Wide-band & Intensity-related spectral analysis of Cygnus X-1 with Suzaku

~ PhD thesis of University of Tokyo ~

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Wide-band *Suzaku* Spectra of Cyg X-1

Dec. of 2010 ~ 40 ks
High/Soft State
- disk + powerlaw + (reflection)

Oct. of 2005 ~ 20 ks
Low/Hard State
- Spectral Components ?
- Origin of rapid variability ?
Suzaku Obs. of Cyg X-1 from ’05 to ’09

All 25 obs.; each ~ 20 ks
Suzaku Obs. of Cyg X-1 from ’05 to ’09

All 25 obs.; each ~ 20 ks

RXTE-ASM

Counts/sec

Hard State

25 samples of high-sensitive & wide-band spectra in Hard state.
Suzaku 1st obs. of Cyg X-1 (K. Makishima + '08)

- Two Compton continua
  \( \tau \sim 1.5 \) and \( \tau \sim 0.4 \)
  \( T_e \sim 100 \text{ keV} \) (common)
  \( R_{\text{seed}} \sim 210 \text{ km} \) (2 comp. sum)

- Directly visible disk emission
  \( T_{\text{in}} \sim 0.2 \text{ keV} \), \( R_{\text{in}} \sim 250 \text{ km} \)
  \( \Rightarrow \) In total, \( R_{\text{in}}/R_g \sim 15 \)

The disk is truncated at \( \sim 15 \, R_g \)

- Mildly broadened Fe-K line
  @ 6.3 keV, EW 290 eV,
  \( \sigma \sim 1 \text{ keV} \) \( \Rightarrow \) \( R_{\text{in}}/R_g \sim 12 \)

- Reflection \( \Omega/2\pi \sim 0.4 \)

Any model-independent evidence?
(cf. Nowak+11)
Suzaku Spectra of 25 obs.
Great care for Pileup & Dipping phase
developed “aepileupcheckup.py” to automatically analyze pileup extent.

Applied “color-color plot” (Nowak+11) to avoid dipping phases.
Suzaku Spectra of 25 obs.
Comparison bet. spectra of $\Delta t >$ days

Spectral ratio to 3$^{rd}$ obs.
Comparison bet. spectra of $\Delta t >$ days

What the ratio shows
- Soft excesses below $E < 10$ keV
- The soft excesses increases as flux increases.
- The spectra becomes softer as it gets brighter.
Intensity-sorted spectroscopy

1. With XIS, judging high/low phase on $\Delta t = 1$
2. Sorting the data according to 1.
3. Extracting high/low spectra.

Counts/s

$\Delta t = 1$

Average

Time (s)

XIS vs. PIN GSO C.C.F

vFv

Bright phase

Dimm phase

Energy (keV)

Time (s)
Intensity-sorted spectroscopy

1. With the XIS, judge high/low of $\Delta t = 1$
2. With the criteria, sorting the data
3. Obtaining high/low spectra.
Comparison bet. Spectra with $\Delta t \sim 1\text{s}$

What the ratio shows
- Hollows below $E < 2\text{ keV}$
- Spectra becomes softer as the source gets brighter.
Comparison bet. Spectra with $\Delta t \sim 1$ s

What the ratio shows
- Hollows below $E < 2$ keV
- Spectra becomes softer as the source gets brighter.
Detailed Comparison of spectra of 14th obs.

\[ \Delta t > \text{days} \]

\[ \Delta t = 1\text{s} \]

Assum. const + pl.
Detailed Comparison of spectra of 14\textsuperscript{th} obs.

\[ \Delta t > \text{days} \]

\[ \Delta t = 1\,\text{s} \]

Assum. const + pl.
Detailed Comparison of spectra of 14\textsuperscript{th} obs.

Energy (keV)

\[ \Delta t > \text{days} \]

\[ \Delta t = 1 \text{s} \]

\( \nu F_\nu \) (cm\(^2\)/s/keV)

Assum.
const + pl.
Detailed Comparison of spectra of 14th obs.

\[ \Delta t > \text{days} \]

\[ \Delta t = 1\text{s} \]

Assum. const + pl.
Detailed Comparison of spectra of 14\textsuperscript{th} obs.

Consistent with spectral changes
On a timescale of \sim day, \sim 1sec

Assum.
const + pl.
consistent with disk
Cross Correlation between 10-20 and 20-60, 100-200 keV

See Torii’s talk tomorrow (Torii, Yamada, Makishima+11)

Hard X-rays changes on shorter time scale than Soft X-rays.
Applying “Shot analysis (Negoro+95)” into Suzaku data

- Folding lots of short flares “shot analysis” (Negoro+’95 w/ GINGA)

Lightcurve of P-sum of XIS (0.5-10 keV)

Shot Profiles
Applying “Shot analysis (Negoro+95)” into Suzaku data

- Ratio to 10-20 keV

- 10–20 keV

- 20–60 keV

- 50–100 keV

- 100–200 keV
Applying “Shot analysis (Negoro+95)” into Suzaku data

- Ratio to 10-20 keV

- 10–20 keV
- 20–60 keV
- 50–100 keV
- 100–200 keV

Time (sec)
Hard X-ray spectral analysis in $\Delta t < 4$ s

What the ratio shows
- Hollows over $E > 100$ keV
- Slightly softer as it gets brighter.
Hard X-ray spectral analysis in $\Delta t < 4 \text{ s}$

What the ratio shows
- Hollows over $E > 100 \text{ keV}$
- Slightly softer as it gets brighter.

