Reflection Spectroscopy with STROBE-X

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X-ray Reflection from Accretion Disks
Why X-ray Reflection is Important?

X-ray reflection is the corner stone of the Fe-line method to measure the spin of Black Holes.

It is also possible to estimate the spin using continuum fitting method, or with QPO’s (not covered in this talk).
AGN Physics I: Measuring the Temperature of the Corona
If the power-law continuum is produced by a Comptonization in a hot gas of electrons:

\[
\Gamma = -\frac{1}{2} + \sqrt{\frac{9}{4} + \frac{1}{\theta_e \tau_e (1 + \tau_e/3)}}
\]

where \(\theta_e = kT_e/m_e c^2\) and \(m_e c^2 = 511\) keV is the electron rest mass (Lightman+Zdziarski 1987).

In practice:

\[
E_{\text{cut}} \sim 2 - 3kT_e
\]

Typically \(E_{\text{cut}} \sim 200\) keV (but it can be higher!)

(Courtesy of A. Marinucci.)
Effects on the Reflection Spectrum

Changes in $E_{\text{cut}}$ also affects the ionization balance in the disk atmosphere

García et al. (2015)
**Effects on the Reflection Spectrum**

Different $E_{\text{cut}}$ changes the shape of the Compton hump at $E > 20$ keV

Changes in the ionization affect the emission at soft energies!

(Cannot be mimicked by adjusting ionization parameter)

García et al. (2015)
NuSTAR Simulations

XMM + NuSTAR Simulation - TBabs*relxill

1 mCrab
10 mCrab

XMM: 0.5-8 keV
NuSTAR: 3-79 keV

1 mCrab = 2 \times 10^5 cts

200 ks Exposure

García et al. (2015)
Similar constraints at a fraction of the time!

Extending the upper limit from 30 to 80 keV improves the constraints by 20-30%
AGN Physics II: The Origin of the Soft-Excess
Understanding the Soft-Excess

Suzaku (50 ks) and NuSTAR (200 ks) simultaneous exposure of Mrk 509

Table 1

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Instrument</th>
<th>ObsId</th>
<th>Date</th>
<th>Exp (ks)</th>
<th>Counts ($10^5$)</th>
</tr>
</thead>
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<td>NuSTAR</td>
<td>FPMA/B</td>
<td>60101043002</td>
<td>2015-04-29</td>
<td>166</td>
<td>3.2</td>
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<td>2015-06-02</td>
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<td>0.6</td>
</tr>
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<td>Suzaku</td>
<td>XIS0/1</td>
<td>410017010</td>
<td>2015-05-01</td>
<td>47</td>
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</tbody>
</table>

In their analysis of the XMM-Newton and INTEGRAL campaign, \textsuperscript{?} proposed that the clearly observed soft excess in Mrk 509 is due to the presence of a warm corona, which they reproduced using a Comptonization model with the appropriate parameters. This corona can then be visualized as a warm ($kT_e \ll 1$ keV) but optically thick ($\tau \ll 1 \times 10^{-20}$) atmosphere seating on top of the accretion disk. This extended, slab-like corona is much colder than the centrally (as possibly spherical) located corona responsible for the power-law continuum emission that extends to high-energies. The emission of the hot corona was fitted with a second Comptonization model, with a higher coronal temperature ($kT_e \ll 100$ keV) and lower optical depth ($\tau \ll 0.5$).

We have adopted the \textsuperscript{?} prescription to fit the soft excess. For this, we have implemented two Comptonization components using the \texttt{nthcomp} model \textsuperscript{REF} with the required parameters to reproduce the the power-law continuum (hot corona), and the soft-excess (warm corona). A data-to-model ratio is shown in the top panel of Figure 3. These two Comptonization components, which are independent from each other, provide a good fit to both the continuum and the soft excess, and the only obvious residuals are those from the Fe K fluorescence emission due to X-ray reflection.

