AGN Feedback: Simulations of Black Hole

Ramesh Narayan
Galactic Nucleus

$M_{BH} \sim 10^6 - 10^{10} M_{\odot}$

Image credit: Lincoln Greenhill, Jim Moran
Three Accretion Regimes

**ADAF/Slim Disk**
Super-Eddington, radiation trapped
(Begelman ‘79; Abramowicz et al. ‘89)

**Thin Accretion Disk**
(Pringle & Rees ‘72; Shakura & Sunyaev ‘73; Novikov & Thorne ‘73)
Quasars, XRBs in high soft state

**ADAF/RIAF**
Radiatively inefficient
(Ichimaru ‘77; Rees et al. ‘82; Narayan & Yi ‘94, ‘95; Abramowicz et al. ‘95)
Accretion and Outflows

- Analytic disk theory (1D) is okay for understanding basic physics of accretion
- Jets and outflows involve 2D motions and are beyond analytical theory
- We need numerical simulations:
  - GR (black hole – Kerr metric!) ✔️
  - MHD (magnetic fields essential) ✔️
  - Radiation (tough problem) ?✔️
Numerical Simulations

- Simulations of varying degrees of complexity have been done over the years
  - Pseudo-Newtonian hydrodynamics
  - Pseudo-N magnetohydrodynamics (MHD)
  - General Relativistic MHD (GRMHD)**
  - Radiation hydro/MHD $\rightarrow$ GRRMHD

- **Good news:** GRMHD simulations
  - Produce jets and winds from “generic” initial conditions
  - Provide new insights on accretion/jet physics
  - Provide useful information for AGN feedback
Feedback in Radio Mode/Maintenance Mode

**ADAF/RIAF**
Radiatively inefficient
(Ichimaru ‘77; Rees et al. ‘82; Narayan & Yi ‘94, ‘95; Abramowicz et al. ‘95)
GRMHD Simulations of ADAFs

- ADAF/RIAF is the easiest of the three accretion modes to simulate
- We can safely ignore radiation
- Geometrically thick: everything goes fast
- Simulations reach steady state out to fairly large radii
  - \( \sim \text{few } \times 100M \) in the best cases (still \( \ll R_B \))
- ADAFs readily form jets and outflows

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Sadowski et al. (2013)
Two Important Parameters

- BH Jet is powered by BH spin energy
- Jet power is sensitive to BH Spin and Magnetic Flux:
  \[ P_{\text{jet}} \approx \Phi_{\text{mag}}^2 \Omega_H^2 / c \]
- For a given \( M_{\text{dot}} \), there is a limit to how much Magnetic Flux \( \Phi_{\text{mag}} \) can be pushed into the BH
- System at this limit: Magnetically Arrested Disk (MAD)
- GRMHD simulations of ADAFs readily achieve the MAD limit if sufficient coherent magnetic flux is available
- Jets are highly collimated: feedback efficiency low?
Sąadowski et al. (2013)
BH Jet in MAD state can have a large efficiency: $\eta_{\text{jet}} = \frac{P_{\text{jet}}}{M\dot{\text{dot}} c^2}$ can even exceed 100% (Tchekhovskoy et al. 2012)

Strong dependence of $\eta_{\text{jet}}$ on spin parameter $a_*$
The Disk Wind is more boring:

- At best only mildly relativistic: $v \sim 0.1-0.2 \, c$
- Power source is primarily the Disk
- Power depends modestly on BH spin
- Power depends modestly on BH Mag Flux

- Large solid angle: $\sim 2\pi$
- Low power in comparison to jet
- Likely to be efficient source of feedback
Feedback efficiency depends on 3 parameters:

\( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \) (\( \dot{M}/\dot{M} \))

\( \Omega_H \) (range: 0—1)

\( \Phi_{\text{mag}} \) (range: 0—\( \Phi_{\text{max}} \))

Perhaps \( \Phi_{\text{mag}} \rightarrow \Phi_{\text{max}} \) (MAD)

Still, we need \( \dot{M} \), \( \Omega_H \) before we can “predict” how much energy or mmtm feedback occurs.

