X-ray reverberation in accreting black holes

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Δt \sim \text{tens of seconds for } 1\times10^6 \text{ Msun}
Δt \sim < \text{milliseconds for } 10 \text{ Msun}
Discovery of X-ray Reverberation

1H0707-495
XMM- Newton
500 ks

Fabian et al. 2009
Uttley et al., 2014 for review
Discovery of X-ray Reverberation

Figure by Abdu Zoghbi

Image credit: Dan Wilkins

Uttley et al., 2014 for review
Is 1H 0707-495 a unique case?

Well, there is another suspect: IRAS 13324-3809

Ponti et al 09, MNR
Probing the dynamics of the corona

IRAS 13224-3809: 500ks

Time (s)

Soft (ct s$^{-1}$)

Hard (ct s$^{-1}$)

Energy (keV)

Ratio

Lag (s)

Temporal Frequency (Hz)

Fabian, EK, et al., 2012
Probing the dynamics of the corona

IRAS 13224-3809

Low flux

Kara et al., 2013
Probing the dynamics of the corona

IRAS 13224-3809

High flux

EK+13b
2012: NuSTAR launches

Zoghbi et al., 2013 - Lags can be measured through time domain techniques, allowing for reverberation measurements even from data with gaps.

Swift J2127.4+5654

Interpreting the lag-energy spectra at different regions. The plot in Fig. 4 shows different emission region sizes. Comparing flares at different time-scales (i.e. temporal lags) probes different regions. From this principle, the rest energy of the iron K line is 6.4 keV. The lag-energy spectrum at the lowest frequencies peaks at lower energies. The line profile of a relativistic line from an accretion disk is well understood. Photons in the red wing of the line are emitted deeper in the black hole potential and they are not known accurately, but it is of the order of a few kiloseconds at a distance.

The analysis in section 3.1.1 shows that by simply comparing flares at different regions, there is a lag dilution factor caused by both the amount of dilution of the primary and reflected components contributing to the reverberating region. The widths of the flare changes accordingly. In a reverberating region, the widths should be narrowest for the energies where the primary continuum dominates, and in this picture, the widths should be narrowest for the energies below and above it. The lag-energy spectrum roughly traces the shape of the frequency band as the left panel. The orange squares are for frequencies 3 and 5 × 10^10 Hz, the black circle for 10^11 Hz. The central frequencies for the two bins are: 6 × 10^4 − 700 seconds at the highest frequencies (Fig. 4). This factor changes from 30% at few to several kiloseconds. The light crossing time in the source in the observations used here will be discussed in Wilkins and Fabian (2013). Although the spectrum of the primary continuum that has a power-law shape, one can hope to measure the shape of the relativistic iron line itself. The measured shape for MCG–5-23-16 is clearly not a narrow line, indicating that relativistic iron K line the lag-energy spectrum roughly traces the shape of the frequency band as the left panel. The orange squares are for frequencies 3 and 5 × 10^10 Hz, the black circle for 10^11 Hz. The central frequencies for the two bins are: 6 × 10^4 − 700 seconds at the highest frequencies (Fig. 4). This factor changes from 30% at few to several kiloseconds. The light crossing time in the source in the observations used here will be discussed in Wilkins and Fabian (2013). Although the spectrum of the primary continuum that has a power-law shape, one can hope to measure the shape of the relativistic iron line itself. The measured shape for MCG–5-23-16 is clearly not a narrow line, indicating that relativistic iron K line itself. The measured shape for MCG–5-23-16 is clearly not a narrow line, indicating that relativistic iron K line itself. The measured shape for MCG–5-23-16 is clearly not a narrow line, indicating that relativistic iron K line itself.
Black hole transients: analogous to AGN?

Equivalent duty cycle in AGN is millions++ of years
Studying the inner accretion flow in BHBs with XMM-Newton

Reverberation lags due to thermal reprocessing

Uttley et al., 2011

De Marco & Ponti 2017
The NICER Observatory

Highest ever soft band effective area (2x XMM or 20x Swift XRT)
Highest time resolution: >100 ns time resolution (25x RXTE)
~100 eV resolution at 6 keV
March 2018: MAXI J1820+070 emerges
NICER observations of MAXIJ1820+070
NICER measures short reverberation lags

Lags between 0.5-1 keV and 1-10 keV

Signature of light echoes

(Temporal Frequency — how rapidly light curve varies)

Reverberation in XRBs: Uttley et al., 2011, De Marco et al., 2017
NICER measures short reverberation lags

Lags evolve to higher frequencies

Reverberation in XRBs: Uttley et al., 2011, De Marco et al., 2017
relativistic reflection and reverberation

Broad line is constant over time

Lags evolve to higher frequencies

Kara et al., *Nature*, 2019
Consistent picture between spectra and timing analyses!
Using the narrow core of the line to measure kinematics at large scales.

Compare to inner disc.

Miller et al., 2018
HETG observations of NGC 4151
6.4 keV Fe I is not gaussian

Tilted discs?

Flared accretion disc?
(don’t look too hard—that’s a schematic of a protoplanetary disc)
But is there relativistic reflection in NGC 4151?

Spectra is complex, doesn’t require broad line

No signatures of reverberation

High mass black hole, short observations → Are we probing long enough timescales?

Zoghbi, Miller & Cackett 2019
Using the narrow core of the line to measure kinematics at large scales

MCG-5-23-16

Zoghbi et al., 2013

Energy (keV)

Lag (ks)

Energy (keV)
Where will we be at the next X-ray Astronomy Conference in Bologna?

MCG-5-23-16

100 ks Chandra HETG

100 ks XRISM

To launch early 2022!
Conclusions

**Spectral-timing** techniques provide a new probe of accretion physics in compact objects.

**X-ray reverberation mapping** maps out compact corona and accretion disc and their evolution.

We are at the dawn of an era with **new and future time domain and timing instruments** across the EM spectrum.