X-ray AGN
(Active Galactic Nuclei)

X-Ray Astronomy School V
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Based on course material by
Tom Aldcroft
Antonella Fruscione
Aneta Siemiginowska
and references therein
and original material on Quasar Jets
What are AGN?

Phenomenological:

- **Highly luminous**: $L_{\text{bol}} \sim 10^{42} - 10^{48} \text{ergs s}^{-1}$
- **Compact**: size $<< 1\text{pc}$
- **Broad-band** continuum emission:

  \[ \frac{dL}{d\log \nu} = \text{roughly constant} \]
  
  From IR to X-rays and $\gamma$-rays

- **Variable**: stronger variations on smaller timescales at shorter wavelengths
- **Polarized**: typical 1% linear in optical
- **Radio emission**: Common, but wide range
- **Emission/abs. lines**: High velocity, non-stellar
Markarian 421 – broad-band spectrum
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Time variable in all bands

IRAS 13225-3809

NGC 5548 emission lines

BL Lacertae

NGC 5548 UV continuum
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X-Ray absorption: High velocity outflow in PG 1211+143

Velocity of outflowing ionized gas based on observed line broadening
\[ \sim 0.09-0.1c \]
What is an AGN?

Physical:

- **Supermassive Black Hole**: $M \approx 10^5$ to $10^{10} \, M_\odot$
- In the center of a galaxy
- **Powered by Accretion**: $L = \eta \frac{d (M c^2)}{dt}$
- **Scale**: Eddington Luminosity: $F_{\text{radiation}} = F_{\text{gravity}} \Rightarrow L_{\text{Edd}} \approx 1.3 \times 10^{38} \, (M/M_\odot) \, \text{ergs s}^{-1}$
- **Scale**: Schwarzschild radius:
  $R_g = \frac{2GM}{c^2} = 2.95 \times 10^5 (M/M_\odot) \, \text{cm}$
What are AGN called?

- Quasars (quasi-stars)
- QSO’s (quasi-stellar objects)
- QSRS’s (quasi-stellar radio sources)
- BL Lac objects
- Blazars (BL Lac type quasars)
- OVV (Optically Violent Variables)
- Seyfert Galaxies (which may be Type 1, Type 2, Type 1.x, Narrow line type 1)
- Narrow Emission Line galaxies
- LINER’s (Low ionization nuclear emission region)
- LLAGN (Low Luminosity AGN)
What can X-rays tell us?

- **Time Variability:**
  - Scale/Size of the emitting and reprocessing regions

- **X-ray Spectra:**
  - Absorption:
    - Amount of absorbing material
    - Outflow/Inflow velocity
    - Cold/Warm absorbers
    - Ionization State
  - Thermal emission from hot gas: $10^5$-$10^7$ K  => hot gas is there!
  - Non-thermal emission: synchrotron, Comptonization  => relativistic plasma!
  - Emission lines
    - General Relativistic effects

- **X-ray Imaging:**
  - Nucleus – unresolved component
  - Extended emission on different scales: parsec to hundreds kpc
  - Jets and radio lobes
Structure of AGN

Scales for $M = 10^8 \, M_\odot$

- Black hole: $3 \times 10^{13}$ cm
- Accretion disk: $1 - 30 \times 10^{14}$ cm
- BLR: $2 - 20 \times 10^{16}$ cm
- Torus: $10^{17}$ cm ??
- NLR: $10^{18} - 10^{20}$ cm
- Jets: $10^{17} - 10^{24}$ cm

This picture based on integrated emission is only part of the story!

Absorbing outflows in AGN

- AGN of all stripes show absorption in optical through X-ray
- Outflowing material with ejection velocities up to $\sim 0.2c$ in extreme BALQSOs, but typically narrow with $v_{\text{out}} \sim$ few 1000 km/s in Seyferts
- Absorption presents opportunity for detailed physical analysis along a single sightline (vs. integrated emission)
Optical/UV Absorption due to IGM
=> Studies of Matter in the Universe

Ly$\alpha$ Forest
Damped Ly$\alpha$

Quasar
Intervening gas

To earth

H emission from quasar

H absorption

‘Metal’ absorption lines

Pettini 2003
X-RAY ABSORPTION: the intergalactic medium

Mrk 421 (z=0.03) observed by Chandra ACIS/HRC-LETG as a powerful “background” light source.