What the fits show
- $T_e$ decreases before the peak.
- Opt. depth. increases before the peak.
- Instantly recover after the peak.
Hard X-ray spectral analysis in $\Delta t < 4$ s

What the ratio shows
- Hollows over $E > 100$ keV
- Slightly softer as it gets brighter.

What the fits show
- $T_e$ decreases before the peak.
- Opt. depth. increases before the peak.
- Instantly recover after the peak.
First measurement of shot profiles of $E \sim 0.5\text{-}1.0$ keV

non-scattered disk emission exists. (possibly)

seed photons provided by disk
Inhomogeneous corona ($\Delta t < 1 \text{ s}$)

$\Delta t \sim 1 \text{ s}$

$\Delta t > 1 \text{ days}$

$\sim 10 \text{ Rg}$

$\sim 100 \text{ Rg} \ (t_{\text{dy}} \sim 1 \text{ s})$

Disk ($\Delta t > \text{days}$)

Inhomogeneous corona ($\Delta t < 1 \text{ s}$)
Other latest results from Suzaku
BHB spectra in High/Soft State with Suzaku

able to test disk models more precisely than ever.
The innermost circular orbit is certain. How about BH spin?

Steiner+ 2010
Jeff M., Narayan, Lijun, Ron. R., Yamada
Testing the latest disk model (Kubota+10)

LMC X-3 Suzaku 1st obs.
bhspec (Davis+’05)
kerrbb (Li+’05)

edges of O

absorption edge features are not needed.
Is it possible to determine a BH spin?

No absorption edge feature.

Model: simpl * (kerrbb)
BH spin \( a^* = 0.16 \pm 0.05 \)
\( \chi / \text{d.o.f} = 482/368 \)
\( T_{\text{col}}/T_{\text{eff}} = 1.7 \)

If \( T_{\text{col}}/T_{\text{eff}} = 1.8 \)
BH spin \( a^* < 0.03 \)
\( \chi / \text{d.o.f} = 467/367 \)

Need more studies on disk models.
Collaboration between MAXI and Suzaku

MAXI successfully observed the whole outburst of XTE J1752-223

A entire burst for \( \sim 8 \) months

MAXI can trace evolution of \( T_{\text{in}}, R_{\text{in}} \)

\( R_{\text{in}} \) is constant at \( \sim 116 \) km.

\( 2-4 \) keV

\( 4-10 \) keV

\( 10-20 \) keV

\( 2-20 \) keV

\( 4-10 \) keV/2-4 keV

\( T_{\text{in}} \) (keV)

\( r_{\text{in}} \) (km)

\( \bullet \) Disk flux

\( \bigcirc \) PL flux

\( \bigcirc \) Suzaku
Suzaku results on XTE J1752-223

ignoring 4-7 keV, diskbb + powerlaw → a broad Fe line & a strong reflection !?
Suzaku results on XTE J1752-223

A weakly Comptonized disk reproduces the data (131.4/133) w/o a broad Fe-line.

Nakahira, Koyama, Yamaoka 2011, submitted

diskbb+powerlaw

diskbb+powerlaw+gauss

compps+powerlaw+gauss

\( \tau \sim 0.2, \ Te \sim 10 \text{ keV} \)
Comparison bet. BHB and a Neutron star

Suzaku Low/Hard state

LMXB (a neutron star) Aql X-1 x 10

An electron temperature lower than that in Cyg X-1

⇒ see Sakurai’s poster
Application of Intensity-sorted analysis into AGN

Mrk 509 with Suzaku High and Low spec.

High / Low spec.

stable ~ 50 ks ~ 30 R_g

vFv

Soft Comptonization?

⇒ Noda’s Poster
Summary

- The decomposition of disk + hard Compton + soft Compton, is consistent with the spectral variability.
- As Cyg X-1 gets brighter within 1s, the spectral cutoff at $\sim 100$ keV decreases, return to the average in shorter than $\sim 0.1$ s after the peak.
- Disk models and its relation to powerlaw should be more studied.
- Suzaku have been revealing more on continuum and its variability for neutron stars and AGNs, as well as black hole binaries.

Future Prospects

Polarization GEMS 2014~
Gas Electron Multiplier (GEM) developed by RIKEN, pre. Makishima, Tamagawa group

Astro-H 2014~
Spectral polarimetry
GEMS
SGD
Astro-H simulation $\sim 100$ ks