Black Hole Binaries

What are BHC?, II

Stars end their life as one of three kinds of different compact objects:

White Dwarf: $\rho \sim 10^5 \ldots 10^6\,\mathrm{g\,cm^{-3}}$, $R \sim R_\oplus$, Equilibrium between gravitation and pressure from degenerate electrons, $M < 1.44\,M_\odot$ (Chandrasekhar-limit).

Neutron Star: $\rho \sim 10^{13} \ldots 10^{16}\,\mathrm{g\,cm^{-3}}$, $R \sim 10\,\mathrm{km}$, this density causes inv. β-decay ($\mathrm{p} + \mathrm{e}^- \longrightarrow \mathrm{n}$), i.e., star consists (mainly) of neutrons. $1.44\,M_\odot < M \lesssim 3\,M_\odot$ (Oppenheimer-Volkoff limit).

Black Hole: For $M \gtrsim 3\,M_\odot$ no stable configuration known

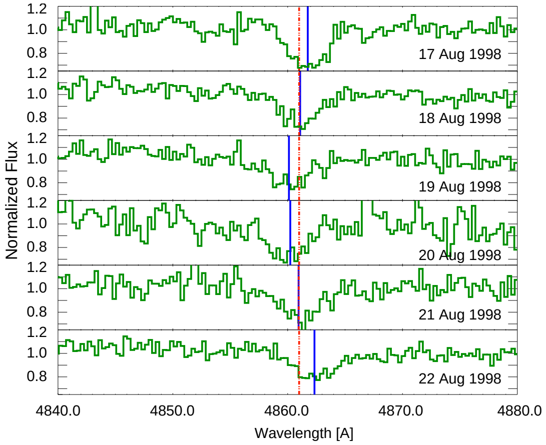
$\Longrightarrow$ Star collapses completely

$\Longrightarrow$ Black Hole

Size scale: $R_\mathrm{S} = 2GM/c^2 = 3(M/M_\odot)\,\mathrm{km}$

$\boxed{\text{If mass of compact object } M > 3\,M_\odot\text{: Black Hole Candidate}}$

What are BHC?, IV



Motion of the Hβ line in HDE 226868/Cyg X-1 (Pottschmidt, Wilms)

In binary system: Determine mass of compact object using Kepler's 3rd Law

$$\frac{a^3}{P^2} = \frac{G(M_1 + M_2)}{4\pi^2}$$

(a: semi-major axis, P: period, $M_{1,2}$: Masses).

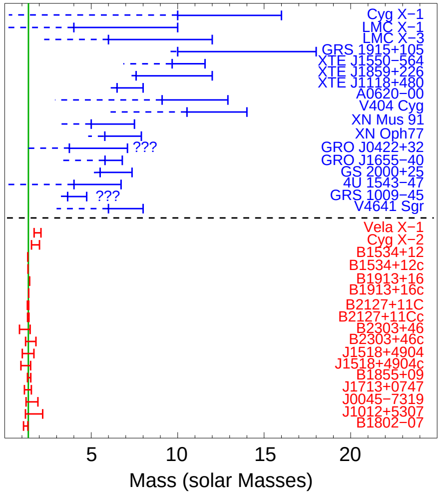
Derive from this the mass function

$$\mathrm{MF} = \frac{M_2^3 \sin^3 i}{(1 + (M_1/M_2))^2} = \frac{K_1^2 P}{2\pi G}$$

MF is lower mass for M_2.

(K_2 : velocity amplitude)

What are BHC?, V



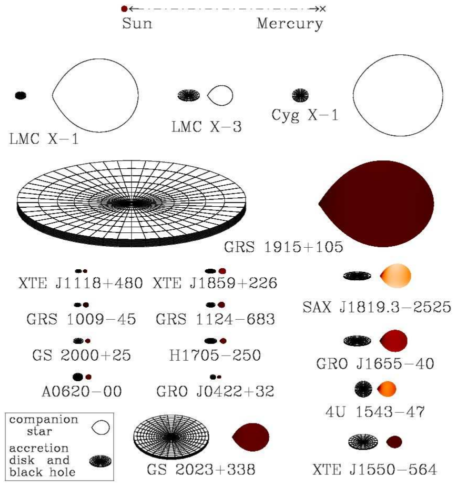
after Orosz (2004, priv. comm.)

- 1971: First BHC (Cyg X-1)
- 1983: LMC X-3
- Currently 20 dynamically confirmed Galactic Black Holes

Statistics:

- 3 High Mass X-ray Binaries
- Low Mass X-ray Binary BHC: mainly transient sources
- Masses $< 20\,M_\odot$

What are BHC?, VI



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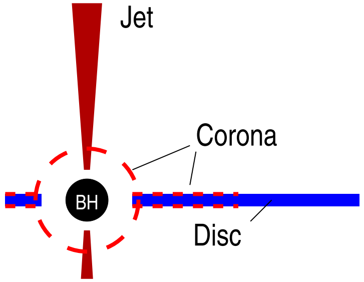
Orosz (2004, priv. comm.)

