r^2 v_\theta^2}}. \]
Spectral breaks trace shocks?

Synchrotron break

Gas Expansion $\sim \nabla \cdot \mathbf{v}$
Spectral breaks trace shocks?

Synchrotron break

Gas Expansion

$\sim \nabla \cdot \vec{v}$
Raytraced Images

Thermal Only

230 GHz

136 THz infrared

2 keV X-ray
Raytraced Images

Thermal Only

230 GHz

136 THz infrared

2 keV X-ray

Thermal + Nonthermal
Synchrotron Spectra

Thermal only

HEROIC: includes IC + free-free

grtrans

w/ non-thermal

$\nu L_\nu$ (erg s$^{-1}$)

$\nu$ (Hz)

$\nu^{-0.75}$
Nonthermal effects on Sgr A* variability

Ball et al. 2016
Takeaway Points

Flows around Sgr A* and M87 should be 2 temperature and have an additional non-thermal electron population.

We now have a method to simulate the evolution of non-thermal electron distributions in global GRMHD simulations.

The electron heating/injection prescription is still very uncertain.
Next Steps

- Investigate different injection prescriptions to better capture physics of injection and reproduce variability.
  - In progress: dissipation fraction based on PIC simulations of reconnection (instead of Landau damping)
  - Spectral changes in flares: varying injection slopes, varying minimum Lorentz factor.
  - To reproduce flaring activity: Localized nonthermal injection
Next Steps

• Investigate different injection prescriptions to better capture physics of injection and reproduce variability.
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• Full 3D simulations & polarized radiative transfer

• Investigate different accretion regimes – where IC / free-free / feedback important.
Questions?
What about absorption?

• For $\gamma \gg 1$, to $2^{nd}$ order in $h\nu/mc^2$, the evolution equation is:

$$
\left( \frac{\partial n}{\partial t} \right) = -\frac{\partial}{\partial \gamma} \left[ \gamma \dot{n}(\gamma) \right] + \frac{\partial}{\partial \gamma} \left[ \gamma^2 C(\gamma) \frac{\partial}{\partial \gamma} \left( \frac{n(\gamma)}{\gamma^2} \right) \right]
$$

• Where:

- Emission: $1^{st}$ order
- Absorption: $2^{nd}$ order

\[\dot{\gamma} = -\int \frac{\epsilon(\nu, \gamma)}{mc^2} d\nu \propto \left( \frac{h\nu}{mc^2} \right)\]

\[C(\gamma) = \int \frac{I_\nu \epsilon(\nu, \gamma)}{2\nu^2 m^2 c^4} d\nu \propto \left( \frac{h\nu}{mc^2} \right)^2\]

Requires radiation spectrum and emissivity spectrum!
Thermal and Nonthermal Power

Nonthermal Rad. Power

Thermal Rad. power