Stellar mass black hole accretion disks in the low-hard state

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Introduction: Geometry and Spectral components

The origin of the hard powerlaw-like component is still not established:
- Base of a jet
- Patchy corona/Magnetic flares
- Advection-dominated region

The innermost extent of the accretion disk in the low-hard state (LHS) is still not established.
Introduction: Shakura-Sunyaev accretion disk

Characteristic blackbody temperature can be approximated as

$$kT \sim (M/10 M_\odot)^{-1/4}(L/L_{Edd})^{1/4} \text{keV}$$

Stellar-mass black holes in the low-hard state

$$L \sim (0.1 - 1)\% L_{Edd}$$

$$kT \sim 0.1 - 0.3 \text{keV}$$

Need low energy coverage

If the disk is truncated the temperature will be colder
**Our approach:**

Systematically investigate spectra of various X-ray binaries in the LHS

Low energy coverage (<3 keV)

XMM-Newton, Chandra, Swift and Suzaku.

Physical parameters (mass, distance and inclination) obtained from the literature

Physical parameters + spectral fitting = constraint in the position of the innermost radius of accretion
The sample:

<table>
<thead>
<tr>
<th>Source</th>
<th>Inclination (degrees)</th>
<th>Distance (kpc)</th>
<th>Mass (M$_\odot$)</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>GX 339-4</td>
<td>10–30</td>
<td>6–10</td>
<td>10–20</td>
<td>XMM-Newton</td>
</tr>
<tr>
<td>J1650-500</td>
<td>47–70</td>
<td>1.9–3.3</td>
<td>5.3–11.3</td>
<td>XMM-Newton</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>25–50</td>
<td>2.0–2.2</td>
<td>7–25</td>
<td>Suzaku</td>
</tr>
<tr>
<td>J1753.5-0127</td>
<td>49–57</td>
<td>7.2–10.0</td>
<td>4–16</td>
<td>XMM-Newton</td>
</tr>
<tr>
<td>J1655-40</td>
<td>68.3–87</td>
<td>3.0–3.4</td>
<td>5.8–6.8</td>
<td>Suzaku</td>
</tr>
<tr>
<td>J1118+480</td>
<td>60–83</td>
<td>1.2–2.4</td>
<td>7–10</td>
<td>Chandra</td>
</tr>
<tr>
<td>J17497-2821</td>
<td>10–80</td>
<td>5–10</td>
<td>5–20</td>
<td>Suzaku</td>
</tr>
<tr>
<td>J1817-330</td>
<td>10–80</td>
<td>1–15</td>
<td>4–15</td>
<td>SWIFT</td>
</tr>
</tbody>
</table>
Results: 0.5-10 keV fit with absorbed PL
Results: Masking the presence of a disk...

...with an artificially low column density ($N_H$)

Average hydrogen column density in direction of Cygnus X-1 is $\sim 7.2 \times 10^{21}$ cm$^{-2}$ (Kalberla et al. 2005)
**Results: PL + Diskbb**

\[
N = \left( \frac{R_{in}}{D} \right)^2 \times \cos \theta
\]

