X-ray Quasi-Periodic Oscillations from Black Hole Binary Systems

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Outline

- Introduction
- X-ray States ←→ QPOs
- Properties of Low-Frequency QPOs (LFQPOs)
- Properties of High-Frequency QPOs (HFQPOs)
- Obs. Challenges for Jet Theory and GR MHD
- The Future?

Science Goals for BHBs in Outburst

- **Locate stellar size black holes**
  100% from X-ray astronomy
- **Measure Black Hole Properties ← QPOs**
  mass (M_x) and spin ($a_* = cJ / GM_x^2$) ; event horizon ?
- **Understand Accretion Physics ← QPOs + broad peaks**
  different physical structures in each state ; jets
  primary variables: M_x ; a_* ; θ_{disk}; *dM/dt* ; outflow; global *B*; plasma β ?

Recent Reviews and global studies:

McClintock & Remillard 2003;
Fender 2003; Fender & Belloni 2004;
Charles & Coe 2003;
Done & Gierlinski 2003
Zdziarski & Gierlinski 2004
van der Klis 2004

Inventory: Black Hole Binaries

Dynamical BHBs: Measure radial velocities of companion: K, P_{orb}

$$P_{orb} K^3 / 2\pi G \;=\; M_x \sin^3(i) / (1 + M_c/M_x)^2 \;>\; M_x$$

→ M_x = 4 - 18 M_o (> 3 M_o neutron star limit)

BH Candidates: no pulsations + no X-ray bursts + properties of BHBs

	Dynamical BHBs	BH Candidates
Milky Way	18	21
LMC	2	0
-------------------	--------	--------
total	20	21
X-ray Transients	**17**	**20**
RXTE Archive	**3300 obs; 12 Msec**	**1400 obs; 5 Msec**

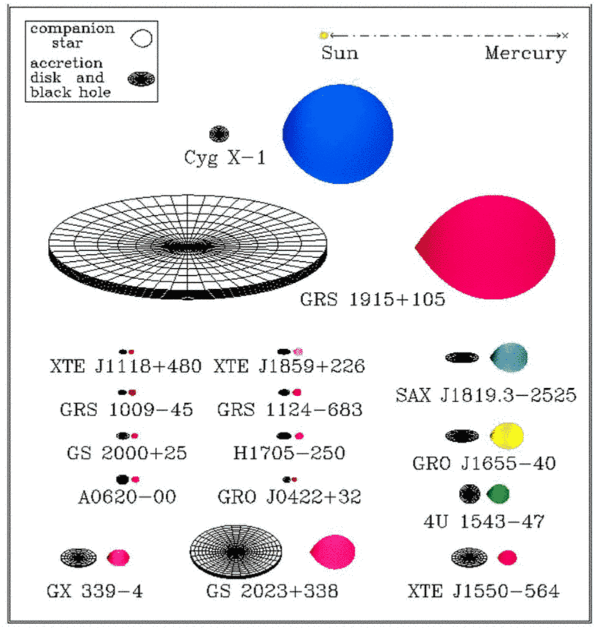
Black Holes in the Milky Way

18 Black-Hole Binaries in the Milky Way

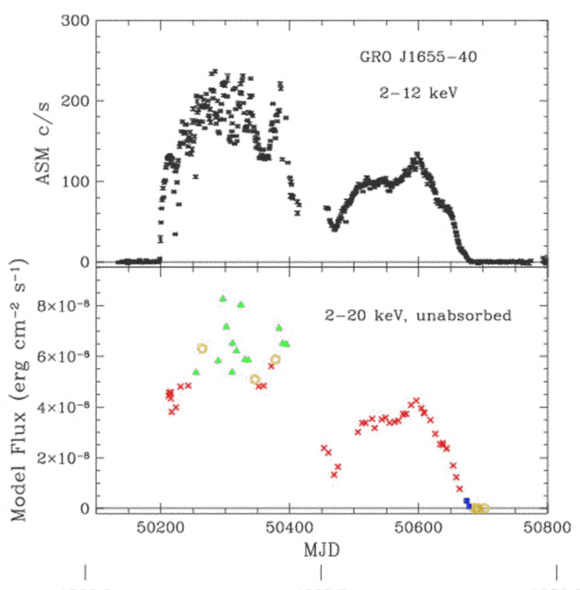
16 fairly well constrained →

(Jerry Orosz)

Scaled, tilted, and colored for surface temp. of companion star.



BH X-ray Transients



GRO J1655-40

$M_x = 6.3 \pm 0.5\ M_o$

Outbursts: 1994-95 + jets ; 1996-97, radio-quiet ; new outburst 2005

Define X-ray States

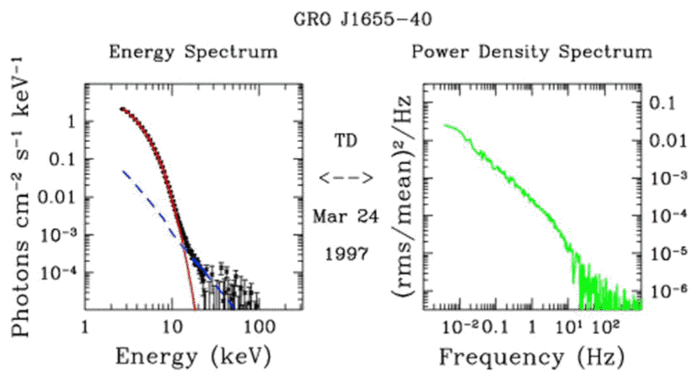
X-ray Spectra (thermal + power-law)

