X-ray Spectral timing of Accreting Black Holes

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STRONG GRAVITY

• Gravitational redshift ✔️

• Strong Light Bending (radian scale) ✔️

• Shapiro delay ✔️

• Dragging of Inertial Frame ✔️
SCHEMATIC SED

keV$^2$ (Photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$)

Energy (keV)

Opt  UV  X-ray
keV² (Photons cm⁻² s⁻¹ keV⁻¹)

Energy (keV)

DISK

X-ray

CORONA

Opt

UV
Direct Power-law → To observer

"Reflection" spectrum

Accretion disc
Reflection from cold matter of cosmic abundance

C Reynolds
Reflection from ionized gas Ross+Fabian05; Garcia+13
Relativistically Broadened Line

- Newtonian
- Special relativity
- General relativity
- Line profile

Transverse Doppler shift
Beaming
Gravitational redshift

Photon/cm² s keV

6m–30m

Schwarzschild
Kerr disk

Fabian+89, Laor 90...
Probing Black Hole Spin

No spin

Max spin

Brennemann+Reynolds08

Energy

Flux
Direct Power-law

To observer

Corona

“Reflection” spectrum

Accretion disc
Reflection spectrum

relativistic blurring

Soft excess – broad iron line – Compton hump
SWIFT J2127.4+5454

Marinucci+14

XMM+NuSTAR

a=0.58
Soft excess – broad iron line – Compton hump
and Galactic sources too

Parker, Tomsick+, JMiller+13,15
Strong light bending close to BH

Martocchia & Matt, Miniutti & Fabian

GR + lightbending make emissivity steep
Change in height of corona - more or less light bending
High Reflection Fractions  
= Strong Light Bending

Dauser+14
Black Hole Spin from Reflection Spectrum

Reynolds14, Vasudevan+15
50% OF POWER FROM WITHIN 5 $R_G$
Brightest objects seen should be high spin.
Observed distribution consistent with uniform spin distribution above $a=0.4$
High spin objects can dominate XRB

Vasudevan+15
X-ray Background Spectrum

\[ E^2 N(E) \text{ (keV}^2\text{s/cm}^2\text{/keV)} \]

- \( h = 2 R_g \)
- \( h = 3 R_g \)
- \( h = 10 R_g \)
- \( h = 100 R_g \)
- direct power-law
- X-ray background

Energy (keV)
Direct Power-law \rightarrow \text{To observer} \\

Path difference leads to \textit{reverberation}
Broad iron-L and iron-K emission lines (XMM)

Reflection dominated

Power-law dominated

Fabian+09
Powerlaw leads reflection: Reverberation
High frequency lag shows iron,
So is reverberation.

Low frequency lag
featureless so
NOT reverberation.

Akn564
Kara+13
High frequency lag shows iron so IS reverberation

Low frequency lag featureless so NOT reverberation

Akn564
Kara+13
Fe K lags
42 sources
13 published
8 new
Kara+16
Corona is compact

Need to understand anisotropy of corona in order to improve precision on strong gravity
Coronal Size from Microlensing: Coronae are Compact
Emissivity profiles enable coronal height and radius to be determined

Wilkins+Fabian12
Outflowing Corona

Mild relativistic outflow in corona can beam primary radiation outward
Mkn335

Wilkins+14
Rise of corona can explain 3.5 keV dip

Wilkins+16
Coronal Collapse

When \( h \) drops from 10 to \( 2r_g \)
Into the Abyss

NuSTAR

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

Energy (keV)

1H0707-495  Kara+14
July 2014
May 2014

ratio

Energy (keV)

July 2014
May 2014

1H0707 Kara+14
Mkn 335  Parker+14
Most emission from $1-2r_g$

IRON LINE

COMPTON HUMP

Mkn 335  Parker+14
Results from within 2 $r_g$
Relativistic Reflection is a common feature of luminous accreting black holes.

Spectral-timing analyses reveal inner strong gravity regime.
Relativistic Reflection is a common feature of luminous accreting black holes.

Strong gravitational effects (redshift, light bending etc) are INEVITABLE.
The Near Future

• VERY LONG (Ms) observations of Key Objects will study dynamic behaviour of corona

• Launch of ASTRO-H (scheduled for Feb 12 2016)
IRAS13224-3809 - Example of a key object
STRONG GRAVITY

- Gravitational redshift ✔
- Strong Light Bending (radian scale) ✔
- Shapiro delay ✔
- Dragging of Inertial Frame ✔

Red wing
Reflection Strength
Reverberation
High Spin
Summary

• We’re now doing Relativistic Astrophysics of the immediate region around accreting black holes – the central engine of quasars.

• Quasars are the most luminous persistent sources in the Universe and, through feedback, determine the final stellar mass of galay bulges
2D transfer function

Cackett+13

\[ h = 10 \text{ RG}, \]
\[ i = 45 \text{ deg}, \]
\[ a = \text{max} \]
SPIN

Luminosity X 5
Density

Azimuthal field

Reynolds & Fabian 08
Assume illumination by source on symmetry axis of accretion disk at \( D_s = 6r_g \)

\[
\xi \equiv \frac{4\pi F_i}{n_{ph}} = 122 \left( \frac{h/r}{0.1} \right) \left( \frac{D_s}{r} \right) \left( \frac{\tau_e}{10^3} \right)^{-1} \left( \frac{r}{10 r_g} \right)^{-1} \left( \frac{L_i}{L_{Edd}} \right) \left( \frac{n_{ph}}{n_{ph}} \right) \frac{\langle n \rangle_{\text{erg cm s}^{-1}}}{\text{erg/s/cm}^2}
\]
Relativistic Disc Lines are a common feature of luminous accreting black holes

With NuSTAR now considering second order effects
Microlensing shows that Corona is compact.
1H0707-495  Fabian+12

![Graph showing Normalised count rate (0.5-10 keV, ct s⁻¹) vs Modified Julian Date](image-url)
Reflected flux

XTE J1650-500  Reis+12

Flux_{\text{RefionX}} (\text{erg} \text{s}^{-1} \text{cm}^{-2})

See also Rossi+05

Flux_{\text{Powerlaw}} (\text{erg} \text{s}^{-1} \text{cm}^{-2})

Powerlaw flux
XTE J1650-500 Reis+12

Reflected flux

Powerlaw flux

Intrinsic change

Light Bending Effect

See also Rossi+05
$h = 10.0 \text{ GM}/c^2, \quad i = 60.0^\circ, \quad \text{ISCO} = 6.0 \text{ GM}/c^2$

$\tau = 0.00 \text{ GM}/c^3$

Cackett13
Walton+14
The *NuSTAR* spectrum of Mrk 335: Extreme relativistic effects within 2 gravitational radii of the event horizon?

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Rapid variability in AGN
CORONAL PHYSICS

\[ \frac{L \sigma_T}{R mc^3} \]

compactness

\[ \frac{kT}{m_e c^2} \]
temperature

\[ e^-e^- \text{ coupling} \]

\[ e^-p \text{ coupling} \]

\[ t_B = t_C \]

Fabian+15

Svensson 1984

Stern 1995
Corona lies a few $r_g$ above the disc
Low frequency lag featureless so NOT reverberation

High frequency lag shows iron so reverberation

Akn564
Kara+13
WINDS and OUTFLOWS
X-ray

Optical

Morgan+12
Broad iron-L and iron-K emission lines (XMM)

Fabian+09