X-ray spectroscopy: a ruler for Active Galactic Nuclei (AGN)

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• Brief refresh on Active Galactic Nuclei (AGN) and their high-energy emission

• Measuring spatial scales of the:
  – Disk-corona system
  – Disk outflows
  – Ambient (nuclear gas)

• Implications of the results on the:
  – AGN structure model
  – AGN environs
  – AGN feed-back
  – AGN unified scenario (interpretation thereof)
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AGN Spectral Energy Distribution (SED)

“IR peak”: Reprocessing of nuclear emission by nuclear dust

Radio: Signature of a relativistic jet (or lack thereof)

“Blue bump”: thermal emission from the accretion disk

X-rays: corona Comptonizing disk photons

Radio-loud AGN (Elvis et al. 1994)
Radio-quiet AGN (Elvis et al. 1994)
COSMOS AGN
Galaxy/starburst templates

Where are X-ray photons produced?

(Reynolds, 2013, astro-ph/1307.3246)
The reflection spectrum

Reflection spectrum from “cold” (=neutral metals) matter

Reflection from ionised matter as a function of the ionisation parameter\[
\xi \equiv \frac{L}{nR^2}
\]

Ross & Fabian, 2007, 381, 1678]

(Fabian et al., 2000, PASP, 112, 1145)
Theoreticians tell us ...

The deepest AGN spectrum ever: 600 ks of RGS exposure on Mkn590

\( V_{\text{out}} = -(10-770) \text{ km s}^{-1} \)

(Detmers et al., 2009, A&A, 534, 38)
A large fraction of AGN exhibit signatures of significant obscuration

\[ \text{Compton-thin: } N_H = 2-3 \times 10^{22} \text{ cm}^{-2} \]
In the most extreme cases (Compton-thick, $N_H \geq 1.6 \times 10^{24} \text{ cm}^{-2}$) the primary is entirely suppressed, only the Compton-reflection remains visible.

Compton-thick: $N_H = 2-4 \times 10^{24} \text{ cm}^{-2}$

Beware the Fe-K line!
AGN ingredients

- Supermassive BH
- Accretion disk
- Disk winds
- Obscuring gas

Can we put a scale on this (in)famous plot?

(adapted from Urry & Padovani, PASP 107, 803)
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Measuring spatial scale at other wavelengths

- **MIR interferometry** (Jeffe et al., 2004, Nat, 427, 49)
  - Resolve parsec-scale warm dust clouds (implying a continuous input of kinetic energy to prevent their collapse)

  - Determine the location of the Broad Line Region clouds (~light-days/weeks) through the response of optical/UV emission line to change of the continuum

- **Radio**
  - Resolve sub-parsec jet cores

(Courtesy Y.Y.Kovalev, MipFR, Bonn)
Extremely compact nuclear source: SgrA* and micro-lensing

1.3mm VLBI measurement of SgrA*:

Size \sim 40 \mu\text{arcsec} \approx 4r_g

(Doleman et al., 2008, Nat, 455, 78)
Extremely compact X-ray source: occultation experiments

The spectra of a few AGN (NGC1365 in the example) show extreme variations of the absorption column density, on time-scales as low as 2 days

If due to a single cloud crossing the line-of-sight in Keplerian motion: \( \text{Size}_{\text{X-ray}} < 10^{14} \text{ cm} \)

The X-ray source is extremely compact (as also suggested by rapid X-ray variability)

First direct evidence of accretion disk reverberation

Recent discovery of “soft lags” in the spectrum of X-ray bright nearby AGN

“Lag” implies that a light curve follows another with a certain temporal delay

The light curve dominated by disk reflection (0.3-1 keV) lags the light curve dominated by the primary (1-4 keV) by ≈30 s

If this delay is due to light crossing time, this implies a corona-disk distance ~a few gravitational radii

(Fabian et al., 2009, Nature, 459, 540)
These “reverberation lags” scale with the BH mass (as predicted ...)

[Alternative interpretation: X-ray scattering by an absorbing medium whose opacity decreases with increasing energy with a high covering fraction, and that partially covers the source (cf. Miller et al., 2010, MNRAS, 408, 1928)]
Theoreticians tell us that accretion disks create outflows

Why do we care about AGN outflows?