Current Questions



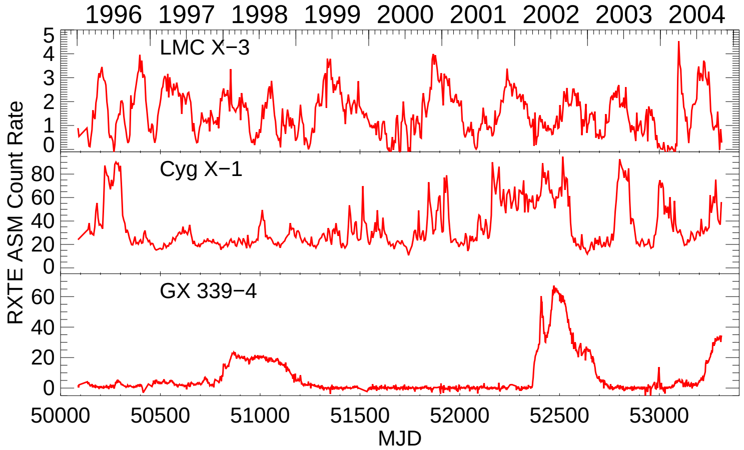
What we want to learn:

1. What does the accretion region look like: “accretion geometry”
2. What are the physical processes responsible for the broad-band emission?
3. Is there evidence for GR effects?

Active Galactic Nuclei and BHC have similar geometry $\Longrightarrow$ study similar physical processes!

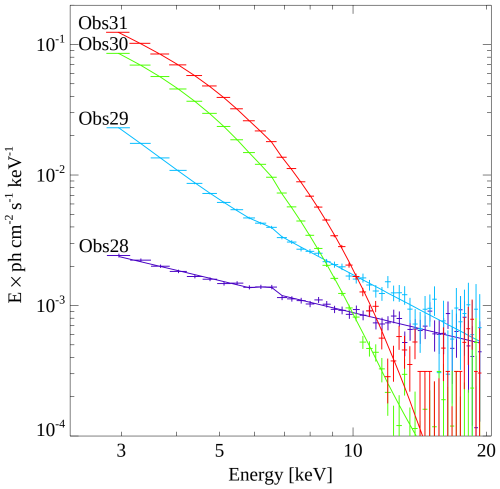
X-rays produced close to event horizon, observations give *one of the few constraints* to study physics in the strong gravitational field limit.

Long-Term Evolution



Black Holes: Variability on all time scales

Spectral States

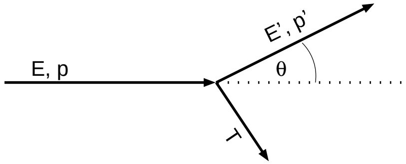


X-ray States:

- $L_\mathrm{X} \gtrsim 0.05\,L_\mathrm{Edd}$: soft state/high state:
  - thermally dominated
  - low variability (few percent rms)
- $L_\mathrm{X} \lesssim 0.05\,L_\mathrm{Edd}$: hard state/low state:
  - power law spectrum,
  - high variability (few 10 percent rms)

(LMC X-3; Wilms et al., 2001)

Hard State: Comptonization



Sunyaev & Trümper (1979): power law continuum caused by Comptonization

Frame of rest of electron: Photon's energy change due to Compton scattering:

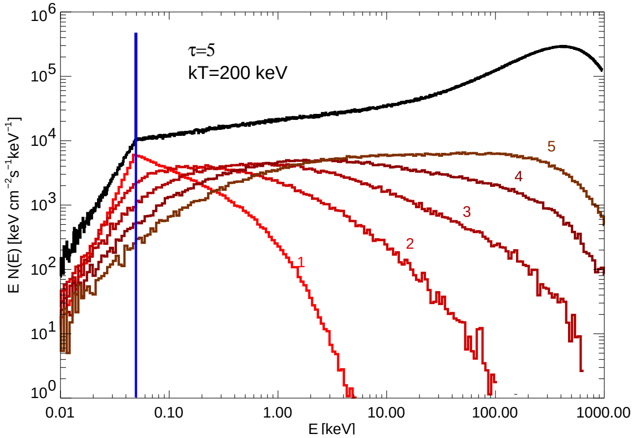
$$E' = \frac{E}{1 + \frac{E}{m_\mathrm{e}c^2}(1 - \cos\theta)} \quad \text{, for } E \ll m_\mathrm{e}c^2\text{:} \quad \frac{\Delta E}{E} \sim -\frac{E}{m_\mathrm{e}c^2}$$

If electron not at rest: energy transfer onto photon possible.

