The close environments of accreting black holes: a X-ray spectral-timing view

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Why are we interested?
BHs are fundamental engines in our Universe

Observing them is a technological challenge

Understanding them is a scientific challenge
Astrophysical BHs

Most efficient mechanism of “persistent” energy production
Astrophysical BHs

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[Image: M87 with event horizon, EHT collaboration]
Astrophysical BHs

Most efficient mechanism of “persistent” energy production

Powerful X-ray emitters (~$10^{37}$-10$^{46}$ erg/s)
Most efficient mechanism of “persistent” energy production

Powerful X-ray emitters ($\sim10^{37} - 10^{46}$ erg/s)

X-ray flux highly variable (timescales from years to $\sim10^{-3}$ s)
BH-accretion: a complex phenomenology

Accretion states in stellar-mass BH binary systems

3 outbursts of GX 339-4

How radiation is distributed in the X-ray waveband
BH-accretion: a complex phenomenology
Accretion states in stellar-mass BH binary systems

How much radiation is emitted

3 outbursts of GX 339-4

<table>
<thead>
<tr>
<th>$F_{3-10\text{ keV}}$ erg/s/cm²</th>
<th>$F_{6-10\text{ keV}}/F_{3-6\text{ keV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-11}$</td>
<td>0.05</td>
</tr>
<tr>
<td>$10^{-10}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>0.5</td>
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<tr>
<td>$10^{-7}$</td>
<td>1</td>
</tr>
</tbody>
</table>

1) Quiescence
Undetected X-ray source, companion star visible

How much radiation is emitted in the X-ray waveband
BH-accretion: a complex phenomenology

Accretion states in stellar-mass BH binary systems

How radiation is distributed in the X-ray waveband

1) Quiescence

2) Rise in hard state

3 outbursts of GX 339-4

Strong hard X-ray (10-100 keV) emission, fast variability, compact IR-Radio jets

Undetected X-ray source, companion star visible

How much radiation is emitted

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$F_{3-10 \text{ keV}}$ erg s$^{-1}$ cm$^{-2}$ vs $F_{6-10 \text{ keV}} / F_{3-6 \text{ keV}}$
**BH-accretion: a complex phenomenology**

*Accretion states in stellar-mass BH binary systems*

1) Quiescence

2) Rise in hard state

3) Transition to soft state

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Accretion states in stellar-mass BH binary systems

1) Quiescence
2) Rise in hard state
3) Transition to soft state
4) Soft state

How radiation is distributed in the X-ray waveband

strong soft X-ray (1 keV) emission, variability low or absent, jet weak or quenched

3 outbursts of GX 339-4

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BH-accretion: a complex phenomenology

Accretion states in stellar-mass BH binary systems

1) Quiescence
2) Rise in hard state
3) Transition to soft state
4) Soft state
5) Transition to hard state
6) Back to quiescence

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How much radiation is emitted
**Accretion disc emission**

Thermal emission due to dissipation of gravitational energy

\[ T_{\text{disk}} \propto M_{\text{BH}}^{-1/2} \]

[Shakura & Sunyaev '73; Novikow & Thorne '74; Page & Thorne '74; Eardley & Lightman '75]
**Accretion disc emission**

Thermal emission due to dissipation of gravitational energy

Disc thermal (multi T black body)

\[ T_{\text{disk}} \propto M_{\text{BH}}^{-1/2} \]

Can explain the soft state of BHBs

[Cyg X-1, Gierliński+ ’99]

[Shakura & Sunyaev ’73; Novikow & Thorne ’74; Page & Thorne ’74; Eardley & Lightmann ’75]
The hard X-ray source

Disc photons get energized in a hot inner plasma (corona, hot flow...)

Comptonization region

Disc

Stellar-mass BH

Disc thermal

Compton upscattered (power law)

Cyg X-1

Gierliński + ’99

Needed to explain the hard and intermediate states of BHBs

[Thorne & Price ’75; Shapiro +’76; Sunyaev & Trümper ’79; Sunyaev & Titarchuk ’80; Haardt & Maraschi ’91, ’93; Dove +’97; Poutanen +’18]
Open questions

What is the nature of the different accretion states?

How are jets launched?

What is the nature of the X-ray source and where is it located?
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What is the nature of the different accretion states?

How are jets launched?

What is the nature of the X-ray source and where is it located?

Inner accretion flow geometry may play an important role
**Accretion states: variations of inner flow geometry**

to explain the outburst evolution of BHBs

**Soft state: Disc close to ISCO**

![Diagram showing accretion states]

1) Quiescence
2) Rise in hard state
3) Transition to soft state
4) Soft state
5) Transition to hard state
6) Back to quiescence

**Quiescent state:** Disc far from ISCO

[e.g. Esin+'97; Poutanen+'97; Zdziarski+'99; Meyer+'00; Narayan & McClintock ’08; Kylafis & Belloni ‘15]
Accretion states: variations of inner flow geometry
to explain the outburst evolution of BHBs

Soft state: Disc close to ISCO

How do the disc and the X-ray source evolve in between?
Seeking for observational evidences….

