Black hole astrophysics in the new century

X-ray probes of strong gravity and cosmic feedback

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A new era of black hole research

- Existence of both stellar and supermassive black holes seems secure
  - Exotic physics required to escape black hole conclusion in Galactic Center

- Every galactic bulge seem to host a supermassive black hole

Movie from Genzel group
Similar work by Ghez group
The wider importance of black holes

- Supermassive black holes have cosmological importance…

- Energy output from black holes growth may be crucial factor in formation/evolution of massive galaxies

- Galaxy and SMBH growth coupled by powerful feedback processes

Kormendy & Gebhardt (2001)
Gebhardt et al. (2000)
Ferrarese & Merritt (2000)
Open issues…

- Are black holes really described by General Relativity?
  - Is the Kerr metric a good description of black hole spacetime?

- How does black hole accretion and jet production work?
  - How is accretion energy channeled into radiation & kinetic energy?
  - What is the role of black hole spin?

- How is massive black hole growth and galaxy formation coupled?
  - How do feedback processes couple enormous spatial scales?
Outline

• Talk about progress due to developments in X-ray instrumentation

• Probing the strong gravity regime with X-ray spectroscopy
  – The robustness of the relativistic signatures
  – Confronting accretion disk theory with data
  – Measurements of black hole spin

• Large scale environmental impact of black holes
  – The cooling flow problem and the radio-galaxy solution
  – Difficulties faced by radio-galaxy feedback models and possible solutions
I : PROBES OF THE STRONG GRAVITY REGIME

- ASCA observation of MCG-6-30-15…
  - Revealed extremely broadened/skewed iron emission line (Tanaka et al. 1995)
  - Confirmed by XMM

- What are we seeing?
  - Believe line to originate from surface layers of innermost accretion disk
  - Line broadened and skewed by Doppler effect and gravitational redshifting

Power-law continuum subtracted
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Pseudo-Newtonian MHD simulation Ray-traced through Schwarzschild metric
Iron line from X-ray reflection

Backscattered spectrum from X-ray irradiation of the “cold” optically-thick disk...

- Fluorescence/radiative recomb. lines
- Radiative recombination continuum
- Compton backscattered continuum

Self-consistent model of X-ray reflection from ionized disk (Ross & Fabian 2005)
Iron lines in AGN

MCG-5-23-16 (Dewangan 2003)

PG 1211+143 (Pounds 2003)

Lockman hole (Streblyanskaya et al 2004)

IRAS 18325 (Iwasawa 2004)
Iron lines in Galactic Black Hole Binaries

GX 339-4 (XMM)

GRS 1915+105 (CXO)

$R_{in} = 2.9^{+0.1}$

GX 339-4 (CXO)

XTE J1650-500 (XMM)
Must be careful to account for effects of absorption...
• Fitting 3-6 keV and 8-10 keV band, can reproduce "red-wing" curvature from iron-L absorption (Kinkhabwala 2003; PhD thesis)

• Generic prediction - significant iron K line absorption from FeXVII-FeXXIII (~6.4-6.6 keV)
Clearly do not see the FeXVII-FeXXIII absorption lines that accompany a "broad-line mimicking" wa

TESTING BLACK HOLE ACCRETION DISK MODELS

- Current paradigm
  - Accretion proceeds through disk due to MHD turbulence (Shakura & Sunyaev 1973; Balbus & Hawley 1991)
  - Full GR-MHD simulations of **non-radiative** disks possible
- Radiatively-efficient disks
  - Gross properties amenable to semi-analytic modeling
  - Novikov & Thorne (1974)
    - Geom. thin, efficient disk
    - Material plunges into BH ballistically once within the innermost stable circular orbit

Hirose et al. (2004); also see Koide et al. (2000), McKinney (2005), Komissarov (2005).
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\[
\begin{align*}
    r_{in} & \to \frac{6GM}{c^2} \quad a = 0 \\
    r_{in} & \to \frac{GM}{c^2} \quad a \to 1
\end{align*}
\]
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\[ a = 0.9981 \]
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Deep Minimum of MCG-6-30-15
XMM (Reynolds et al. 2004)
Iron lines broader than predicted from NT disk ⇒ Irradiation more centrally concentrated than NT prediction

Underlying disk is NT-like, but X-ray irradiation does not track local dissipation (need light bending)

Irradiation tracks a dissipation that is much more centrally concentrated than NT law
Gravitational light bending?

- Suppose X-ray source is base of a jet?
  - X-rays will be gravitationally focused onto central parts of disk
  - Can produce very centrally concentrated irradiation pattern!
  - Data suggest $h \sim$ few $GM/c^2$

- Geometry first discussed in Fe-K line context by Marttochia & Matt (1996)
- Applied to ASCA data for MCG-6-30-15 by Reynolds & Begelman (1997)
- Applied to XMM data for MCG-6-30-15 by Minuitti & Fabian (2004)
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Enhanced dissipation in central regions of disk?