Power Density Spectra (power continuum & QPOs)

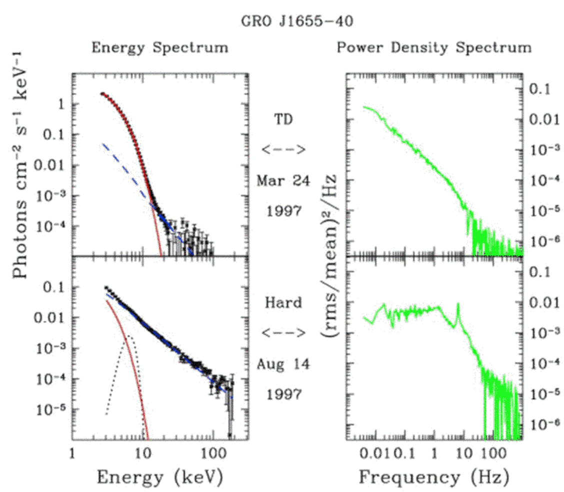
Active Accretion States of BHBs

1. Thermal State: f_{disk} > 75%; *rms* < 0.075 ; no QPOs (a_{max} < 0.5%)

inner accretion disk classical physics: $T(r) \sim r^{-3/4} \rightarrow L(r) \sim r^{-2}$



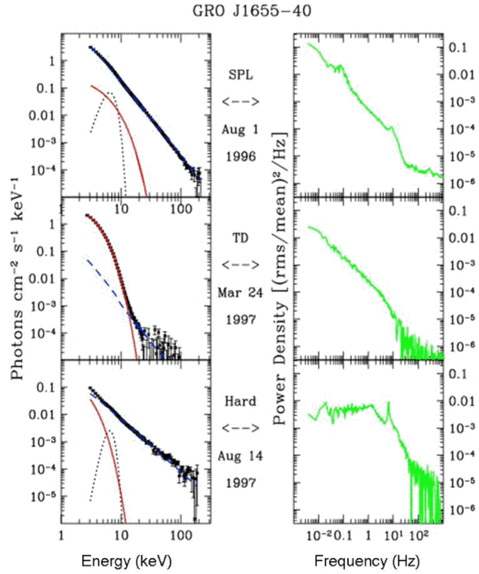
Active Accretion States of BHBs



2. Hard State f_{disk} < 20%; $\Gamma \sim$ 1.4 - 2.1; *rms* > 0.10

steady jet (inverse Compton or synchrotron ??)

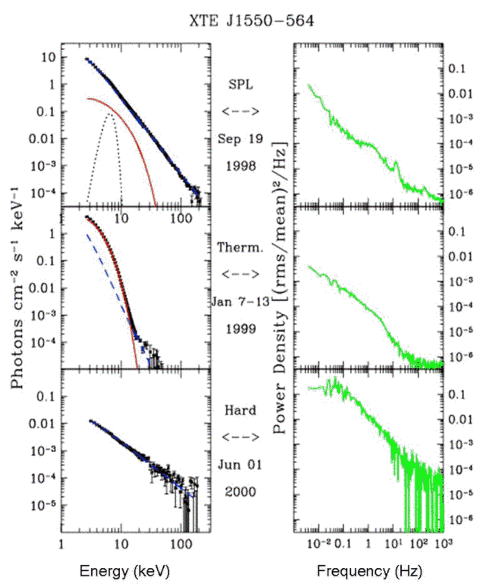
Active Accretion States of BHBs

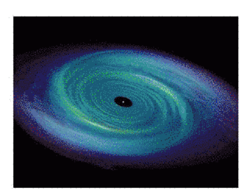
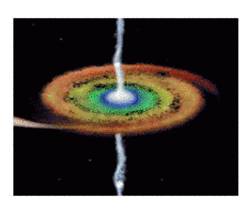


3. steep power law **compact corona**

$\Gamma > 2.4$; *rms* < 0.15 ; $f_{disk} < 80\%$ + QPOs
(or $f_{disk} < 50\%$)

Physical Models for BHB States



State	physical picture
➔ steep power law	Disk + ??
➔ thermal	
➔ hard state	

Features in X-ray Power Spectra

QPOs ($Q = \nu_0$ / FWHM > 2)

High Frequency (40-450 Hz)

Low Frequency (0.05 – 25 Hz)

Very Low Frequency Oscillations (mHz)

Broad Power Peaks (Q < 2)

Multi-Lorentzian PDS & Global Freq. Relations	Nowak 2000; Psaltis et al. 1999; Belloni et al. 2002 ; Pottschmidt et al. 2004
High-Frequency Broad Peaks	Klein-Wolt et al. 2003