For thermal electrons:

$$\frac{\Delta E}{E} \sim \frac{4kT_\mathrm{e} - E}{m_\mathrm{e}c^2}$$

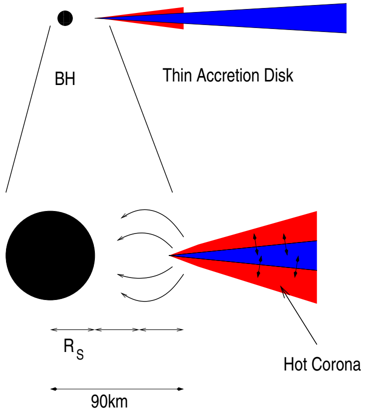
Hard State: Comptonization

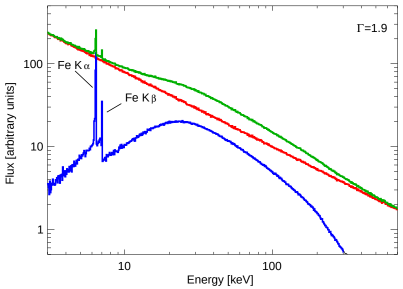


Computation of spectrum either through solution of Kompaneets equation or directly through Monte Carlo simulation

$\Longrightarrow$ Power law with exponential cutoff.

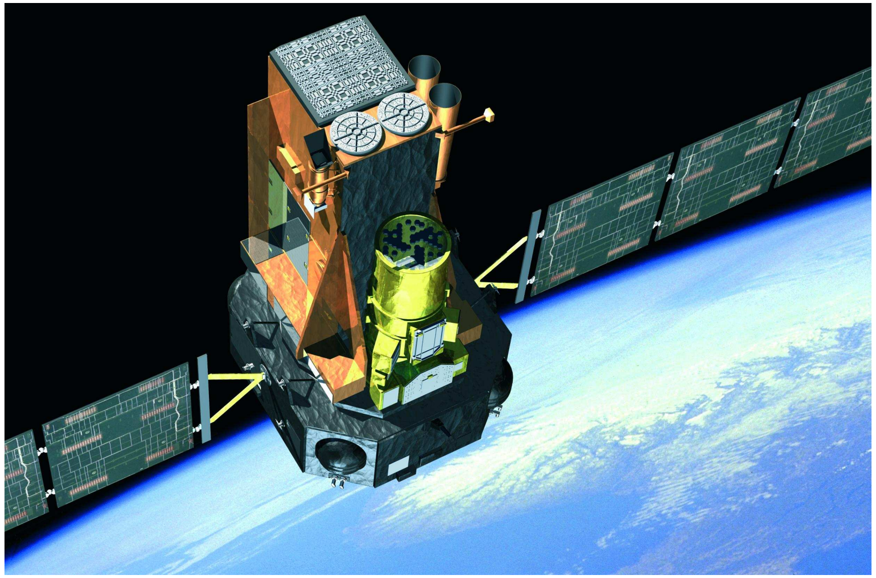
Hard State: Comptonization





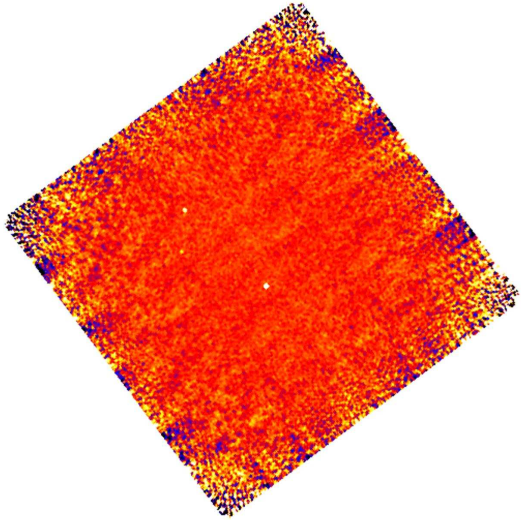
Black Hole X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.
- Thomson scattering of power law photons in disk: Compton Reflection Hump
- Photoabsorption of power law photons in disk: fluorescent Fe Kα Line at ~6.4 keV

