X-ray Observations of Cosmic Accelerators

Greg Madejski
SLAC/KIPAC

Outline:

• Continuing on the case studies and “X-ray insights” into the questions of particle acceleration in the cosmos

• Today: - active galaxies and relativistic jets
- clusters of galaxies
Active galaxies and strong gravity

• Many galaxies contain exceptionally bright nuclei that are also point-like sources of radio and X-ray emission

• In some cases, the nuclei are so bright that the galaxy can be barely detected

• We now believe that the origin of this emission is the release of gravitational energy by matter flowing onto a supermassive black hole, with a mass of $10^6$ or more times the Sun

“Normal” galaxy M74
Active Galactic Nuclei: the “working picture”

- Discovery of active galaxies – a.k.a. quasars - was one of the successes of astronomy outside of the visible band (optical IDs of radio sources, high redshifts -> large distances)

- Active galaxies are bright and given their large distances, very luminous

- Our best model for all active galaxies includes the same basic ingredients: a black hole accreting via disk-like structure, located in the center of a galaxy: this emission is mostly isotropic

- In some active galaxies the radiation is dominated by emission from relativistically boosted jet, so bright that the jet outshines the isotropic emission

- Connection to the jet one of the central questions of the AGN research

Diagram from Padovani and Urry

Optical spectrum of a high-redshift quasar 0746+25
Radio galaxy M87 (Virgo-A) studied with the Hubble Space Telescope

Seyfert galaxy NGC 4258 studied using H$_2$O megamaser data (Miyoshi et al. 1995)

- Black holes are a common ingredient of nearly all (!) galaxies
- When “fed” by galaxian matter, they shine – or produce jets – or both
- The BH mass is very important to understand physical processes involved
Second high-quality example: after the “archetypal” NGC 4258: IC 2560 (Greenhill, Madejski, …) - black hole mass: $2.8 \times 10^6 \, M_\odot$

Megamasers important – can provide an independent measures of the Hubble constant
“Central engine” – clues from the X-ray spectra of AGN

- Asca, XTE, OSSE data for bright AGN IC 4329a (from Done, GM, Zycki 2003); average spectrum of ~20 AGN looks essentially the same

- General description of the broad-band intrinsic X-ray spectrum of a “non-jet” emission from an AGN is a power law w/photon index ~ 2 & exponential-like cutoff at ~ 200 keV, modified by “environmental effects” (absorption, Compton reflection from the accretion disk, …)
Iron K line as a probe of the innermost regions of the accretion region

Asca X-ray spectrum of the Fe K line region for an active galaxy MCG-6-30-15 (from Tanaka et al. 1995)

Fe K emission line (n=2 -> n=1) is a great tool to study the kinematics of the accreting material:
* relatively simple atomic physics,
* high fluorescence yield with appreciable abundances,
* no contamination by other elements, ...

Profile of the Fe K line in the active galaxy MCG-6-30-15 measured with the ASCA satellite (Tanaka et al. 1995) shows a red wing expected in strong gravity.
“Central engine” – clues from the X-ray spectra of AGN

* Spectral formation: multiple Compton scattering of soft accretion disk photons by trans-relativistic corona with kT ~ 100 keV:
  -> “scaled-up” Galactic black hole binaries
* As in the Galactic binaries: what heats / accelerates the electrons in the corona?

Origin of the individual ingredients of the X-ray spectrum

Model: black hole, (red) disk, (blue) corona
Heavily obscured AGN “hiding in the dust”:
Important ingredient of the Cosmic X-ray Background?

Spectrum of the CXB at $E > 5$ keV is hard, cannot be due to soft, unobscured AGN (“Seyfert 1s”)
- but it (presumably) *can* be due to superposition of AGN with a broad range
  of absorption in addition to a range of $L_x$, $z$

*Is there a need for truly diffuse component contributing to the hard X-ray Cosmic Background?*

Example: absorbed (“Seyfert 2”) active galaxy NGC 4945
Jets in active galaxies

- Jets are common in AGN – and radiate in radio, optical and X-ray wavelengths
- Blazars are the objects where jet is pointing close to the line of sight
- In many (but not all) blazars, the jet emission dominates the observed spectrum - which can extend to the highest observable energy (TeV!) gamma-rays
- Connection of the jet to the central source not fully understood

X-ray, radio and optical jets in the active galaxy M87
AGN jets are relativistic

- Large scale images (arc-sec, corresponding to ~1,000 light years) reveal jets, but small-scale (milliarcsec, or ~1 light year) reveal co-aligned time-variable outflows.

- Those are “faster than the speed of light” – but this is just a projection effect.

- 3C279 (z~0.5) is just one such “superluminal” example - most bright blazars are monitored with VLBI.

- Such monitoring reveals Lorentz factors $\Gamma_{\text{jet}} \sim 10$.

Example of VLBI superluminal expansion of a 3C279 (Jorstad et al. 2001)
Particle acceleration in AGN jets must be “local”

Example of a large-scale (~kiloparsec, ~ $10^{21}$ cm) X-ray emitting jet in PKS 0637-752 (top panel) with radio contours; bottom panel shows radio polarization.