- Recent work suggests importance of “torqued accretion disks”
  - Magnetic fields may lead to continued extraction of energy/ang-momentum of matter plunging within ISCO
  - Plunging matter exerts torque on rest of disk
  - Work done by torque dissipated in innermost regions of the disk

- In extreme case, this might produce a Penrose process and allow the BH spin to be tapped.


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Deep Minimum of MCG-6-30-15
XMM (Reynolds et al. 2004)
BLACK HOLE SPIN

• Importance of spin
  – Large energy store (upto 29% of rest mass energy)
  – Spin may retain memory of black hole formation
  – First step in testing Kerr metric

• Diagnose spin through its effects on the accretion disk structure
  – Major effect change in the location of the innermost stable circular orbit (ISCO)
If we assume no X-ray reflection from within the ISCO…

- For progressively more rapidly rotating BHs…
  - ISCO moves inwards to a higher gravitational redshift region
  - For given inclination, maximum redshift of iron line increases

- Applied to long (350ks) XMM dataset for MCG-6
  - Data strongly prefers rapidly spinning BH solution
  - $a = 0.95 \pm 0.04$

Brenneman & Reynolds, in prep
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THE PROMISE OF CONSTELLATION-X

- Constellation-X
  - Major component of NASA’s Beyond Einstein program
  - Imaging spectroscopy with superior spectral resolution and collecting area

- Allows study of short-term broad iron line variability
  - Dynamical timescale variability ⇒ trace orbits of distinct structures in disk
  - Light crossing timescale variability ⇒ follow echos of X-ray flares across disk
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Similar features from outer disk already hinted at by XMM-Newton NGC3516 (Iwasawa et al. 2004) & Mrk 766 (Turner et al. 2005)
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Reynolds et al. (1999)
Young & Reynolds (2000)
II : MASSIVE BLACK HOLES & MASSIVE GALAXY FORMATION

- Galaxy luminosity function
  - Suppressed at high and low luminosity end compared with simply $\Lambda$CDM predictions
  - High-L suppression must be more efficient than star formation

- Do AGN suppress high-end of galaxy LF?

Benson et al. (2003)
Intracluster medium (ICM) Hot ($10^7$-$10^8$K), tenuous (0.001-0.1cm$^{-3}$) plasma.

XMM-Newton observation of Virgo cluster Matsushita et al. (2002)

THE COOLING FLOW PROBLEM
The Λ87 Jet
How can AGN jets heat ICM isotropically?

Cocoon structure; Scheuer (1974)

Can heat isotropically by either shock heating or dissipation of sound waves

2-d hydro simulations
Reynolds et al. (2002)
Chandra observations of cooling-core clusters

- Cygnus-A
  Smith et al. (2002)

- Perseus-A
  Fabian et al. (2000)

- Hydra-A
  Nulsen et al. (2004)

- Abell 4059 / PKS2354-35
  Heinz et al. (2002)

- Virgo/M87
  Young et al. (2002)

Synopsis:
Jet-blown cavities common
“Ghost” cavities common
Strong shocks elusive!
Modeling the feedback loop

- Feedback model $\Rightarrow$ average AGN heating balances ICM cooling
- Analysis of ICM cavities shows that kinetic power and cooling luminosity are indeed related
- Nature must modulate AGN fueling according to ICM properties
- First attempts to model this…
  - Ideal hydro model of jet/ICM interaction
  - Jet power proportional to cooling flow rate
  - FAIL to produce successful balance

Also see McNamara (2000)
Does the “feedback” loop work?

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Delayed fueling scenario
Vernaleo & Reynolds, submitted

Runaway cooling in the equatorial regions
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What ingredients are missing from the feedback model?

- MHD and Plasma transport processes
  - Thermal conduction and Viscosity
  - Dissipation of wave energy
  - New instabilities of the ICM atmosphere
- Precession of the jet axis
  - Need to be quasi-isotropic on cooling timescale (few×10^8 yr)
- Dissipation of energy stored in global ICM modes?

Evidence for dissipation of sounds waves by thermal conduction (see Fabian, Reynolds et al. 2005)
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3C401 (Chandra and MERLIN cont.)
Reynolds, Brenneman & Stocke (2005)
Conclusions

• New era of black hole research
  – Detailed studies of black hole physics and relativistic accretion
  – Impact of black holes on galactic scale structure

• Strong gravity studies with XMM and Chandra
  – Robust signatures of strong gravity exist
  – Measurements of black hole spin and signs of interesting spin-related astrophysics
  – Constellation-X and LISA will bring tremendously exciting future

• Jetted AGN and cluster cooling flows
  – Puzzles; how are ICM cores being heated?
  – Need for more physics
The End
Iron line variability

Low flux data: Reynolds et al. (2004)
High flux data: Fabian et al. (2002)
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The way forward

- Better modeling
  - More physics (MHD, plasma processes)
  - Put in cosmological setting
- Better data
  - More deep Chandra observations
  - Direct kinematics from high-resolution X-ray spectroscopy (rebuild of Astro-E2?, Constellation-X)