- Are these outflows an intrinsic, indispensable ingredient of any AGN?
- Do these outflows have an impact on the host galaxy chemical enrichment?
  \[ \dot{M}_{\text{out}} = 8\pi r N_H \mu m_p C_g v_r \]
  \[ \dot{M}_w = 0.8\pi m_p N_H v_r R f(\delta, \phi) \]
- Do these outflows have an impact on the host galaxy evolution?
  \[ L_{KE} = \frac{1}{2} \dot{M}_{\text{out}} v^2 \]

We need to know column density \((N_H)\), outflow velocity \((v_r)\), covering factor \((C_g)\), launching radius \((R)\)
Independent ways to estimate the warm absorber launch radius


\[
\tau_{\text{rec}}(X_i) = \left( \alpha_r(X_i)n \left[ \frac{f(X_{i+1})}{f(X_i)} - \frac{\alpha_r(X_{i-1})}{\alpha_r(X_i)} \right] \right)^{-1}
\]


  - \( r_{\min} \leq c \geq v_{\text{esc}} = (2GM/R)^{1/2} \)
  - \( r_{\max} \leq \Delta R/R < 1 \) (i.e., the number density for a given \( \xi \) falls off rapidly)

- **Density diagnostics on emission lines** (e.g., the He-like triplets; more later)

- **Density diagnostics if the gas is heated by free-free absorption in soft spectra** (Różańska et al. 2008, A&A, 487, 895)
Outflows launching radii

Distribution of launching radii in a flux-limited sample of bright AGN

Possible wind structure (MHD acceleration)

(Laha et al., in preparation) (Kazanas et al., 2012, AstRv, 7, 92)
AGN feed-back require that \( \geq 5\% \) of the radiated luminosity is required to quench star formation, and reproduce the relation between BH mass and star velocity dispersion.

This requirement is reduced by one order of magnitude if the AGN outflow drives a wind in the hot ISM (Hopkins & Elvis, 2010, MNRAS, 401, 7) (di Matteo et al., 2005, Nat, 433, 604)
Outflows feed-back

UFOs Intermediate Warm absorbers

Extremely compact X-ray source: occultation experiments

The spectra of a few AGN (NGC1365 in the example) show extreme variations of the absorption column density, on time-scales as low as 2 days.

If due to a single cloud crossing the line-of-sight in Keplerian motion: Size_{X-ray} < 10^{14} cm

The X-ray source is extremely compact (as also suggested by rapid X-ray variability)

(Barr & Mushotzky, 1986, Nat, 320, 421)
The spectra of a few AGN (NGC1365 in the example) show extreme variations of the absorption column density, on time-scales as low as 2 days.

**NGC1365**: if due to a single cloud crossing the line-of-sight in Keplerian motion:

\[
\text{Distance}_{\text{cloud-X-ray source}} < 10^{16}\text{ cm}
\]

Relation with disk winds

Is the assumption of Keplerian motion of a spherical cloud reasonable?

In a long-look Suzaku observation of NGC1365, variation of the absorber covering factor allows to constrain the comatary geometry of the absorbing clouds.

NGC5506: the Fe K$_\alpha$ line (optically thick reprocessing) remain constant over years.

Distance to the inner side of the torus $\geq 2.5$ pc

Similar cases: NGC2992, $d\approx 3.2$ pc (Weaver et al. 1996); NGC4945 $d\geq 30-50$ pc (Marinucci et al. 2012)

Direct imaging of optically thick matter

Direct hard X-ray imaging of optically-thick reprocessing on scales $\sim 10^2$-$10^3$ pc

NGC4945 Chandra/ACIS

NGC1068 Chandra/ACIS


Evidence of scattering through a clumpy medium

- **Mkn3**: (Guainazzi et al., 2012, A&A, 547, 31)
  - correlated variability between primary and Compton-reflection consistent with small clouds of size \( \leq 0.05 \)
  - Extended emission around the Fe K\( _\alpha \) line on scales \( \approx 300 \) pc
  - This two statements are consistent only if the reprocessing medium is **clumpy**

- **ESO323-G77**: (Miniutti et al., in press)
  - First (tentative) detection with XMM-Newton/EPIC of hard X-ray scattering component through a **clumpy absorber**

  - **clumpy** distribution of clouds better fits the MIR spectra of nearby obscured AGN
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Conclusions

(Adapted from Urry & Padovani, PASP 107, 803)
Observations compel us to change this scheme in three fundamental ways:

1) Scale
2) Structure
3) Interpretation

(adapted from Urry & Padovani, PASP 107, 803)
Implication I: AGN scales

Caveat: the geometry of the X-ray corona is still unknown: lamppost? Extended?

(Courtesy A. Merloni & S. Bonoli)
Implication II: - AGN environmental gas structure

No longer separate physical systems, but a continuum of properties

(Miniutti et al., in press)
Implication III – orientation-dependent effects interpretation

Probabilistic interpretation of the Unified Scenario for AGN

panel (c) of Figure 1. Therefore, in a sample of AGNs with a distribution of covering factors, those with a larger $C_T$ will have a higher probability to be viewed as type-2 by a random observer, implying that AGNs are drawn preferentially from the distribution of covering factors; type-1 are more likely drawn from the distribution lower end, type-2 from its higher end. Contrary to the widespread notion that AGNs of types 1 and 2 are intrinsically the same objects, fundamental differences between their average properties do exist.