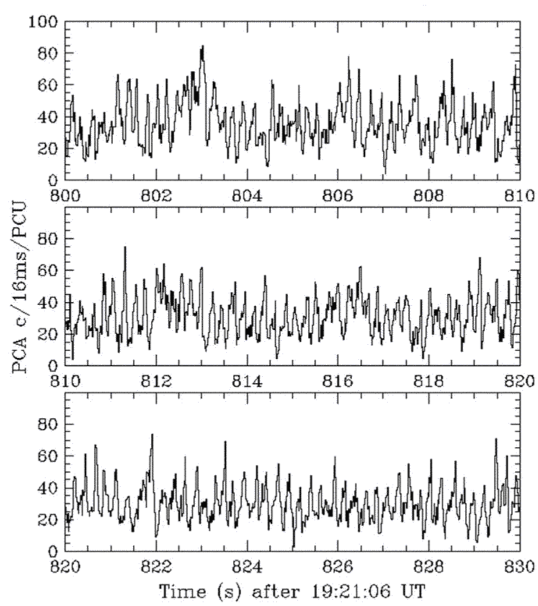
High Amplitude LFQPOs

XTE J1550-564
1998 Sept. 23

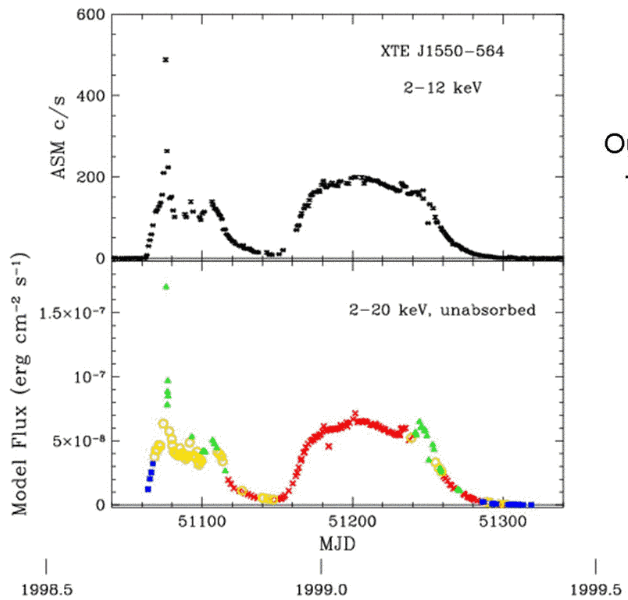
QPO: 4 Hz, 12% rms
Q ~ 9

Flux 2 Crab (~0.2 L_{Edd})
f_{pow} = 0.9

QPO wave-tracking
(see Morgan et al. 1997)



BH X-ray Transients



XTEJ1550-564

M_x = 9.6 ± 1.2 M_o

Outbursts: 1998 ; smaller, 2000;
+ 3 minor hard-state outbursts
2001, 2002, 2003

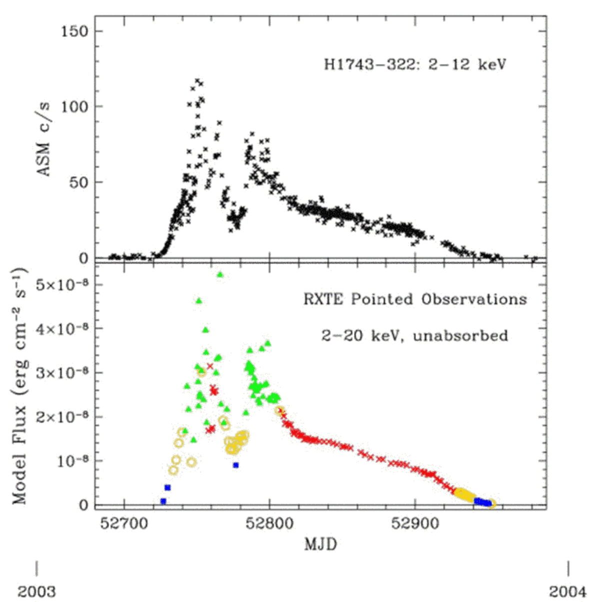
Thermal x

Hard (jet) ■

Steep Power Law Δ

Intermediate O

BH X-ray Transients



H1743-322

M_x unknown (ISM dust)

HEAO-1 outburst: 1977
RXTE: 2003; minor outburst 2005

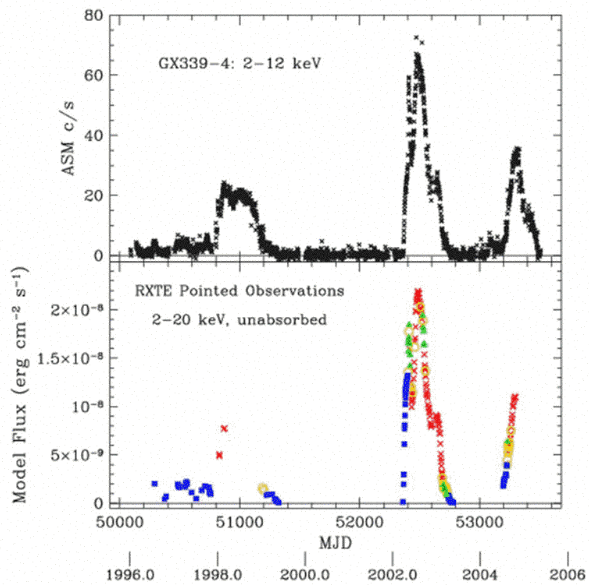
Thermal x

Hard (jet) ■

Steep Power Law Δ

Intermediate O

BH X-ray Transients



GX339-4

M_x = 5 – 15 M_o

Frequent outbursts: 1970 - 2005
+ extended, faint, hard states

Thermal x

Hard (jet) ■

Steep Power Law Δ

Intermediate O

X-ray States

How does the Radiation Engine Function?