Available in principle in cosmological simulations (Sadowski et al. 2013)

\[
\begin{align*}
\dot{E}_{\text{jet}} & \approx 0.5 \left( \frac{\Phi}{\Phi_{\text{max}}} \right)^2 \left( \frac{\Omega_H}{0.2} \right)^2 \dot{M}c^2 \\
\dot{E}_{\text{wind}} & \approx 0.005 \left[ 1 + 3 \left( \frac{\Phi}{\Phi_{\text{max}}} \right)^2 \left( \frac{\Omega_H}{0.2} \right)^2 \right] \dot{M}c^2 \\
\dot{P}_{\text{jet}} & \approx 0.5 \left( \frac{\Phi}{\Phi_{\text{max}}} \right)^2 \left( \frac{\Omega_H}{0.2} \right)^2 \dot{M}c \\
\dot{P}_{\text{wind}} & \approx 0.1 \dot{M}c
\end{align*}
\]
MAD Limit
Major Caveat

- We do not have very good information on mass loss in the wind
- Serious limitation for feedback estimates

Unless we figure out the mapping between $\dot{M}_{\text{dot}}^B$ and $\dot{M}_{\text{dot}}^{BH}$, it will be hard to come up with a predictive prescription for AGN energy/mmtm feedback in the maintenance mode.
MIND THE OTHER GAP

Gas Accretion on SMBH
AGN
Jets, Winds, Radiation

Local ISM
Host galaxy
Universe

8 - 12 July, 2013 at the Institute of Astronomy & Kavli Institute for Cosmology (KICC)
University of Cambridge, UK. Website: http://www.ast.cam.ac.uk/meetings/2013/MindTheGap

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Quasar Mode:

- Thin Accretion Disk
  (Pringle & Rees '72; Shakura & Sunyaev '73; Novikov & Thorne '73)
  Quasars, XRBs in high soft state

- Classic QSO
Make robust predictions for the radiative luminosity $L_{\text{disk}}$ (no $\alpha$ dependence)

Radiative feedback is straightforward
- $\eta_{\text{disk}}(a_*)$

How about mechanical feedback via jets and winds?

GRMHD simulations have become feasible in recent years, so we can check
No Jets in Simulations of Thin Accretion Disks

- Thin disk simulations do not show anything that looks like a jet
- However:
  - thin disks are hard to simulate
  - models are converged only to $R \sim 20M$
  - No jet or wind out to 20M
- XRBs in the Thermal-Dominant State (thin disk regime) do not have jets
Quasar Mode: II

**ADAF/Slim Disk**
Super-Eddington, radiation trapped
(Begelman ‘79; Abramowicz et al. ‘89)

Radiative luminosity should be limited to at most $\sim$ few $L_{\text{Edd}}$

What if $\dot{M} \gg \dot{M}_{\text{Edd}}$? What happens to all the energy?

How much energy comes out via a jet or a wind?

Need 3D Radiation GRMHD simulations

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Numerical Simulations of Super-Eddington Accretion

- The field has been dominated by Ohsuga (2003...): Radiation hydro/MHD
- Important results on winds
- However, no GR or even SR
- Recent developments:
  - GR+Hydro+Rad(M1) (Sadowski+ ‘13)
  - GR+MHD+Rad(M1) (McKinney+ ‘13)
- First results will be out soon
McKinney et al. (2013)
Preliminary!!

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Very Preliminary

\[ \dot{M}_{\text{BH}} = \frac{78 L_{\text{Edd}}}{c^2} \]

\[ L_{\text{radiation}} = 1.1 L_{\text{Edd}}, \eta_{\text{rad}} = 0.015 \]

\[ L_{\text{Poynting}} = 9.2 L_{\text{Edd}} \]

\[ L_{\text{matter}} = 2.3 L_{\text{Edd}} \]

\[ L_{\text{total}} = 12.6 L_{\text{Edd}}, \eta_{\text{total}} = 0.16 \]
Summary

- Given $M_{BH}$, $M_{dot_{BH}}$, $\Omega_{H}$, $\Phi_{mag}$ ($= \Phi_{max}$?), BH simulators are able to estimate $E_{dot_{jet}}$, $P_{dot_{jet}}$, $E_{dot_{wind}}$, $P_{dot_{wind}}$

- What other quantities would you like?
  - Angular distribution of energy/mmtm?
  - Lorentz factor/velocity?
  - SMBH spinup/spindown?

- But major uncertainty: $M_{dot_{B}}$ vs $M_{dot_{BH}}$
  - Prognosis is uncertain
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Eve Ostriker

Virginia Bennett
Cathie Clarke
Tiago Costa
Mike Curtis
Martin Haehnelt
Simon Kirk

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