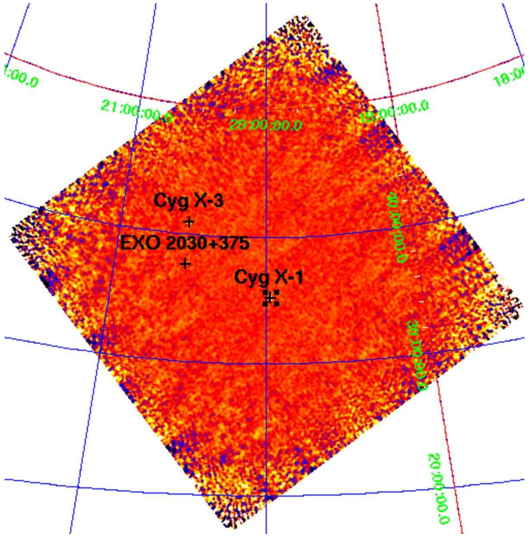


INTEGRAL

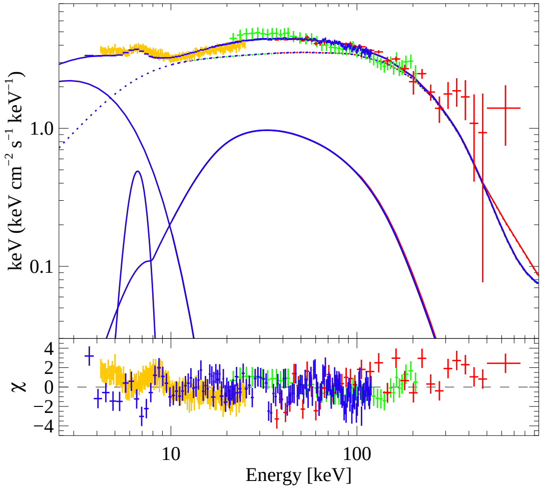
Broad Band Spectrum, II



Broad Band Spectrum, III



Broad Band Spectrum, IV

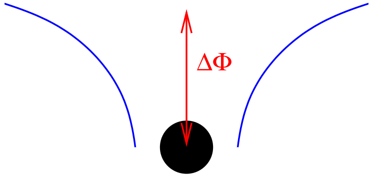


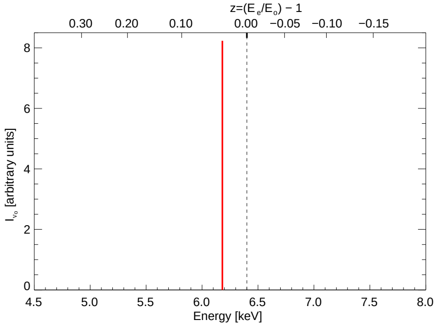
Fritz et al. (2006)
see also Pottschmidt et al. (2003)

Fit of Comptonization model to *RXTE*/*INTEGRAL*.

$kT_{\text{max}} = 1.21$ keV,
$\tau_{\text{p}} = 1.01$,
$\ell_{\text{h}}/\ell_{\text{s}} = 2.70$,
$\ell_{\text{nt}}/\ell_{\text{th}} = 0.05$,
$\Omega/2\pi = 0.3/2$
$\chi^2/\text{dof} = 466/348$

Relativistic Lines

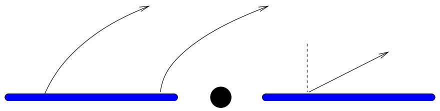


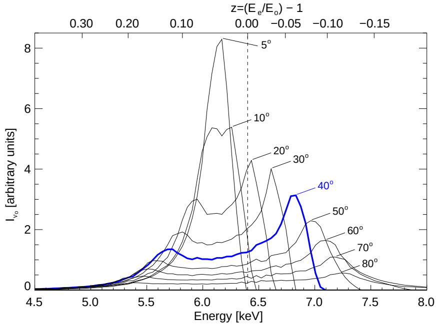


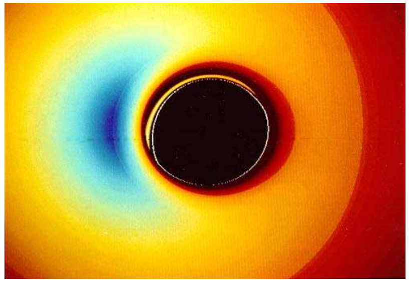
Total observed line profile affected by

- grav. Redshift

Relativistic Lines



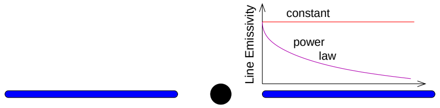


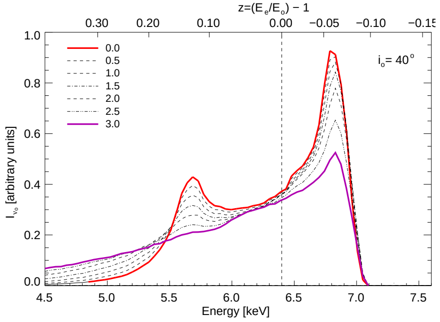


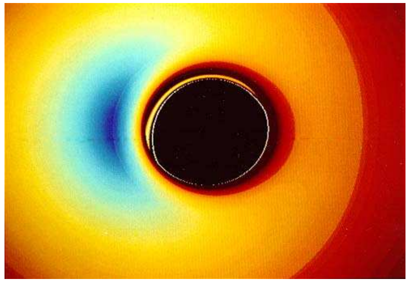
Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift

Relativistic Lines



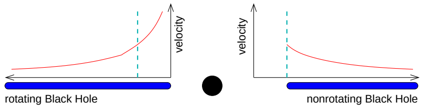


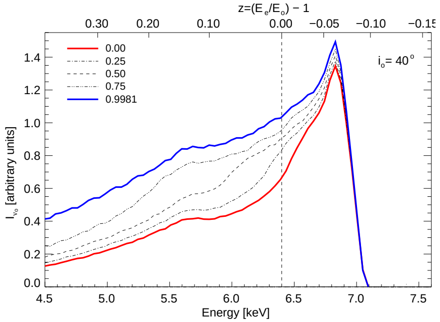


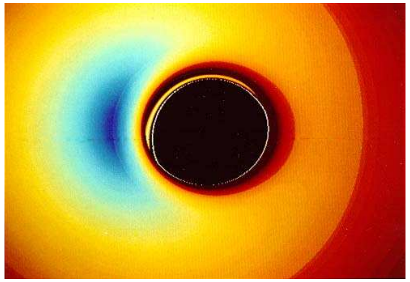
Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift
- emissivity profile

Relativistic Lines





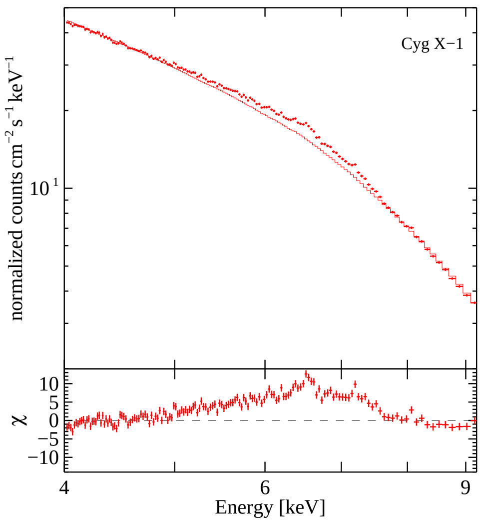


Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift
- emissivity profile
- spin of black hole

XMM-Newton

Relativistic Lines



Wilms et al. (2006)

XMM-Newton Observation of Cyg X-1: Power-law fit to $E \leq 5$ keV and $E \geq 8$ keV: strong residuals in Fe Kα region

uses a modified timing mode of the EPIC-pn camera on *XMM-Newton*; inner 3 CCD columns ignored because of pile-up

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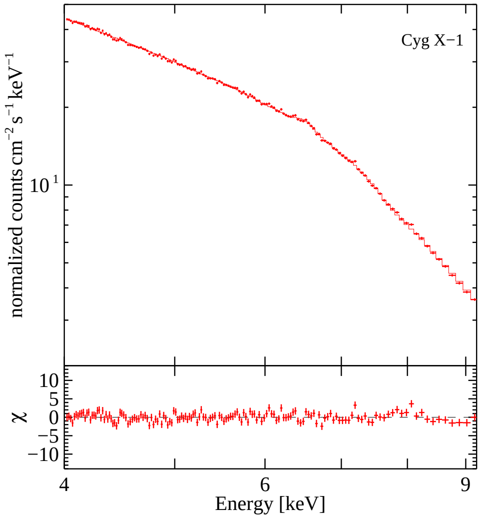
Relativistic Lines



Wilms et al. (2006a)

4–9 keV spectrum: well explained ($\chi^2_{\text{red}} = 1.3$) with:

- Power law

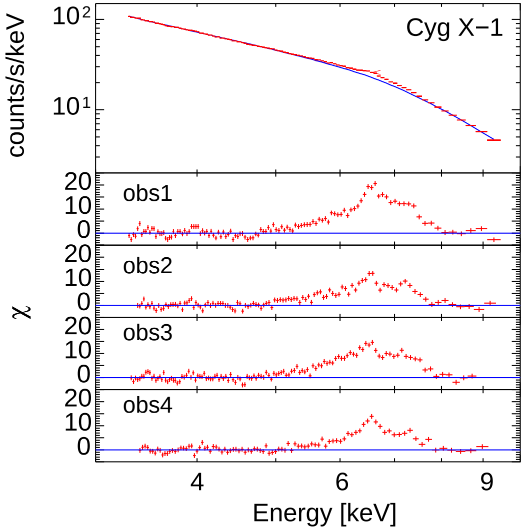
  $\Gamma = 1.90 \pm 0.01$
- narrow line

  $E = 6.52 \pm 0.02$ keV,
  $\sigma = 80 \pm 35$ eV,
  EW=14 eV
- relativistic line (Kerr)

  $E = 6.76 \pm 0.1$ keV,
  emissivity $\propto r^{-4.3\pm0.1}$,
  EW=400 eV

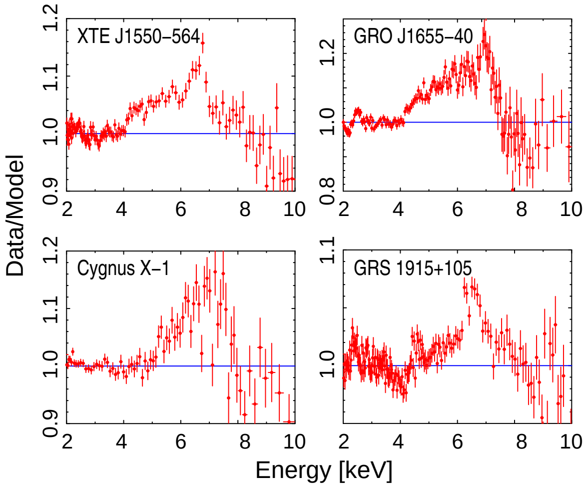
Parameters similar (but not equal) to *Chandra* intermediate state observations (Miller et al., 2002)