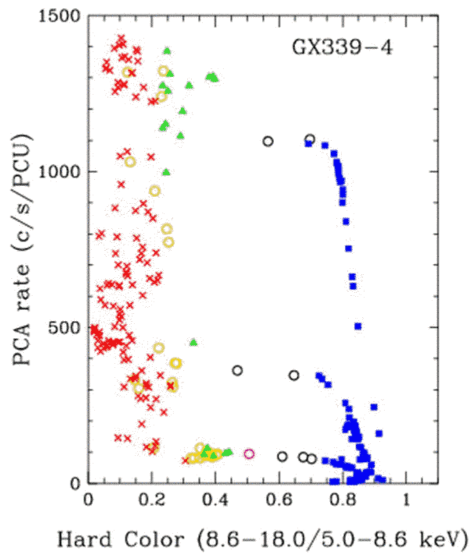
(collapse the time domain)

- Two Formats Used to Display X-ray States:
  - Color : Intensity Diagram

    (hard X-ray color is proxy for states; used for jet diagram)
  - Disk Flux vs. Power-Law Flux Diagram

    (investigate energy flow, coupling, states vs. Lx)
- Study further dimensions (e.g. QPOs, radio flux, state asignments, etc.) with symbol types and colors.

BH X-ray Transients



GX339-4

Color-Intensity diagram

All RXTE outbursts

Thermal x

Hard (jet) ■

Steep Power Law Δ

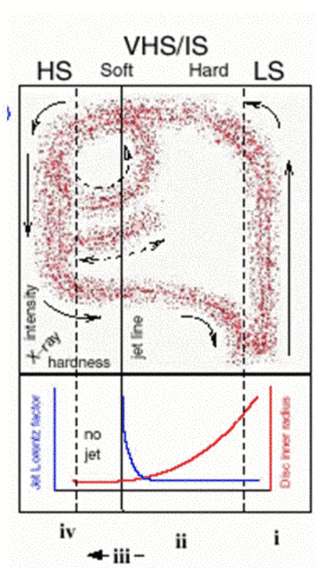
Int. Th. <-> SPL O

Int. Th. <-> Hard O

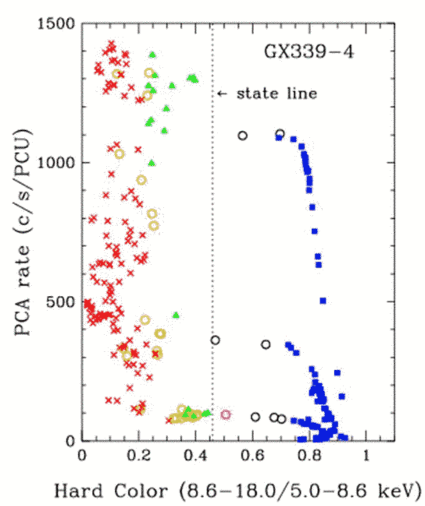
Int. SPL <-> Hard O

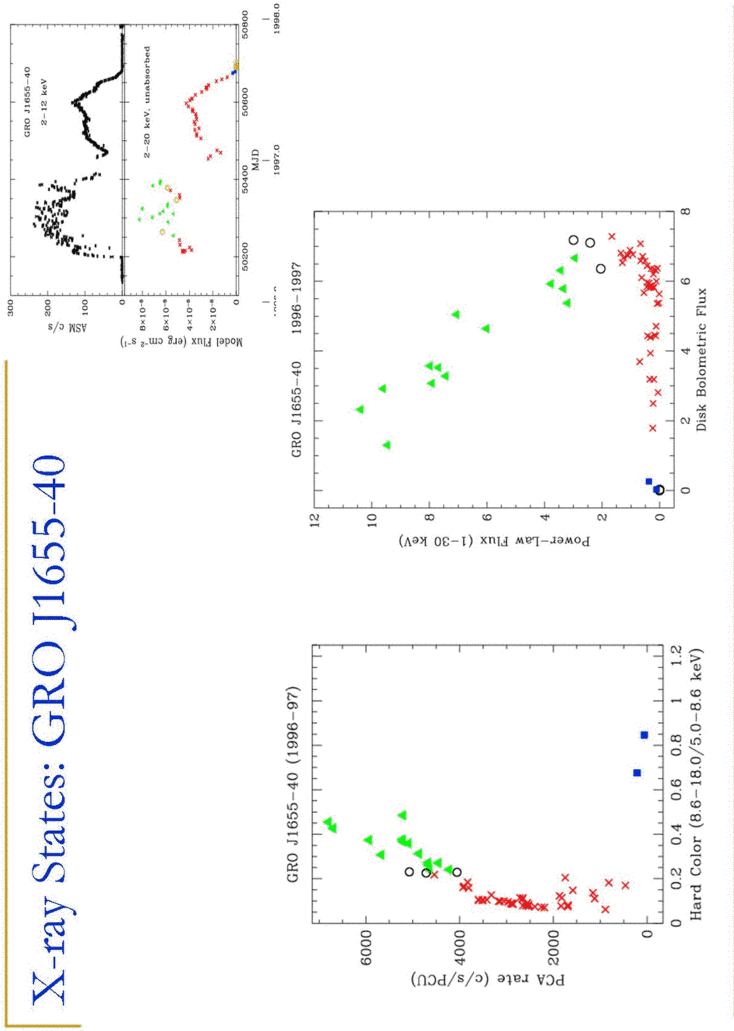
"Unified Model for Jets in BH Binaries"

