New Observational Insights into the Low/ Hard state of Cygnus X-1 with Suzaku

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Low/Hard state Black-Hole Binaries

**Soft state**
- Optically thick and geometrically thin accretion disk
- Multi-color blackbody, \(\sim 1\) keV

**Low/Hard state**
- Opt. thin and geom. thick disk
- Thermal Compton cloud with \(T_e \sim 100\) keV
- Intense time variability

**Size/Shape of the Compton cloud? Seed photons?**
**The nature of the fast variation?**

**Wide-band Spectroscopy** – detailed Comptonization modeling

**Intensity-sorted Spectroscopy** -- fast changes of Comptonization
**Suzaku Observation of Cygnus X-1**

- **Cygnus X-1**
  - $D \sim 2.5$ kpc, $i \sim 45$ deg.
  - $M \sim 15 M_\odot$
  - 70% Low/Hard state

- **Wide-band spectra with Suzaku**
  - **Suzaku Observation**
    - Oct 5\textsuperscript{th}, 2005 (17 ks)
    - Low/Hard state
    - $4.7 \times 10^{37}$ erg/s (2.5 kpc)

- **Crab ratios**

![Graphs showing XIS, HXD-PIN, HXD-GSO, PIN-BGD, GSO-BGD, Cyg X-1/ Crab, and GRO J1655 / Crab ratios.](image)
More prominent Soft excess (not due to different $N_H$) Stronger Disk

Stronger Iron line

Spectral Ratios

\[ \text{Energy (keV)} \]

Cyg X-1
GRO J1655-40

Stronger reflection
Slope difference
Broad-band Spectrum Modeling of Cygnus X-1

Simultaneous fitting “Double-Comptonization” (Frontera + 2001)

- Thermal Compton (xspec compPS)
  - Hard optical depth $\sim 1.5$
  - Soft opt. dep. $\sim 0.4$
  - $T_e \sim 100 \text{ keV}, R_{\text{seed}} \sim 210 \text{ km}$

- Directly visible cool disk
  - $T_{\text{in}} \sim 0.2 \text{ keV}, R_{\text{in}} \sim 250 \text{ km}$

The disk is truncated at $\sqrt{R_{\text{seed}}^2 + R_{\text{in}}^2} \sim 15 R_g$

- Weakly broadened Iron line
  - $E_C 6.3 \text{ keV}, EW 290 \text{ eV}$
  - Sigma $\sim 1 \text{ keV}$

No “relativistic diskline” is needed.

- Reflection from the disk
  - Omega / $2\pi \sim 0.4$

The Model reproduces the spectra of both Cyg X-1 and GRO J1655.
Best-fit Model for Cygnus X-1 with GRO J1655-40

Model spectrum removing $N_H$
- Double-Comptonization
  - Hard Compton
  - Soft Compton
- Disk ($T_{in} \sim 0.2$ keV)
- Weakly broadened Fe line
- Reflection

- Cyg X-1 has;
  - Stronger disk BB,
  - Stronger iron line,
  - Stronger reflection,
  - Lower $T_e$.

The spectral difference is explained by inclination effects and a difference of $T_e$.
A Possible Interpretation of the Wide-band Spectra

- Seed photons provided by the cool disk
- Disk; truncated, intruding into ~ half the clouds. visible through Compton Clouds
- Compton Cloud a large scale height inhomogeneous “holes”
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~ 15 Rg
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  a large scale height
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Cyg X-1

GRO J1655-40

BH

Disk

Compton Cloud

~ 15 Rg
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Cyg X-1

GRO J1655-40

Disk

Compton Cloud

“Holes”

~ 15 Rg

BH
A Possible Interpretation of the Wide-band Spectra

- Seed photons provided by the cool disk
- Disk; truncated, intruding into ~ half the clouds, visible through Compton Clouds
- Compton Cloud: a large scale height, inhomogeneous "holes"

GRO J1655-40

Cyg X-1

Directly Visible Disk

Soft Compton

Hard Compton

Iron line

reflection

BH

Disk

Compton Cloud

~ 15 Rg
Fast variability of the thermal Comptonization can be studied
"Intensity-sorted Spectroscopy"

XIS light curve of Cyg X-1 with 1-s binning

Fast variability of the thermal Comptonization can be studied

XIS 1/8 window, deltaT ~ 1sec
HXD delta T = 61 usec

Cross Correlation

XIS-PIN
XIS-GSO
Fast variability of the thermal Comptonization can be studied.
Fast variability of the thermal Comptonization can be studied.
Intensity-sorting in reference to the XIS data

Lightcurves during 400s of Cyg X-1 with Suzaku
Intensity-sorting in reference to the XIS data

Fast variability is well determined by XIS.

High Phase
Low Phase
Applying the sorting to the HXD data --

Fast variability is well determined by XIS.

- **High Phase**
- **Low Phase**

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XIS 0+3 (0.7-10 keV)

PIN (10-60 keV)

GSO (60-200 keV)

Time (sec)
“High” and “Low” spectra

When Cyg X-1 gets brighter,
- **Compton Cloud**
  - Seed photon
  - $T_e$ or tau, or both
  - Hard/Soft
- **Disk**
  - $T_{in}$
  - $L_{total} = L_{raw} + L_{seed}$
- **Iron line**
  - EW
- **Reflection**
  - Omega / 2 pi

High and Low spectra

A Possible Interpretation of Intensity-sorted Spectra

When Cyg X-1 gets brighter,

Omega / 2 pi

Disk

Compton Cloud

BH

Holes” ~ 15 Rg

reflection

Iron line

Directly Visible Disk

Soft Compton

Hard Compton

Low Phase


Iron line reflection

Reflection

Disk

Hard/Soft

Seed photon

L_{\text{total}} ( = L_{\text{raw}} + L_{\text{seed}} )

T_{\text{m}}

T_e or tau, or both

Compton Cloud

~ 15 Rg
“High” and “Low” spectra


A Possible Interpretation of Intensity-sorted Spectra

When Cyg X-1 gets brighter,

- **Compton Cloud** Seed photon
  - $T_e$ or tau, or both
  - Hard/Soft
    - **Disk** $T_{in}$
    - $L_{total} = L_{raw} + L_{seed}$
    - **Iron line** $EW$
    - **Reflection** $\Omega / 2\pi$

Directly Visible Disk

Soft Compton

Hard Compton

Iron line

reflection

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BH
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Disk

Compton Cloud

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~ 15 Rg
“High” and “Low” spectra

A Possible Interpretation of Intensity-sorted Spectra

When Cyg X-1 gets brighter,
• Compton Cloud
  Seed photon
  $T_e$ or tau, or both
  Hard/Soft

• Disk
  $T_{in}$
  $L_{total} = L_{raw} + L_{seed}$

• Iron line
  EW

• Reflection
  Omega / 2 pi

Directly Visible Disk
Soft Compton
Hard Compton
Iron line
Reflection

High Phase Opening fraction decreases

“Holes”

Disk
Compton Cloud


XMM-Newton: The X-ray Universe 2008, Granada 21
Summary

• The 0.7-400 keV Cyg X-1 spectrum with Suzaku is reproduced by “Double-Comptonization” model. The accretion disk is truncated at ~ 15 Rg. No diskline is needed.

• Difference between GRO J1655-40 and Cyg X-1 can be explained by the inclination effects; flat disk, and inflated Compton cloud.

• When Cyg X-1 becomes brighter on ~ 1 sec, the seed photon supply to the clouds increases, and the cloud Te ( or tau ) decreases slightly.

• The Compton cloud is suggested to be highly inhomogeneous, and its opening fraction is varying.