Use estimate of mass, distance and inclination to obtain \( R_{in} \) in gravitational radii
\[
R_g = \frac{GM}{c^2}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>( N_H (\times 10^{22} \text{ cm}^{-2}) )</th>
<th>( \Gamma )</th>
<th>( kT ) (keV)</th>
<th>( N_{\text{Diskbb}} \times 10^3 )</th>
<th>( \chi^2/\nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GX 339-4</td>
<td>0.495 ± 0.006</td>
<td>1.67 ± 0.01</td>
<td>0.254 ± 0.006</td>
<td>5.02^{+0.80}_{-0.67}</td>
<td>2874.0/1633</td>
</tr>
<tr>
<td>J1650-500</td>
<td>0.556 ± 0.004</td>
<td>2.10 ± 0.01</td>
<td>0.310 ± 0.004</td>
<td>55 ± 4</td>
<td>1507.9/1273</td>
</tr>
<tr>
<td>Cygnus X-1 (1)</td>
<td>0.53 ± 0.02</td>
<td>1.71 ± 0.01</td>
<td>0.194^{+0.005}_{-0.004}</td>
<td>236^{+63}_{-54}</td>
<td>783.1/722</td>
</tr>
<tr>
<td>Cygnus X-1 (2)</td>
<td>0.50 ± 0.02</td>
<td>1.70 ± 0.01</td>
<td>0.194^{+0.007}_{-0.006}</td>
<td>155^{+62}_{-49}</td>
<td>719.2/683</td>
</tr>
<tr>
<td>J1753.5-0127</td>
<td>0.197 ± 0.004</td>
<td>1.61 ± 0.01</td>
<td>0.274^{+0.015}_{-0.014}</td>
<td>0.32^{+0.11}_{-0.08}</td>
<td>1961.0/1497</td>
</tr>
<tr>
<td>J1655-40</td>
<td>0.63 ± 0.02</td>
<td>1.67 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td>5.4^{+2.7}_{-2.0}</td>
<td>1618.8/1439</td>
</tr>
<tr>
<td>J1118+480</td>
<td>0.022 ± 0.003</td>
<td>1.69 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td>7.4^{+1.4}_{-1.2}</td>
<td>3747.3/4246</td>
</tr>
<tr>
<td>J17497-2821</td>
<td>4.72 ± 0.08</td>
<td>1.56 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>54^{+49}_{-24}</td>
<td>1102.5/1182</td>
</tr>
<tr>
<td>J1817-330 (1)</td>
<td>0.12(f)</td>
<td>2.1 ± 0.1</td>
<td>0.20 ± 0.01</td>
<td>27^{+9}_{-6}</td>
<td>204.0/207</td>
</tr>
<tr>
<td>J1817-330 (2)</td>
<td>0.12(f)</td>
<td>1.5 ± 0.2</td>
<td>0.21 ± 0.01</td>
<td>1.3^{+1.5}_{-0.6}</td>
<td>69.1/79</td>
</tr>
</tbody>
</table>

Diskbb: Mitsuda et al. 1984
Ezdiskbb: Zimmerman et al. 2005
**Results:** $R_{in}$ always consistent with ISCO!
**Results:** Can the disk be truncated at $100R_g$?

Model thermal component with **DISKPN** (Gierlinski et al. 1999) where $R_{in}$ is a free parameter.

Freeze $R_{in}$ at both 6 and $100R_g$

Models with and without truncation gives **equally satisfactory fits**.

**Only the normalisation** differs between the interpretations.
**Results:** Can the disk be truncated at $100R_g$?

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Only the normalisation differs between the interpretations

\[
N = \left(\frac{1}{f^4}\right)\left(\frac{M}{D}\right)^2 \cos \theta
\]

\[
f = \frac{T_{col}}{T_{eff}} \sim 1.7 < 3
\]

Look at inclination as a function of $f$
Results:

\[ \cos(\theta) = \left( \frac{N D^2}{m^2} \right) f^4 \]
Results:
Results: Inner radius from reflection

Constraints on the disk geometry can also be found using reflection signatures.
Results: Inner radius from reflection

- **GX 339-4**
  - Energy (keV)
  - Ratio: 0.9 to 1.2

- **J1650-500**
  - Energy (keV)
  - Ratio: 0.9 to 1.3

- **Cygnus X-1**
  - Energy (keV)
  - Ratio: 0.95 to 1.1
Results: Inner radius from reflection

An inner radius extending to within $6R_g$ is found in GX 339-4, J1650-500 and J1655-40.

For Cygnus X-1 the radius is constrained to within $12R_g$.

In J1753.5-0127 an inner radius greater than $20R_g$ is excluded at the $3\sigma$ level.
Summary:

- We present a study of 8 black holes in the LHS.
- A thermal disk continuum is clearly detected in all eight sources, down to $\sim 5 \times 10^{-4} L_{\text{Edd}}$.
- In six sources, disk models exclude a truncation radius of $10R_g$.
- Iron-K fluorescence line emission is observed in half of the sample, down to luminosities of $\sim 1.5 \times 10^{-3} L_{\text{Edd}}$.
- Detailed fits to the line profiles exclude a truncated disk in each case.

If the inner disk evaporates in the LHS, it must happen at or below $\sim 1.5 \times 10^{-3} L_{\text{Edd}}$. 