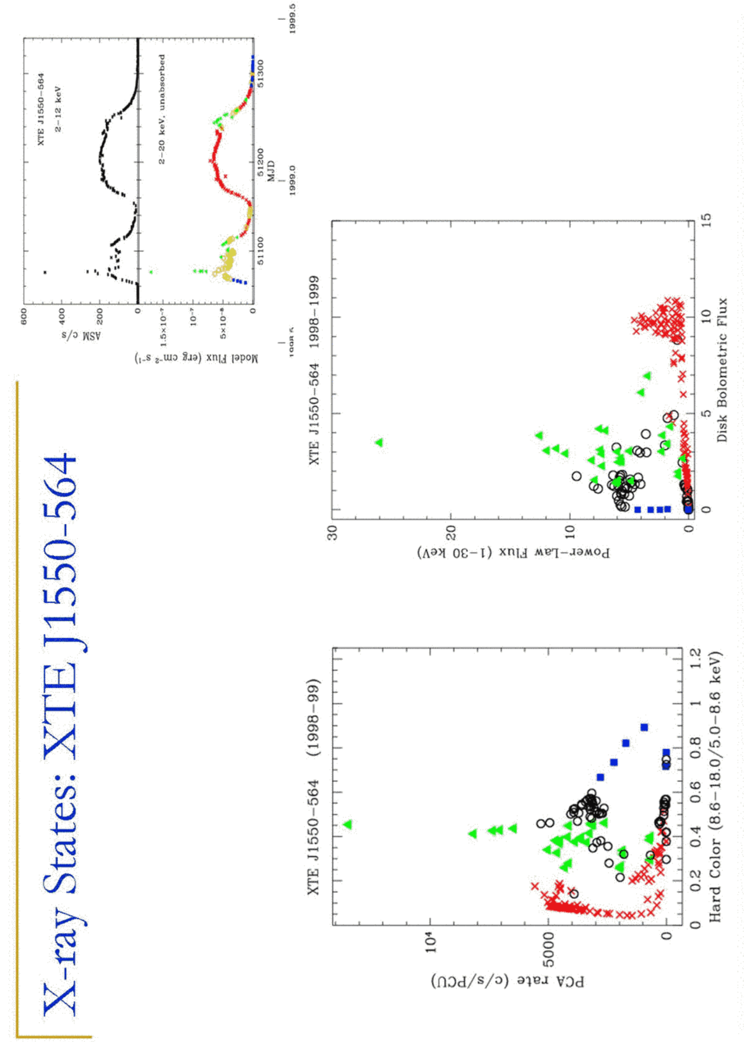
Fender, Belloni, & Gallo 2004



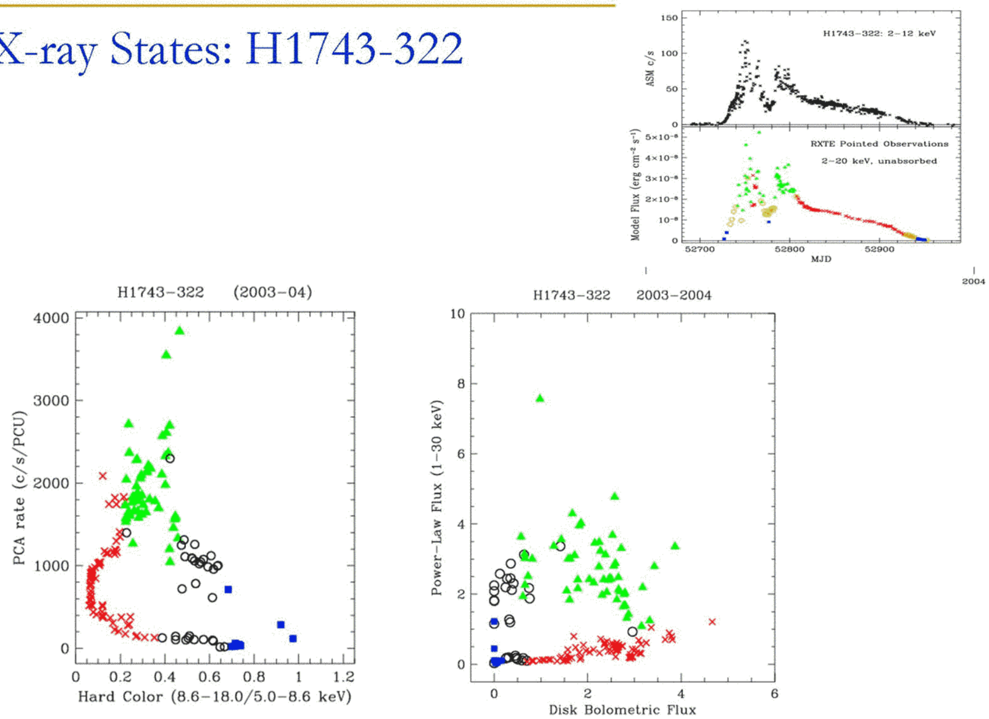
Remillard 2005



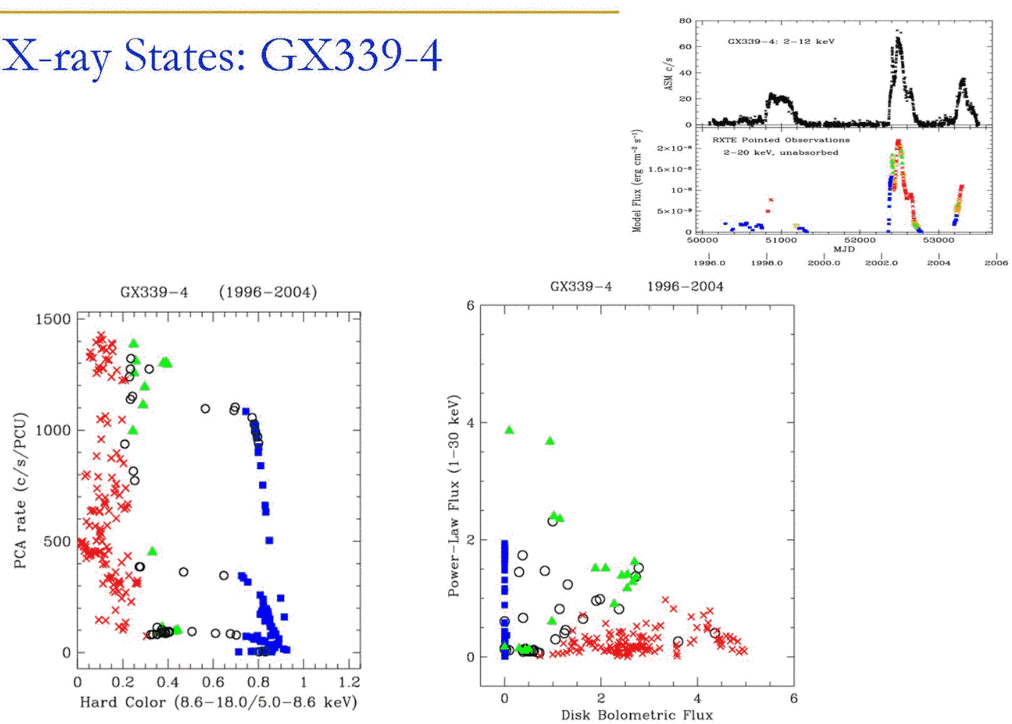

X-ray States: GRO J1655-40
GRO J1655-40
2–12 keV
2–20 keV, unabsorbed
ASM c/s
Model Flux (erg cm-2 s-1)
MJD
GRO J1655-40 1996–1997
Power-Law Flux (1–30 keV)
Disk Bolometric Flux
GRO J1655-40 (1996–97)
PCA rate (c/s/PCU)
Hard Color (8.6–18.0/5.0–8.6 keV)


X-ray States: XTE J1550-564
XTE J1550-564
2–12 keV
2–20 keV, unabsorbed
ASM c/s
Model Flux (erg cm-2 s-1)
MJD
XTE J1550-564 1998–1999
Power-Law Flux (1–30 keV)
Disk Bolometric Flux
XTE J1550-564 (1998–99)
PCA rate (c/s/PCU)
Hard Color (8.6–18.0/5.0–8.6 keV)

X-ray States: H1743-322



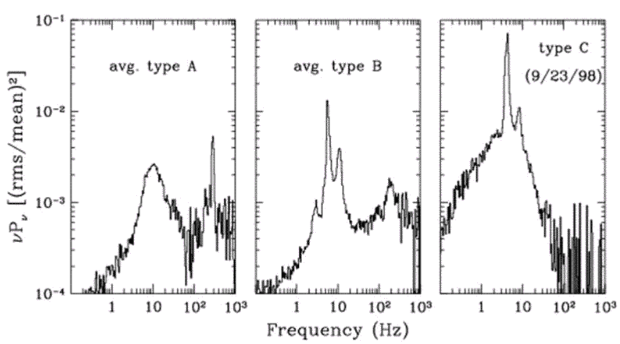
