Advection-Dominated Accretion in Low-Luminosity Black Holes

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20-Year Collaboration with Jeff McClintock

My closest collaborator by far

About 65 papers (50 refereed) over the time period 1996–2014
- ADAF model of BH X-ray binaries
- BH: Event Horizon, spin, mass distribution

Many students: Ann Esin, Kristen Menou, Eric Zimmerman, Rebecca Shafee, Bob Penna, Sasha Tchekhovskoy, Jack Steiner

Many postdocs...
Accretion Disk Theory: Analytical Models

- 1D accretion models have been developed by simplifying the equations (Shakura & Sunyaev 1973; Novikov & Thorne 1973; Narayan & Yi 1994, 1995; Abramowicz et al. 1988, 1995;...)

- These models provide a lot of insight

- Three regimes of accretion have been identified, distinguished by $\frac{M_{\text{dot}}}{M_{\text{dot}_{\text{Edd}}}}$
Accretion Regimes

Super-Eddington Accretion, Slim Disk, ADAF (Abramowicz+ 89; Sadowski+ 15)
Radiation-dominated: ULX, SS433

Thin Accretion Disk: radiatively efficient (Shakura-Sunyaev, Novikov-Thorne 73)
Radiation-dominated: BH XRB soft state

ADAF, RIAF, Hot Accretion (Ichimaru 77; Rees et al. 82; Narayan& Yi 94, 95; Abramowicz+ 95; Yuan & Narayan 14)
Hot, two-temperature, radiatively inefficient: BH XRB low/quiescent state

Graph:
- Slim Disk
- Thin Disk
- Hot ADAF

Graph axes:
- \( \log (\dot{M}/M_{\text{Edd}}) \)
- \( \log (R/R_\odot) \)
**Advection-Dominated Accretion Flow (ADAF)**

- **Thin accretion disk**
  Radiatively efficient
  \[ q^+ \approx q^- \gg q^\text{adv} \]

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  Radiatively inefficient
  \[ q^+ \approx q^\text{adv} \gg q^- \]

\[
\begin{align*}
TdS &= dQ = Q^+ - Q^- \\
\rho T \frac{ds}{dt} &= q^+ - q^- \\
\rho v_r T \frac{ds}{dr} &= q^+ - q^- \\
q^\text{adv} &= q^+ - q^-
\end{align*}
\]
Properties of Hot ADAFs

- Radiatively inefficient (particles meet infrequently)
- Optically thin: radiates via synchrotron, bremsstrahlung, inverse Compton
- Relevant for low-\textit{Mdot} accretion sources
- Two-temperature: $T_i \sim 10^{12} \text{K}/r$, $T_e \sim 10^{10-11} \text{K}$
- Geometrically thick
- Has powerful jets and winds
Geometry of ADAF Model

Sgr A*

External Medium

XRB

Thin Disk
**Cyg X-1**

- **High Soft state:** thin disk
- **Low state:** no thin disk: $kT > 100$ keV

**Soft X-ray Transients**

- Go through a very wide range of $M\dot{e}$ during transient outburst
- Sweep through spectral states via state changes
A Paradigm for Dim BHs


When $\dot{M}$ falls below a few percent of Eddington, a hole opens up in the thin disk, and the inside is filled with a hot ADAF.

As $\dot{M}$ decreases further, the hole grows bigger and radiative efficiency drops significantly.

Esin et al. (1997)
Theoretical model spectra of a 6 M☉ BH accreting at different Ṁ\text{dot}.

Compared to data on Nova Muscae 1991

Esin+ 1997
ADAF model of state transition in Cyg X-1 (Esin et al. 1998)

Other ADAF-related work on BH XRBs:
- N, McClintock & Yi (1996)
- N, Barret & McClintock (97)
- Hameury et al. (97)
- Menou et al. (99)
- Esin et al. (2000, 2001)

Clues from timing:
- Gilfanov et al. (1999)

Conflicting evidence from X-ray reflection

Hysteresis is unexplained
ADAF model of XTE J1118+480

Esin, McClintock et al. (2001)
Guess (based on observations) of how the transition radius $R_{tr}$ varies with $L/L_{Edd}$ (or equivalently $\dot{M}$).
Using ADAFs to Test for the Event Horizon

- Narayan, Garcia & McClintock (1997) suggested comparing quiescent BH SXTs (or X-ray Novae) with quiescent NS SXTs.