[e.g. Esin+’97; Poutanen +’97; Zdziarski+’99; Meyer+’00; Narayan & McClintock ’08; Kylafis & Belloni ‘15]
The X-ray spectrum: reprocessing

A fraction of hard X-ray photons is reflected + thermally reprocessed in the disk

[Guilbert & Rees '88; Fabian +'89; Matt +'97; Ballantyne +'01; Ross & Fabian '93; Matt +’93; Życki & Czerny ’94; Magdziarz & Zdziarski ’95; Nayakshin+’01; Dauser +’16; García+’16; Tomsick +’18]
Relativistic effects in the X-ray spectrum

Relativistic effects create distortions, clearly visible in reflection spectra

- **extreme relativity**: reflecting material located close to BH
- **no-relativity**: reflecting material far from BH

FeK fluorescence line

\[ r_g = \frac{GM}{c^2} \]
Relativistic effects in the X-ray spectrum

Relativistic effects create distortions, clearly visible in reflection spectra

Fitting reflection spectrum allows us to obtain constraints on the inner radius of the accretion disc

[Reynolds ’14]
Constraints on the inner disc radius in hard state

Powerful method, but not unique solution

[Plant +’15]
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Results span \(~3\) orders of magnitude!
**Constraints on the inner disc radius in hard state**

*Powerful method, but not unique solution*

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**Results span $\sim 3$ orders of magnitude!**

Some estimates suggest the disc reaches close to the ISCO very early in the outburst.
Alternative methods to constrain geometry
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**X-ray variability**
Combined spectral-timing methods can be used to map geometry very close to the BH!
X-ray variability time scales depend on the distance

Allows separating radiation produced at different distances from the BH

Faster variability from the inner, harder regions

Slower variability from the outer, softer regions
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(Temporal) frequency-resolved flux

Total flux

Emitted Flux

Time
Variable irradiation of the disc produces variable and delayed reprocessed emission.

**X-ray reverberation lags**

Direct variable emission

Comptonization region

Variable reprocessed emission

Flux vs. Time:

Time delays which scale with the distance between the X-ray source and the disc.
**X-ray reverberation during an outburst**

*Distance mapped by the lag decreases towards luminous hard states*

**GX 339-4**

[De Marco + '17]

- End of soft-to-hard transition,
- Hard state (descending)
- Hard state (rising)
X-ray reverberation during an outburst
Distance mapped by the lag decreases towards luminous hard states

The geometry of the inner flow changes in the hard state
Expected if disc inner radius not fixed at ISCO in the hard state

End of soft-to-hard transition,
Hard state (descending)
Hard state (rising)

[De Marco+’17]
Evolution of reverberation lag

Same behaviour seen in different sources

[De Marco+ ’15; De Marco & Ponti ’16]

The reverberation lag decreases as the source rises in luminosity throughout the hard state
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However, data insufficient to map the hard state intensively and to cover the transition…
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XMM-Newton not designed to perform intensive monitoring and to observe very bright sources.

GX 339-4
H 1743-322

XMM-Newton

$L_{3-10 \text{ keV}} / L_{\text{Edd}}$

$5 \times 10^{-3}$

0.02

20

50

100

200

500

1000

Lag ($r_g/c$)
The Neutron star Interior Composition Explorer (NICER)
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56 (52 operative) X-ray "concentrator" optics (XRC) each paired to a silicon drift detector (SDD)
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56 (52 operative) X-ray "concentrator" optics (XRC) each paired to a silicon drift detector (SDD)

Large collecting area, fast timing capabilities, no limitations to observe very bright source
One of the brightest X-ray binaries ever observed

MAXI J1820+070

Peak flux ~4 Crab
> Sun at its maximum

[Kara+'19; Stiele+'19; Bright +’20; Espinasse +’20; Homan+’20…]
One of the brightest X-ray binaries ever observed

MAXI J1820+070

Peak flux ~4 Crab
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First detailed simultaneous multiwavelength monitoring of hard-to-soft state transition

[Kara+’19; Stiele+’19; Bright +’20; Espinasse+’20; Homan+’20…]
X-ray reverberation

Direct X-ray emission

Delayed disc emission

De Marco+'21

[De Marco+ ’21]
X-ray reverberation

Direct X-ray emission

Delayed disc emission

[De Marco+ ’21]

Reverberation Lag

Freq (Hz)

Lag (s)
X-ray reverberation

Direct X-ray emission

Delayed disc emission

Reverberation

Lag

[De Marco+'21]
Delayed disc emission

Direct X-ray emission

Reverberation

Lag

[De Marco+’21]
What happens at transition?
The inferred (qualitative) physical picture

Disc approaching the BH throughout the hard state

This trend breaks at transition: X-ray source increases in size, disc close to ISCO
The inferred (qualitative) physical picture

Disc approaching the BH throughout the hard state

This trend breaks at transition: X-ray source increases in size, disc close to ISCO

Long reverberation lags, colder inner disc
The inferred (qualitative) physical picture

Disc approaching the BH throughout the hard state

This trend breaks at transition: X-ray source increases in size, disc close to ISCO

Increasingly shorter reverberation lags,
increasingly warmer inner disc

Long reverberation lags, colder inner disc

Increasingly shorter reverberation lags, increasingly warmer inner disc
Very long reverberation lags, very hot inner disc

The inferred (qualitative) physical picture
Disc approaching the BH throughout the hard state

This trend breaks at transition: X-ray source increases in size, disc close to ISCO

Increasingly shorter reverberation lags, increasingly warmer inner disc

Long reverberation lags, colder inner disc
Conclusions

BHs can be studied using their X-ray spectral and timing information

Combining the spectral and timing information allows us to break degeneracies of standard methods

NICER is making significant inroads for our understanding of stellar-mass BH in binary systems

NICER data of MAXI J1820+070 point to a steady decrease of the inner radius of the accretion disc as the source evolves throughout the hard state, and a major change in the X-ray source geometry right before the transition to the soft state
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Thank you!