X-ray States: GX339-4



Low Frequency QPOs

- Properties
  - ν range: 0.05 – 30 Hz (most 0.5 – 10 Hz)
  - amplitude: 1 – 20 % (rms, 2 – 30 keV)
  - Q (= ν / $\Delta\nu$) 3 – 20 (typical 8.5)
  - Phase lags -0.1 to +0.2 (2-6 keV vs. 13-30 keV)
- X-ray States: QPOs?
  - Hard/jet often (high L_x ; when disk visible)
  - Thermal no (but 2 cases < 0.5% in sum{TD})
  - Steep Power Law yes
  - Intermediate yes (especially hard ←→ SPL)
- Physical Correlations
  - QPO ν correlations: disk flux, Γ_{pow}
  - *a*(keV) resembles f_{pow}(keV) (QPOs have hard spectra)

LFQPO Subtypes



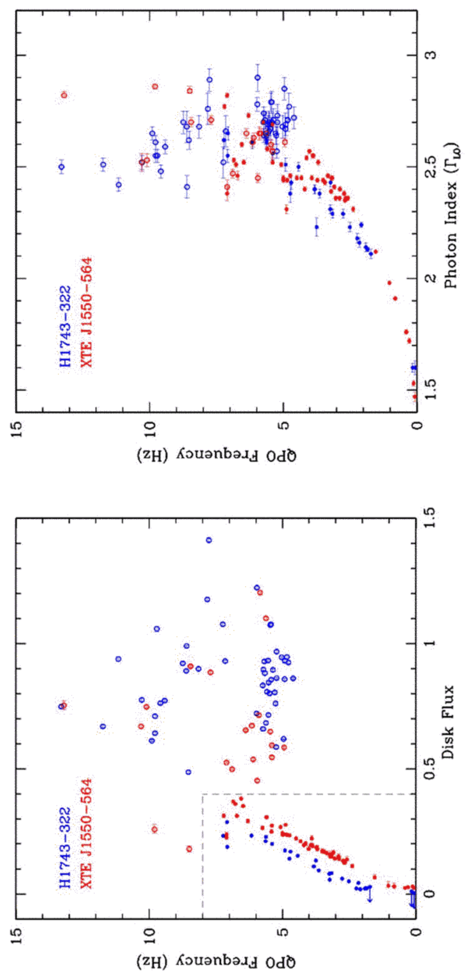
Wijnands et al. 1999
Cui et al. 1999
Remillard et al. 2002
Rodriguez et al. 2004
Casella et al. 2005

