Black Hole Astrophysics

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Why care about black holes?

- **Astrophysics**
  - BHs responsible for most extreme astrophysical sources in current-day universe
  - Might be central component of structure formation story

- **Physics**
  - Strong-field GR has yet to be tested! BHs provide prime opportunity to perform tests
  - New physics close to the event horizon?
Core of the Perseus cluster (Chandra)
Fabian et al. (2003)
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  - New physics close to the event horizon
  - Black Hole electrodynamics
Outline

- A brief primer on black hole accretion
- Why use X-rays?
  - We’re already probing up to the event horizon!
- Spectral studies – emission lines from inner disk
- Timing studies – oscillation modes of inner disk
- Accreting black holes and Beyond Einstein
I : A primer on accretion

- Accretion disk
  - The “engine” that converts
    \[ E_{\text{grav}} \rightarrow E_{\text{rad}} + E_{\text{kin}} \]
  - Accretion (angular mtm transport) driven by MHD turbulence
  - Can support B-fields that thread the black hole (stretched) horizon

- Efficiency (\( L=\eta \, dM/dt \))
  - Often high (\( \eta=10-30\% \))
  - Low (\( \eta <<1\% \)) in certain situations (low or high accretion rate)

Lynden-Bell (1969)
Shakura & Sunyaev (1973)
Novikov & Thorne (1974)
Pringle (1981)
Rees (1982)
Balbus & Hawley (1991)
Narayan & Yi (1994)
Rapid X-ray variability of AGN strongly suggests X-rays come from innermost regions of accretion disk

MCG-6-30-15
HST/WFPC-2

XMM-Newton 0.5-10keV light curve
(Fabian et al. 2002)
Relativistically broad and skewed emission lines from inner disk

(High-frequency) quasi-periodic oscillations in accreting stellar mass black hole systems
III : Spectral studies and broad X-ray emission lines

Iron line profile in MCG-6-30-15
(Tanaka et al. 1995)
X-ray “reflection” imprints well-defined features in the spectrum

Reynolds (1996)
Iron Kα fluorescence from the Sun

Iron fluorescence is a simple, well-understood, well-studied physical process!

Parmar et al. (1984)
Solar Maximum Mission
(Bent Crystal Spectrometer)
We observe very broad lines
- naïve interpretation gives velocities of 100,000 km/s
- Well fit by disk models
- Needs emission from very close to black hole (R~R_{Sch})
- Fe fluorescence ~6-7keV band and (possibly) O/N/C recombination emission (<1keV)

Can start doing strong-field gravitational astrophysics using these tools

MCG-6-30-15 from XMM-Newton
Continuum subtracted
Fabian et al. (2002)
Are these features robust?

- Calibration problems?
  - **NO!** Many well studied X-ray sources do not show such features.
- Problems with continuum subtraction?
  - Maybe broad line is just a curved continuum?
  - Maybe continuum suffers complex absorption?
  - What about broadening mechanisms?

- All of these effects are calculable and can be folded into the models we use to examine the data.
A portion of the June-2001 dataset for MCG-6-30-15
unfolded spectrum
Simple Power Law and accretion disk line

$\text{ph/cm}^2/\text{s}$

Energy (keV)
Maybe additional absorption from iron K absorption lines could make this work... fine tuning needed? Astro-E2 will assess this model.
A taster of the current field...

- See broadened emission lines in many (~25%) sources
- Find very broad lines in MCG-6-30-15 and GX339-4
- Assuming validity of GR, the need for rapidly-rotating black holes is unambiguous
- Very centrally concentrated pattern of X-ray illumination needed to produce such lines
  - Strong light bending effects? (Fabian, Minutti, Vaughan et al.)
  - Magnetic torquing of inner accretion disk by spinning black hole? (Wilms, Reynolds et al. 2001; Li 2001; Reynolds et al. 2004)
- Either way, we’re debating processes occurring within the inner 2-3GM/c²
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Accretion Luminosity

Dissipation of work done by torque at radius of marginal stability

MCG-6-30-15
Fit with a Novikov-Thorne/Page-Thorne disk
Fit with an Agol & Krolik torqued disk (need “infinite efficiency case)
Alternatively…
IV : High-frequency QPOs

- HFQPOs displayed by many accreting stellar-mass black holes
  - Moderate quality factors (Q~few-10)
  - Highest frequency QPOs > orbital frequency of non-rotating BH
  - Often come in pairs with approximate 3:2 ratio
- Quantitative probe of strong gravity regime…
  - Probably seeing the tip of a whole series of spectrum of QPOs
  - But need a model to get anywhere…

From review by McClintock & Remillard (2003)
“Diskoseismology”