- If both systems accrete via a radiatively inefficient mode (ADAF), then NS SXTs should be significantly brighter than BH SXTs, since NSs will radiate the advected energy from their surfaces, whereas BHs will swallow the energy.

- Results: Narayan et al. (1997), Asai et al. (1998), Chen et al. (1998), Menou et al. (1999), Garcia, McClintock, Narayan et al. (2001)
Garcia et al. (2001): Chandra data!

BH SXTs are more than 100 times fainter than NS SXTs.

Such a large difference is expected IF:
1. The accretion is radiatively inefficient,
2. BHXN have event horizons and NSXN have surfaces.
Black Holes Really Are Black!!

- If we see a dim BH SXT, we might think that it is dim simply because very little gas reaches the center.
- But, when a nearly identical NS SXT is 100+ times brighter, we know that it is more than just gas supply.
- Most straightforward interpretation: quiescent BH SXTs are much dimmer than NS SXTs because they swallow the gas, and heat energy, through the Event Horizon.
- If this interpretation is correct, then the X-ray data imply that black holes really are really black!
ADAF Thermodynamics is Highly Uncertain

- The plasma is collisionless
  - Electrons/protons do their own thing
- Non-equilibrium: Two-temperature
- Each particle remembers its heating history and radiates accordingly
- We need to understand plasma heating processes to make good models
Collisionless Accretion flow
Viscous dissipation
Heat

Ions
Coulomb

Thermal Electrons
Coulomb

Nonthermal Electrons

Radiation
Simulating Fundamental Plasma Processes

- So far, ADAF models have used toy prescriptions for particle heating, based on guesses, or clues from observations.
- Now, people are beginning to study particle heating via detailed Particle-in-Cell (PIC) simulations (billions of particles)
  - Spitkovsky, Sironi, Li, Uzdensky, ...
  - Xinyi Guo, Michael Rowan
Magnetic Reconnection

Rowan, Sironi & Narayan (2017)
Electron vs Ion Heating in Low Mach Number Shocks

\[ \delta_e / (1 - \delta_e) \] vs Shock Mach Number

Guo, Sironi & Narayan (2018a,b)
Numerical simulations of BH accretion can include all the complex physics that purely analytical methods cannot handle.

- Multi-dimensional $\rightarrow$ 2D/3D Hydrodynamics
- General Relativity (BH) $\rightarrow$ 2D/3D GRHD
- Magnetic field (MRI) $\rightarrow$ GRMHD
- Radiation $\rightarrow$ GRRMHD
- More Thermal Physics $\rightarrow$ Plasma processes
- Nonthermal Physics $\rightarrow$ Plasma processes
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Jets
No Jets??

Graph showing the relationship between mass accretion rate ($\dot{M}/M_{Edd}$) and radius ($R/R_s$) with arrows indicating the presence or absence of jets.
MOVIE

3D GRMHD simulation (Tchekhovskoy+ 2011,12)

Non-radiating ADAF around a rapidly spinning BH accreting in the MAD state

A really Powerful Jet

Clear evidence for energy (and angular momentum) outflow from the BH
GRRMHD simulation: $M=10M_\odot$, $a^*=0$, $\dot{M}=10\dot{M}_{\text{Edd}}$,
(Sądowski et al. 2015: KORAL) (ULX)

Produces jets, winds, ultrafast outflows
ADAFs and Jets

- Both kinds of ADAF happily produce powerful outflows and jets.
- The most powerful and most relativistic jets are obtained when
  - the BH spins rapidly, and
  - strong magnetic field around BH
  - Blandford-Znajek (1977) process