X-ray emission absorbed by intervening filaments of gas - the warm-hot intergalactic medium (WHIM)

Detection two intergalactic ionized absorbers at redshifts $z=0.011$ (NVII,OVII,OVIII) and $z=0.027$ (CIV,NVI,NVII,OVII and NeIX)
Accelerating bi-conical wind

BALs

Polarization

hollow cone

no absorption lines

Thin quasi-vertical wind

BELs

WAs

NALs

Supermassive black hole

Accretion disk

X-ray/UV ionizing continuum

accelerated radially to become a conical flow

Elvis Structure for Quasars

- BAL
- Embedded BEL clouds
- WHIM X-ray Warm Absorber
- Full continuum High Ionization BEL
- NAL
- Filtered continuum Low Ionization BEL
- Continuum Source

\[ \delta R < 10^{15} \text{cm} \]
\[ r (\text{CIV}) = 10^{16} \text{cm} \]
\[ r (\text{NAL}) = 10^{15} - 10^{18} \text{cm} \]

Total column density: \( N < 10 \) \( N \sim 10^{22.5} \)
Low Resolution Spectral Analysis – High Counts
Case Study: Spectrum of UM425A

- First goal: understand the X-ray spectrum of the bright UM425A
- With ~5000 counts this is one of the highest S/N X-ray observations of a BALQSO

Science drivers
- Is the hard powerlaw a typical $z\sim1$ RQ QSOs?
- What is the intrinsic absorbing column?
- Is the absorption “warm” or “cold”?

Analysis issues
- Source and background extraction region
- Pileup
- Fit models
- Fit statistics and minimization methods
Source and background extraction regions

- Source extraction region is commonly set to include ~95% of source photons near 1-2 keV
- X-ray mirror PSF is broader for hard photons (scattering)
- For XMM the analysis tools calculate ARF based on extraction region
- For Chandra, standard tools currently do not account for extraction region size
  - Need to be aware of this effect
  - 1" diameter (on-axis) => ΔΓ ≈ 0.10
  - 10" diameter (on-axis) => ΔΓ ≈ 0.02
  - User tools exist to correct ARF\(^1\)

- For background, usually choose a large source-free annulus. If not available use pre-made background files

- Evaluate source contamination

\(^1\)http://www.astro.psu.edu/xray/acis/recipes/non-www_scripts/xpsf/xpsf.pro
PILEUP

Multiple photon events within a single or adjacent pixels during a single readout can cause either energy or grade migration.

For bright sources this causes distortion in the image and spectrum.

An initial estimate of pileup for ACIS can easily be made with PIMMS. For XMM the SAS tool epatplot can be used as a diagnostic.

For moderate pileup in ACIS there is a CIAO thread\(^1\) that gives details of how to include the jdpileup model\(^2\) in fitting.

For strong pileup, the only option may be to excise the core and fit using only the wings. This introduces serious issues related to PSF energy dependence, assumptions in ARF generation, and grade selection of acis events.

\(^1\)http://cxc.harvard.edu/sherpa/threads/pileup
\(^2\)http://space.mit.edu/~davis/pileup2001.html
Common “Off the Shelf” low-resolution models for AGN
X-ray emission components

Torus

Accretion Disk

Black Hole

Corona

Narrow Fe-Ka ?

powerlaw

Broad Fe-Ka

Soft excess

Galactic absorption

Cold/warm absorber
AGN spectral features

Ark 564
XMM–Newton EPIC
Vignali et al. (04)

Soft X-ray excess
Power law

MCG–6–30–15
XMM–Newton EPIC
Fabian et al. (03)

Broad iron K line

Ionized absn. lines and edges from outflow
Fe K

NGC 3783
Chandra HETGS
Kaspi et al. (02)

Also unidentified features
Also substantial jet–linked X–rays in radio–loud AGN

Spectral fitting options

- Common options for X-ray spectral analysis are XSPEC and Sherpa
- As for other analysis tasks, scripting all fits and plot generation will save much time in the long run
- Fit statistic (e.g. Chi Gehrels, Chi Primini, Model Variance, Data Variance, Cash, C-stat, etc)
- Optimization method
- Binned or unbinned?

<table>
<thead>
<tr>
<th>Binned</th>
<th>Unbinned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtract background</td>
<td>Model background</td>
</tr>
<tr>
<td>Well-defined goodness of fit</td>
<td>C-stat</td>
</tr>
<tr>
<td>Intuitive visual plot of model vs. data</td>
<td>Not easy</td>
</tr>
<tr>
<td>Gaussian assump. invalid &lt; ~20 cts/bin</td>
<td>No restrictions</td>
</tr>
<tr>
<td>Fit statistic needs consideration</td>
<td>Cash is robust, unbiased</td>
</tr>
<tr>
<td>Generally faster</td>
<td>Slower</td>
</tr>
</tbody>
</table>
UM425A spectral fit conclusions

- UM425 is a very typical $z \sim 1.5$ radio-quiet QSO
  - Power law photon index $2.0 \pm 0.1$
  - Optical to X-ray flux ratio index is $\alpha_{\text{ox}} = 1.6$
- This argues against the hypothesis that BALQSOs are a special evolutionary state of AGN
- The ionization state of the X-ray obscuring material is not constrained.