Relativistic Lines



Cyg X-1 (*XMM-Newton*, EPIC-pn modified timing mode, 10–20 ksec each)
(Fritz et al., 2007)

Relativistic Lines



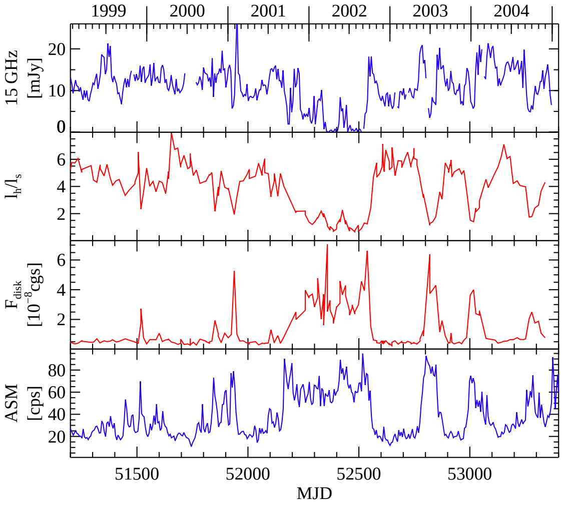
Relativistic lines are seen in many Galactic Black Holes

- GX 339−4: Nowak, Wilms & Dove (2002), Miller et al. (2004)
- GRO J1655−40: Bałucińska-Church & Church (2000)
- Cyg X-1: Miller et al. (2002), Fritz et al. (2007)
- XTE J1650−500: Miller et al. (2002)

. . . and a few more

(*Chandra*; after Miller 2007)

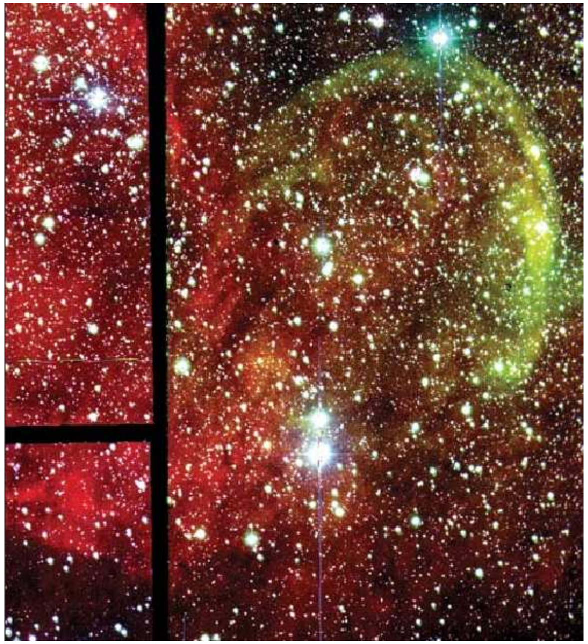
Hard State Monitoring



Cyg X-1 (Wilms et al., 2006b)

Never before have BHC been studied with such good coverage and over such a wide energy range.

Compare to pre-RXTE: 1–2 pointings per year!

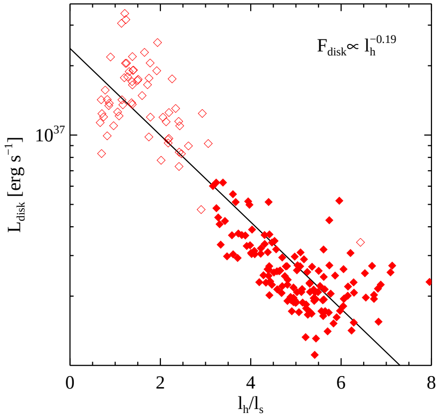


(Maccarone & Koerding, 2006, Figure by D. Russell)

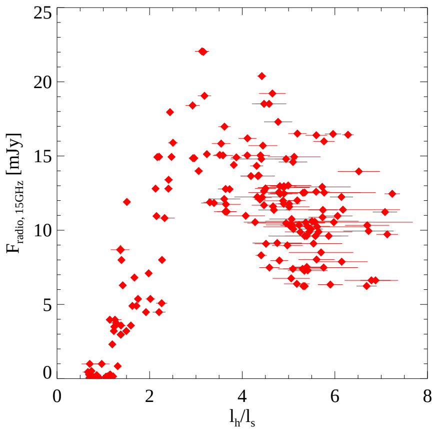
Gallo et al. (2005): Galactic black hole jets can be comparable in power to their X-ray luminosity.

Russell et al. (2007)
For Cyg X-1, $L_{\text{jet}} = 0.3 \ldots 1.0\, L_{\text{X}}$.