Type:	A	B	C
Phase Lag:	soft	hard	near zero
ν_0 (Hz):	~8	~6	0.1 – 15
a (rms %)	few	few	5 – 20
Q :	2 – 3	~10	~10
State:	SPL	SPL	Hard/Int.
HFQPO coupling	yes, $3\nu_0$	yes, $2\nu_o$	no

QPOs across states
Jet → INT → SPL

?? different types or evolution in magnetic instability

LFQPO Freq. vs. Spectral Components



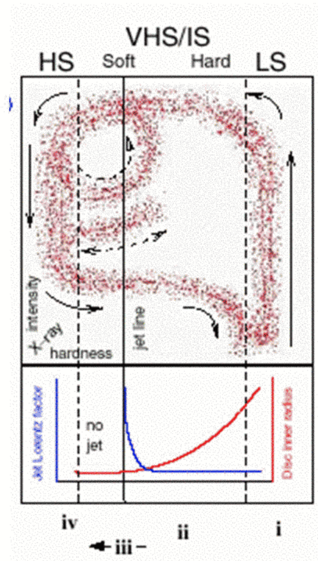
McClintock et al. in prep. ; also see Belloni et al. 2005

LFQPO Mechanisms

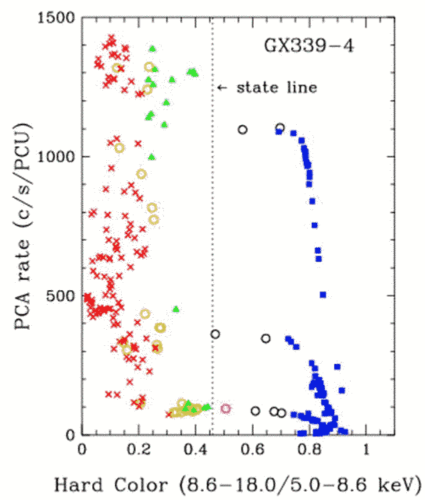
- Alfven waves (C.M. Zhang et al. 2005)
- p-mode Oscillations in a Truncated Disk (Giannios & Spruit 2004)
- Resonance Oscillation Sidebands (Horak et al. 2004)
- Global disk oscillations (Titarchuk & Osherovich 2000)
- Periastron Precession in GR (Stella et al. 1999)
- Accretion-ejection instability & magnetic spiral waves in disk (Tagger et al. 1999)
- Frame Dragging in GR (Stella & Vietri 1998; Fragile et al. 2001)
- Inertial-Acoustic Oscillations (Milson & Taam 1997)
- Radial oscillations in accretion shocks (Molteni et al. 1996; Chakrabarti & Manickam 2000)

"Unified Model for Jets in BH Binaries"

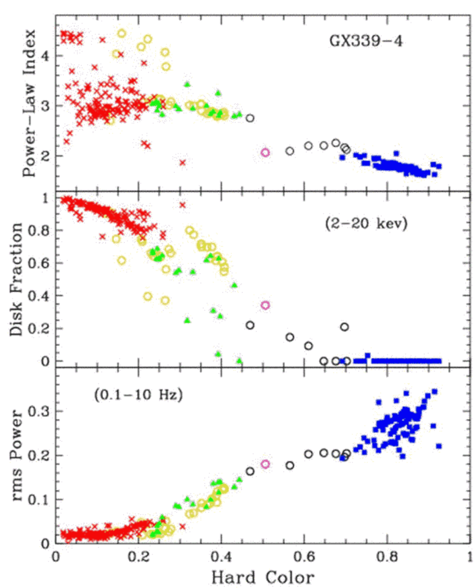
Fender, Belloni, & Gallo 2004



Remillard 2005

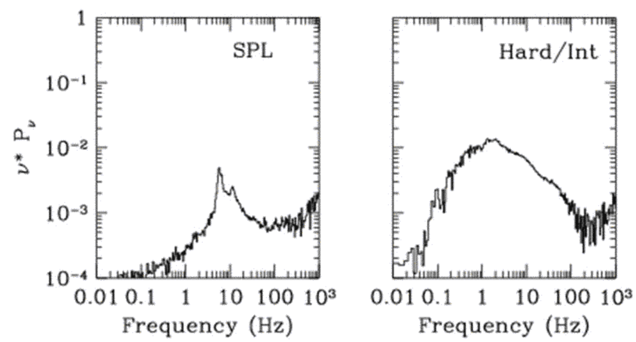


Jet Line vs. X-ray States



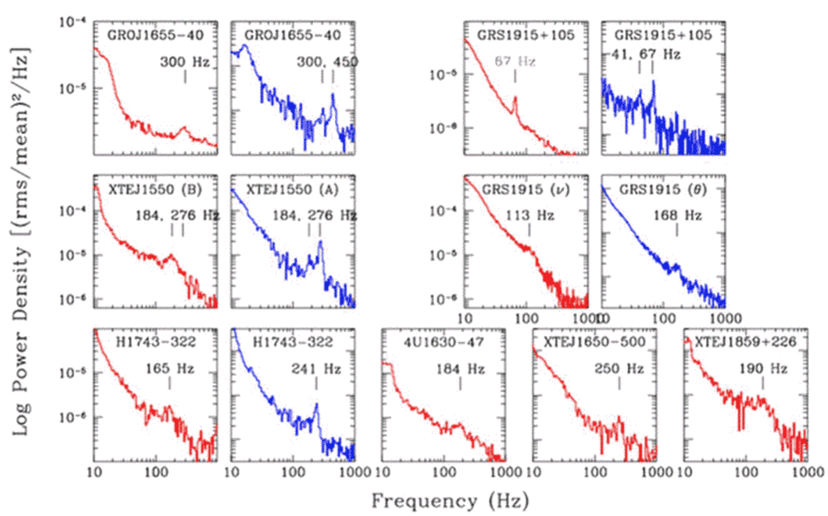
Temporal Signatures of X-ray States

QPOs (0.1-20 Hz)
Common in SPL state



broad power feature near 1 Hz
signature of a steady jet?