- Model 1 (fixed spin): $\texttt{crabcorr} \ast \texttt{Tbabs} \ast (\texttt{relxillCp} + \texttt{xillverCp} + \texttt{gau} + \texttt{gau})$
- Model 2.A (fixed spin): $\texttt{crabcorr} \ast \texttt{Tbabs} \ast (\texttt{relxilllpCp} + \texttt{xillverCp} + \texttt{gau} + \texttt{gau})$
- Model 2.B (fixed $R_{in}$): $\texttt{crabcorr} \ast \texttt{Tbabs} \ast (\texttt{relxilllpCp} + \texttt{xillverCp} + \texttt{gau} + \texttt{gau})$

Figure 3.

Count spectra from the 50 ks Suzaku XIS and the 200 ks NuSTAR FPMA/B exposures. The shaded regions show the level of background for each one of the instruments.

The results from these three fits are summarized in Clear soft-excess emission

García et al. (2017, in prep.)
Understanding the Soft-Excess

The origin of the soft-excess is still unknown. Some possibilities include:

- Thermal disk emission (multicolor blackbody)
- Warm Comptonizing “corona” \( \text{ (kT_e \sim 0.5 \, keV, \tau \sim 10-20)} \)
- Relativistic reflection (high density?)
- Some other diffuse emission (Bremsstrahlung?)
Understanding the Soft-Excess

**The Warm “Corona”**

Two different Comptonization components describe the continuum.

A hot \((kT_e \sim 100\) keV\) and optically thin \((\tau \sim 1)\) corona produces the hard power-law.

While a warm \((kT_e \sim 0.5\) keV\) and optically thick \((\tau \sim 15)\) corona produces the soft-excess (e.g., Petrucci et al. 2013; Porquet et al. 2017).

García et al. (2017, in prep.)
Understanding the Soft-Excess

The two models are statistically indistinguishable, but with very different interpretations —→ Which one is correct?

García et al. (2017, in prep.)
STROBE-X simulated data using the Warm Corona model, and fitted with the Relativistic Reflection model.

\[ \chi^2 = 33 \]

STROBE-X can clearly distinguish between these two models.
Models with high gas density ($n_e >> 10^{15} \text{ cm}^{-3}$) produce a remarkable flux excess at soft energies as free-free emission becomes important.

García et al. (2016a)
High Density Effects in AGN

IRAS 13224—3809

Afe ~ 7-8

\[ \log(n_e) = 15, 16, 17, 18 \]

Jiang et al. (2017)

IH0707–495

Afe > 10

García et al. (2016a)

Strong implications in modeling the soft-excess in AGN!
Spin Measurements (Applicable to BHB & AGN)
STROBE-X Simulations for Spin

Spin accurate constraint at short exposures (for $a > 0.5$)

Once again, spectral resolution seems relatively unimportant.
BHB Physics I: The Controversy of the Disk Truncation
The Case of GX 339-4

Hardness-Intensity Diagram of GX 339-4

Normalized PCA Count Rate vs. X-ray Intensity (L/L_{Edd})

- Truncated Disk: Rin >> Risco
- Truncated Disk? Rin → Risco
- Truncated Disk: Rin >> Risco
- ADAF at low Mdot

- Rin ~ Risco (Stable)
- Strong Disk Emission

Truncated Disk?
Rin → Risco
But how close?
Reflection Signatures

Ratio to a power-law model shows the signatures of reflection

Data/Model Ratio

Energy (keV)

Fe K emission line

Fe absorption K-edge

Compton Hump
Simultaneous fit of the RELXILL model to a 77 million count RXTE spectra revealed changes in disk and corona.

\( \chi^2 = 1.06 \)

0.1% systematics

\( a = 0.95 \pm 0.04 \) (90% conf)

\( i = 48 \pm 1 \) deg

Fe abundance 5x Solar

García et al. (2015)
Controversy on the Disk Truncation

Large disagreement with both spectral (reflection) and timing results!

- RXTE PCA
- Suzaku XIS
- XMM MOS
- XMM Epic PN (Timing Mode)
- Timing (QPOs or Lags)
A truncated disk fitted with $R_{\text{in}} = R_{\text{isco}}$ will under-predict the spin.

With a short exposure (1 ks), STROBE-X will be able to differentiate disk truncation.