- Attempts to understand HFQPOs in terms of normal modes of the accretion disk fluid
  - Resonant cavity formed by relativistic potential
  - g-, p-, and c-modes
  - Theoretically attractive

- No natural explanation in linear theory for the 3:2 ratio

E.g.
Nowak & Wagoner (1991, 1992)
Perez et al. (1997)
Silbergleit et al. (2001)
Wagoner et al. (2001)
Wagoner et al. (2001)
“Parametric resonance”

- Motivated by the 3:2 ratio of HFQPO frequencies
  - Parametric resonance between radial & vertical epicyclic frequencies
  - Expect 3:2 to be strongest resonance
- Precise nature of coupling or driving is not specified
- Two sets of 3:2 HFQPOs in GRS1915+105… can’t both be this parametric resonance?

Kluniak & Abramowicz (2001)
Abramowicz, Kluniak et al. (2004)
M82-ULX source (Strohmayer et al. 2003)
Evidence for an “intermediate-mass” scale BH?
MHD accretion disk simulation (Hawley & Krolik 2001)
V : Black Hole Astrophysics & NASA’s Beyond Einstein

- Future X-ray component of BE is a crucial complement to gravitational wave studies
  - BHFP (EXIST/CASTOR), Con-X and BHI (MAXIM)
- Growth of black holes in the universe
  - Occurs primarily through efficient accretion (Soltan)
- Behavior of matter close to black hole
  - Plasma/particle physics of accretion flows
  - BH electrodynamics (Blandford-Znajek/Penrose mechanisms)
- Strong gravity
  - Quantitative tests of strong-gravity (Kerr metric) using well known types of sources
  - Easy to see deviations from GR (comparatively trivial template fitting)
High throughput spectroscopy
Constellation-X

- Proposed launch NET2016
- Soft X-ray Telescope
  - Microcalorimeter
  - ~5-10 arcsec FWHM
  - 0.25-10 keV band
  - Large effective area and excellent spectral resolution
- Gratings
  - V. high soft X-ray resolution
- Also, focusing hard X-ray telescope (up to 40-60keV)

The Constellation-X Observatory (NASA)
Iron line variability

- Con-X (XEUS) will allow detailed study of line variability
- See effects of non-axisymmetric structure orbiting in disk
  - Follow dynamics of individual “blobs” in disk
  - Quantitative test of orbital dynamics in strong gravity regime

Non-axisymmetric structure may have been seen already...

Chandra-HETG data on NGC3516 (Turner et al. 2002)

Simulation results for inclination of 20 degs (summed over 2 full orbits)

A prime science target for Astro-E2
Relativistic iron line reverberation...

- Reverberation
  - X-ray source displays dramatic flares
  - Flare produces “X-ray echo” that sweeps across accretion disk
  - Iron line profile will change as echo sweeps across disk
  - Needs high throughput spectroscopy – but likely within reach of Con-X

CSR et al. (1999)
Young & CSR (2000)
Sensitive probe of strong gravity
- Get inward and outward propagating X-ray echoes
- Inward propagating echo is purely a relativistic effect
- Inward propagating echo gives red-bump on the iron line profile
- Precise properties of red-bump are probe the Kerr metric (and allow measurement of BH spin)

Side note… we already know that situation is not simple;
- Current data suggest complex ionization changes associated with variability
- Need hard X-ray capability of Con-X to deconvolve effects of disk ionization in a realistic spectrum.
Reynolds et al. (1999)
Constellation-X simulations
The Black Hole Imager
Micro-arcsecond X-ray Imaging Mission (MAXIM)

HST (0.1 arcsec)

MAXIM (0.05 µ-arcsec)
Current MAXIM concept

Group and package Primary and Secondary Mirrors as “Periscope” Pairs

- “Easy” Formation Flying (microns)
- All s/c act like thin lenses - Higher Robustness
- Possibility to introduce phase control within one space craft - an x-ray delay line - More Flexibility
- Offers more optimal UV-Plane coverage - Less dependence on Detector Energy Resolution
- Each Module, self contained - Lower Risk

See talk by W.Cash this afternoon.
GR-MHD simulations by Hirose, Hawley & Krolik (2003)
Conclusions

- Have been dramatic observational and theoretical advances in our understanding of accreting black holes over past decade
- Spectral and timing X-ray observations are already probing region in immediate vicinity of accreting stellar & supermassive black holes
- X-ray astronomy is on the verge of realizing its ultimate promise (BHFP, Con-X, and BHI/MAXIM)
  - Probe of **BH growth** back to cosmic “dark ages”
  - Constraints on **strong field gravity**
  - Detailed understanding of **BH accretion**
  - Accessed through high-throughput spectroscopy (Con-X), and direct imaging (BHI)