Hard State Monitoring

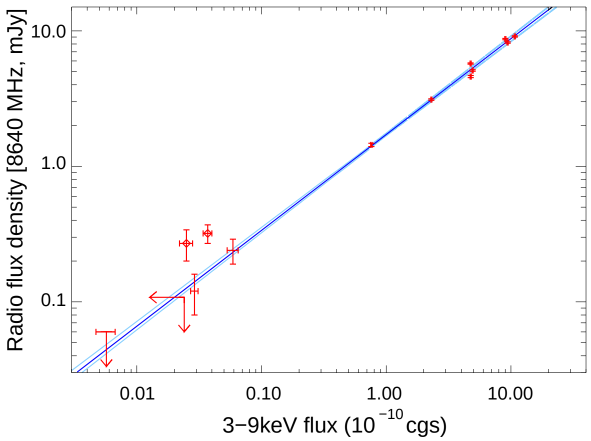


Clear anticorrelation between accretion disk luminosity and coronal compactness ratio, ℓ_h/ℓ_s.



Radio flux is strongest during intermediate states.

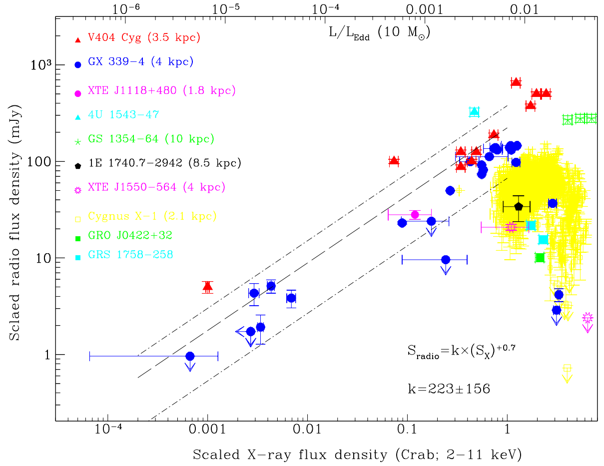
Radio–X-ray connection



Corbel et al. (2003): GX 339−4: During the hard state, there is a clear correlation between X-ray flux and radio flux: $F_{\text{radio}} \propto F^{0.71}_{\text{X, 3–20 keV}}$.

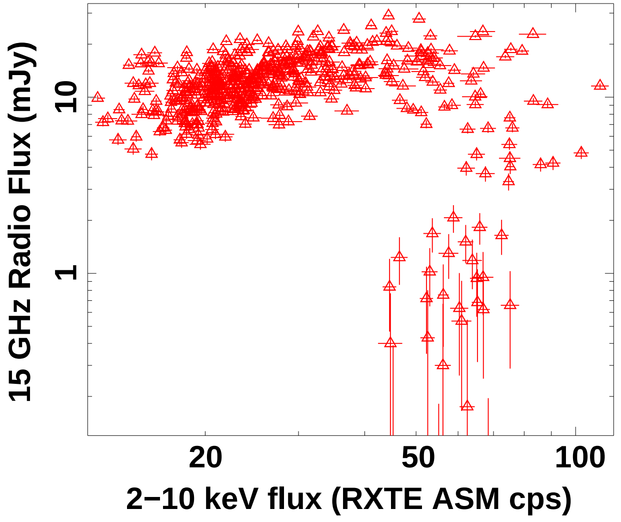
See also Hannikainen et al. (1998), Markoff et al. (2003).

Radio–X-ray connection



Gallo, Fender & Pooley (2003): $L_{\text{radio}} \propto L_{\text{X}}^{0.7}$ also works for sample of GBHs, although there is more scatter (and Cyg X-1 does not work at all).

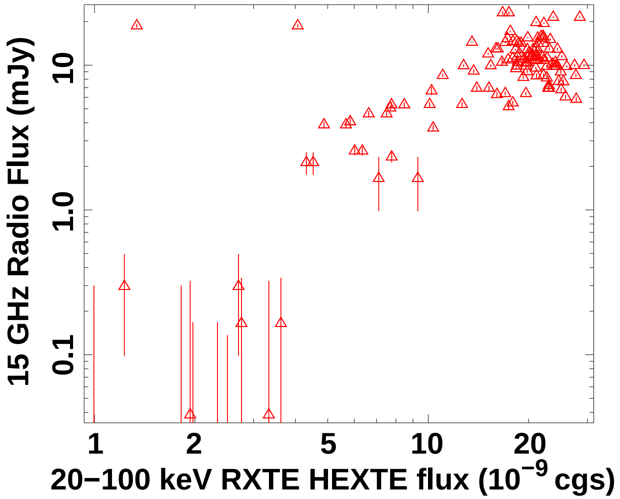
Radio–X-ray connection



Cyg X-1: there is no clear correlation between radio and X-rays in 2–10 keV!