Possibly, we will be able to measure both $R_{\text{in}}$ and spins! (More simulations required…)

Note that similar results apply if the source is even a mildly well illuminated (Dauser et al. 2013). Any firm recommendation to the spin unless the coronal height is small so that the ISCO also applies to spin measurements, which only yield a lower limit.

Note that the most measurable change is relatively small and occurs before the peak of the line. Therefore, one would expect the peak to shift to higher energies, which is consistent with observations. However, the change is not significant enough to be detected in most cases.

To quantify the effect of the assumed emissivity profile, special relativistic outflow, as suggested by Beloborodov (1999; see also Malzac, Beloborodov & Poutanen 2001). Due to special relativistic effects, the emission would be beamed away from the disc, making it harder to detect.

Fabian (2005) rather than just a line.

When a disc is truncated and the inner radius is well illuminated, the emitted spectrum can resemble that produced by a jet. (This extends the simulations shown in Dausch et al. 2013.) The emission line was modelled with the continuum and relativistically-broadened iron K$\alpha$ line resulting from the base of the disc.

Other simulations were simulated using a model consisting of a power-law continuum and an inner disc truncated at different inner disc radii. The dashed line shows the effect of truncating the inner disc radii. The above recommendation, depending on the quality of the data, and source conditions including (Fig. 3). In this extreme example the source height is only a few tenths of the speed of light.

When a radio outburst occurs below the disc, the emission pattern and disc irradiation.

Spin and Inner Radius

When a disc is truncated and the inner radius is well illuminated, the emitted spectrum can resemble that produced by a jet. (This extends the simulations shown in Dausch et al. 2013.) The emission line was modelled with the continuum and relativistically-broadened iron K$\alpha$ line resulting from the base of the disc.

The height of the X-ray source above the disc is manifest in the shape of the emitted line. For example, if the source is too high, the line can be significantly broadened. If the source is too low, the line can be significantly shifted. The exact shape of the line will depend on the source height and the assumed emissivity profile of the accretion disc used in the computation.

The increase in coronal height $h$ and motion could be relevant to jetted sources, such as the low state of black hole binaries, for example. This could well be mimicking the appearance of a high source. This could also be a sign of an accretion disc truncated at the ISCO.

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The Problem of the Iron Abundance (Both AGN and BHB)
Iron abundance determinations using reflection spectroscopy from publications since 2014 tend to find a few times the Solar value!

The Problem of the Fe Abundance

![Histogram showing the distribution of Fe abundance measurements. The x-axis represents Fe abundance (Solar), and the y-axis represents the number of measurements. The histogram includes data for the total sample, AGNs, and BHBs. There are 13 AGNs and 9 BHBs.]
Fixing the Fe abundance to its Solar value resulted in poor fits with $\chi^2 \sim 10$.

A truncated disk with Solar abundance produces an Fe K line similar to an over-abundant disk reaching the ISCO.

García et al. (2015)
There are two possibilities:

1) The over-abundances are **real**, but we don’t know why

2) The over-abundances are **not real**:
   - Exotic mechanisms of apparent enhancement (e.g.; ion levitation)
   - Key physics is missing? (e.g.; high-density plasma effects)
Decoupling Absorption from Reflection (Warm Absorbers, UFOs, Wind-fed Systems)
The reflected spectra is constant while the changes are due to the variation of the absorbing column.

Large changes in the absorbing column are observed throughout the orbital period of Cyg X-1 (Grinberg et al. 2015).

Need high spectral resolution to disentangle these components!
STROBE-X Simulations

Caveats:
- Relatively small number of simulations (should run a lot more)
- Optimistic scenario: bright source, simple spectrum (continuum plus reflection)
- Only one set of relativistic parameters —> Results likely affected by reflection fraction, slope of the continuum, etc.

Questions:
- Why to stop at 30 keV? The effective area is still much larger than NuSTAR in the same band (up to 80 keV).
- Can we reduce the background? This probably limits detections at lower fluxes
- Resolution seems to be unimportant for the coronal temperature (although more detailed simulations are probably needed)

My simulation codes in Github https://github.com/jajgarcia/StrobeXsim