High Frequency QPOs in BHBs & Candidates



High Frequency QPOs

source	HFQPO ν (Hz)
GRO J1655-40	300, 450
XTE J1550-564	184, 276
GRS 1915+105	41, 67, 113, 168
XTE J1859+226	190
4U1630-472	184 + broad features (Klein-Wolt et al. 2003)
XTE J1650-500	250
H1743-322	165, 241
(recent case:	Homan et al. 2004; Remillard et al. 2004)

High Frequency QPOs

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4 HFQPO pairs with frequencies in 3:2 ratio

HFQPOs and General Relativity

- **Resonance Orbits** in the Inner Disk (Abramowicz & Kluzniak 2001)
  - Turbulence 'blobs' and arcs linger at r_{res} ?
  - Resonance related to GR frequencies for 3 coordinates $\{r, \theta, \phi\}$
    → e.g. ν_r, ν_ϕ or ν_r, ν_θ resonance
  - **Ray tracing** feasibility study by Schnittman & Bertschinger 2003
  - **Resonance with Global Disk Warp** (S. Kato 2004)
  - **Simulations** (post-Neutonian) and HFQPOs (Y. Kato 2005)
- **Torus Models** (Rezzolla et al. 2003; Fragile 2005)
- **Other Models** (disk magnetosphere effects: Li & Narayan 2004 ;
  Alfven waves: Zhang et al. 2004)

GR Coordinate Frequencies

$$\nu_{r,\theta,\phi} = f\,(M_x, a_*, r) \quad (r \text{ in units } GM_x/c^2)$$

$$\nu_\phi = c^3/GM_x\,[\,2\pi\, r^{3/2}\,(1 + a_*\, r^{-3/2})\,]^{-1}$$

$$\nu_r = |\nu_\phi|\,(1 - 6r^{-1} + 8a_*\, r^{-3/2} - 3a_*^2\, r^{-2})^{1/2}$$

$$\nu_\theta = |\nu_\phi|\,(1 - 4a_*\, r^{-3/2} + 3a_*^2\, r^{-2})^{1/2}$$

see Merloni et al. 1999

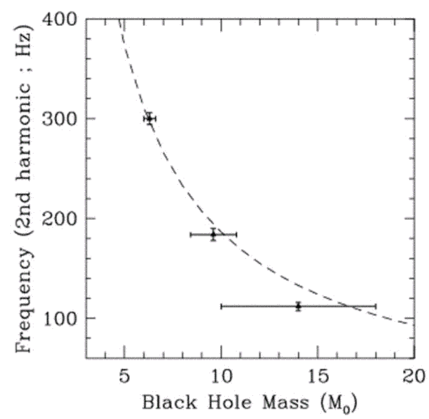
Investigation for neutron star QPOs by Stella et al. 1999

QPO Pairs vs. BH Mass

GROJ1655, XTEJ1550, GRS1915

ν_{qpo} at $2\nu_o$: ν_o = 931 Hz / M_x

- Same QPO mech. And same a_*
  - a_* ~ 0.3-0.4 if QPOs are ν_ϕ and $\nu_\phi - \nu_r$
  - Compare subclasses while model efforts continue.



Applications for Relativistic Astrophysics

steep power law

High Frequency QPOs	**resonances in strong gravity?** **ν_{qpo} = f(M_x, a_*, r_{res})**
Near-Eddington Luminosity	**MHD disk models in GR ?**

thermal state

Thermal Spectrum → N_{DBB}, T_{col}	**GR disk models → measure R_{in} in km ?**
R_{in},= $(N_{DBB} \cos i)^{0.5} d^{-1} f_{atm}$ f(GR)	**$R_{in}(M_x, a^*)$ → constrain spin?**

hard state

steady jet / hard power law	**jet properties; jet mechanisms?**
unstable state transitions	**cause of impulsive jets?**

Conclusions

- High Frequency QPOs in BH Binaries:
  - subtle oscillations (1%)
  - Stable (to 15%), commensurate frequency systems
  - Promising GR "voiceprint" of black hole mass and spin
- Low Frequency QPOs:
  - Multi-typed and variable, yet behavior is highly patterned
  - Types A and B: (5-10 Hz) signatures of SPL state
  - Type C and broad peak (1 Hz): signatures of steady jet
- Non-thermal states (SPL, Hard) require aggressive investigations with magnetic instability models and GR MHD (low β).
- Ballistic jets are further linked to instability strip at state transition (Hard ←→ SPL) and the collapse of the broad power peak.

Future Work

- State Transitions
  - QPOs across HARD ← → SPL transitions
- QPOs vs. Luminosity
  - Steeper dependence in HARD state?
  - 2 ν_0 (→ 3 ν_0) in SPL state at high (→ low) L_x.
- QPOs vs. disk inclination
  - Weaker in face-on systems?
- Broad power peaks
  - frequencies
  - correlations with spectral parameters
- QPO Behavior of Neutron Stars.