(Nowak et al., 2005)

Radio–X-ray connection



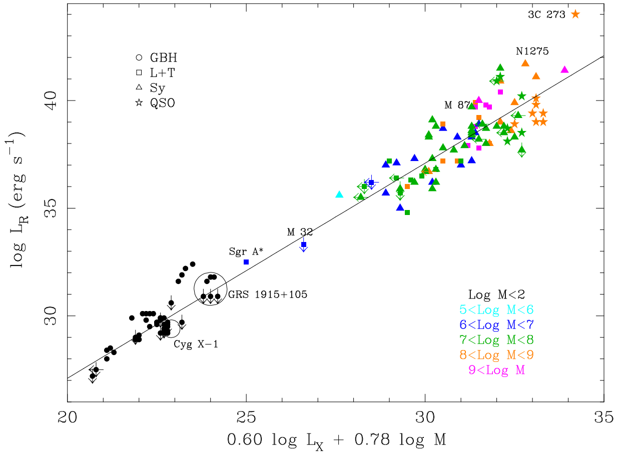
Cyg X-1: there is a clear correlation between radio and X-rays in 20–100 keV.

⟹ Jet is related to whatever makes the hard spectral component

Not surprising, but illustrates the danger of ignoring pointed observations and only using *RXTE*-ASM.

(Nowak et al., 2005)

Radio–X-ray connection



Merloni, Heinz & di Matteo (2003): for scale-invariant jets (Heinz & Sunyaev, 2003), jet properties only depend on M_{BH}, $\dot{M}$ (, and a).

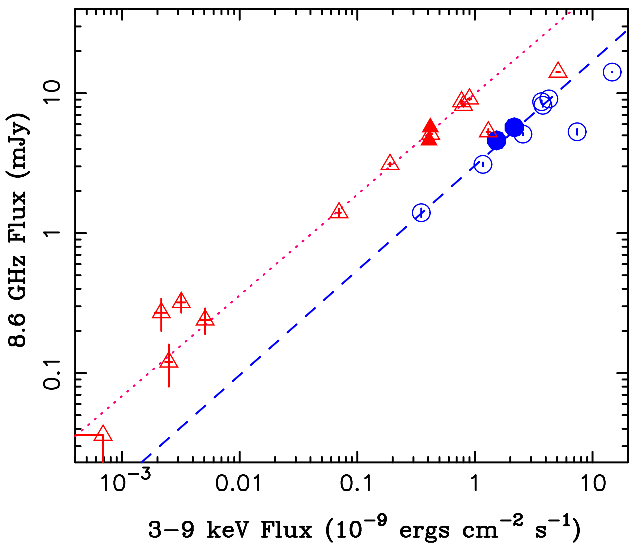
⟹ scatter due to varying black hole mass

⟹ "the fundamental plane of black holes" between L_{X}, L_{radio}, and M_{BH}.

see Falcke, Körding & Markoff (2004) for similar results

$$\log L_{\text{radio}} = (0.60 \pm 0.11) \log L_{\text{X}} + (0.78^{+0.11}_{-0.09}) \log M_{\text{BH}} + 7.33^{+4.05}_{-4.07}$$

Radio–X-ray connection

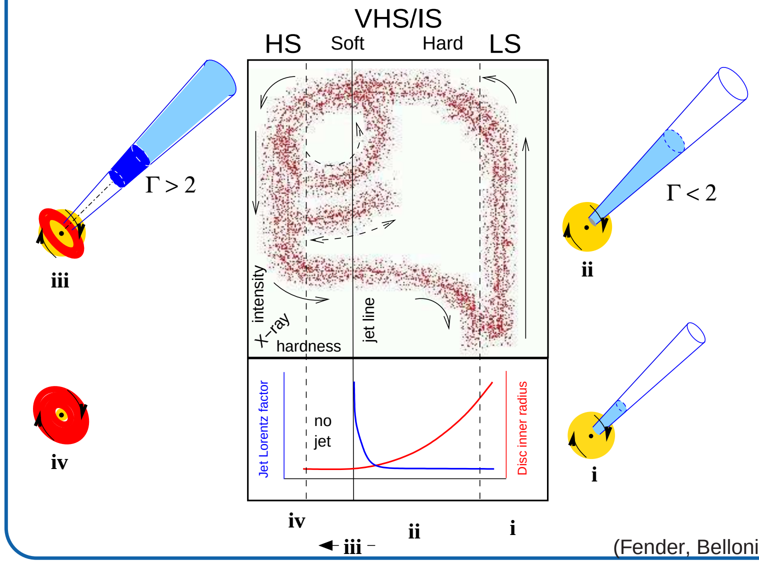


But note: while generally $F_{\text{radio}} \propto F_{\text{X}}^{0.7}$, normalization constant *can* change between outbursts of the same object!

In addition, there are four more hard state BHC that are also underluminous in the radio wrt. to the correlation, see Gallo (2007), see also Xue & Cui (2007).

(GX 339−4; Nowak et al., 2005)

Radio–X-ray connection



(Fender, Belloni & Gallo, 2004)