![Graphs showing correlations between $N_H$ and power law photon index $\Gamma$.]
Emission Lines

• **Originate in the nucleus:**
  - Accreting matter
  - Relativistic broadening – Fe-line
  - BLR clouds

• **Originate in the hot gas away from the nucleus – NLR in Seyfert 2**
Fe-Line Profile

Fabian et. al., 2000, PASP, 112, 1145
A case for a broad line in MCG 6-30-15?

ASCA

Tanaka et al. (1995)

Chandra

Lee et al. (2002)
A case for a broad line in MCG 6-30-15?

Fabian (2002)
X-ray Imaging

“The Chandra image of NGC 6240, a butterfly-shaped galaxy that is the product of the collision of two smaller galaxies, revealed that the central region of the galaxy (inset) contains not one, but two active giant black holes.” (Chandra press release)
Extended Emission: NGC 1068

Fig. 2. Chandra HETGS spectra of the NE cloud, centered in the NE of the nucleus. Binning is the same as in Fig. 1. The forbidden lines (Fe and Mg) are weaker than in the nucleus region (Fig. 1) due to lower column density. The H-like and He-like resonance lines are relatively stronger from photoexcitation. The Fe L emission lines are stronger, indicating a greater Fe abundance. Fe Kα emission is weaker because there is relatively little neutral matter in this region.
Centaurus A

- arclike soft X-ray structures, extending to ~8 kpc in the direction perpendicular to the jet.

- diffuse X-ray and the optical emission in the arcs could originate in a region of interaction (possibly a shock) between the infalling material from the outer regions of the galaxy and the cool dust and H I-emitting material in the center or from an equatorial outflow resulting from an outburst of nuclear activity ~10^7 yr ago.

Karovska et al 2002
Observations of Extragalactic X-ray Jets

Before Chandra:
Only 3 Certain Detections; M87, Cen A, 3C 273

Chandra Launched:
Large numbers of jets detected.

Angular Resolution!
Importance of Jets

• What Do Jets Do?
  – Carry large quantities of energy, to feed radio lobes
  – Significant part of black hole energy generation budget
  – Interact with gas in galaxies and clusters of galaxies

• What Do We Want to Learn
  – Particle composition and acceleration
  – Jet acceleration and collimation

• Why Do We Need X-Ray Data?
  – Spectral Energy Distribution (SED) gives mechanism
  – Particle lifetimes change with observed band
4C19.44 = PKS1354+195
\[ z = 0.72 \]

28" = 203 kpc

PKS 1055+201 = 4C 20.24
\[ 30" = 247 \text{ kpc} \]

\[ z = 1.11 \]

0.5–7 keV
A synchrotron spectrum cannot extend from the radio to the X-ray region. Next simplest is inverse Compton scattering on the cosmic microwave background. Implies that the jet is in relativistic motion.
4C19.44 Jet Structure

Deprojected Distance (kpc)

Distance from Quasar [arcsec]

B [$\mu$G], or $\delta$

4C 19.44 Jet Power

kpc, deprojected

Kinetic Flux [10$^{45}$ erg/s]

Distance from Quasar [arcsec]
Implications of the AGN Jets

- Eddington Luminosity might not limit Accretion Rate

- Jets may Power Cluster Cavities – Stop Cooling Flows

- IC/CMB X-ray jets Maintain Constant Surface Brightness vs. $z$. We will detect them at Arbitrarily Large Redshift.
Related Topics

We were not able to cover

1. AGN number counts. Gives information on the cosmic evolution of various AGN types. Apply the continuity equation:

\[
\frac{\partial N(L, t)}{\partial t} + \frac{\partial (dL/dt N(L, t))}{\partial L} = S(L, t)
\]  \hspace{1cm} (1)

2. Type II AGN and spectral synthesis
   How do the AGN spectra add up to make the diffuse X-ray background?

3. Hardness ratios for low count spectral information

4. Gravitational lensing

5. Different models and modes of accretion

6. Role of AGN outbursts in clusters, to reverse cooling flows.