- The time scale for energy loss by radiating particles are much shorter than the light travel time from the central engine (as much as ~ 300,000 y).
Broad-band spectrum and time variability of the jet in the archetypal EGRET GeV blazar 3C279

* GeV emission dominates the observed flux -> blazars are “extreme accelerators”

* Correlated variability on day time scales is common

* Variability in X-ray and \( \gamma \)-ray bands puts constraints on the minimum relativistic boost (\( \Gamma_j \)) of the innermost region (via \( \gamma-\gamma \) absorption to e+/e- pair production)

(Data from Wehrle et al. 1998)
EGRET All-Sky $\gamma$-ray Map (>100 MeV)
AGN jet emission can extend to the TeV band

Mkn 421 (data from Macomb et al. 1995)

Variability of the TeV blazar
PKS 2155-304 (Aharonian et al. 2007)

Mkn 501 observation by the MAGIC telescope
(Albert et al. 2007)
Modeling the blazar emission

- Approach here is the common in astrophysics “onion peeling”:
  - start with the models for radiation spectrum
  - infer the radiating particle population / geometry,
  - deduce the source structure

- Most viable models are “leptonic” –
  - synchrotron emission for the low-energy peak (polarization!)
  - inverse Compton emission for the high energy peak

- “Seed” photons for inverse Compton scattering can depend on the environment - internal to the jet (“Synchrotron self-Compton”) or external to the jet (“External Radiation Compton”)

From Sikora, Begelman, and Rees 1994
Modeling of radiative processes in blazars

- In the context of the synchrotron models, emitted photon frequency is
  \[ \nu_s = 1.3 \times 10^6 B \times \gamma_{el}^2 \text{ Hz} \]
  where \( B \) is the magnetic field in Gauss
  and \( \gamma_{el} \) is the electron Lorentz factor

- The best models have \( B \sim 1 \text{ Gauss} \), and \( \gamma_{el} \) for electrons radiating at the
  peak of the synchrotron spectral component of \( \sim 10^3 \text{ – } 10^6 \),
  depending on the particular source

- The high energy (Compton) component is produced by the same
  electrons as the synchrotron peak and \( \nu_{\text{compton}} = \nu_{\text{seed}} \times \gamma_{el}^2 \text{ Hz} \)

- Still, the jet Lorentz factor \( \Gamma_j \) is \( \sim 10 \), while Lorentz factors of
  radiating electrons are \( \gamma_{el} \sim 10^3 \text{ – } 10^6 \)

- What converts the bulk motion of the jet to the
  ultrarelativistic particle energies?
Why is the X-ray band important?

Broad-band spectra of two classes of blazars:

3C279 (data from Wehrle et al. 1998)

Mkn 421 (data from Macomb et al. 1995)

Compton component: X-rays probe the total jet content (particles radiating at the low end of the distribution are most numerous)

Synchrotron component: X-rays probe the most energetic end of particle distribution
Content of jets in active galaxies

* Are blazar jets dominated by kinetic energy of particles from the start, or are they initially dominated by magnetic field (Poynting flux)? (Blandford, Vlahakis, Wiita, Meier, Hardee, …)

* There is a critical test of this hypothesis, at least for quasar-type (“EGRET”) blazars:

* If the kinetic energy is carried by particles, the radiation environment of the AGN should be bulk-Compton-upscattered to X-ray energies by the bulk motion of the jet

* If $\Gamma_{\text{jet}} = 10$, then the ~10 eV H Ly$\alpha$ photons should appear bulk-upscattered by $\Gamma_{\text{jet}}^2$ - to $10^2 \times 10$ eV ~ 1 keV

Optical spectrum of a distant blazar: the Ly $\alpha$ line is redshifted to $\lambda \sim 5000$ Å
Jet content cont’d

Suzaku data for PKS 1510-089: possible evidence for “bulk-Compton” bump?

• The soft X-ray excess might be the tentative evidence for the “Sikora bump” – arising by the inverse Compton scattering of BEL light by the cold electrons in the jet – but even if it is not “bulk-Compton”…

• From its isotropic luminosity of $L_{\text{BC}} < 3 \times 10^{44}$ erg/s - we can set a limit on the energy flux $L_{e,\text{cold}}$ carried by the cold electrons and the $e^+/e^-$ pair content of the jet:

\[- \text{since } L_{\text{BC}} = (4\sigma_T/3m_e c^2) U_{\text{BEL}} r_{\text{BLR}} \Gamma_j^3 L_{e,\text{cold}} \]

\[L_{e,\text{cold}} < 2.7 \times 10^{43} (r_{\text{BLR}}/0.1 \text{pc}) (\Gamma_j/10)^{-3} (L_{\text{BEL}}/10^{45} \text{erg/s})^{-1} \text{ erg/s} \]

- Significantly less than the required kinetic luminosity of the jet

- Now the total power delivered by the jet must be $8 \times 10^{44}$ erg/s

- With more realistic parameters, $n_e/n_p$ in the jet is < 5

--> Jet contains more pairs than protons, but cannot be dynamically dominated by $e^+/e^-$ pairs

- For details, see Kataoka, GM, + 08
Recent results from Suzaku X-ray variability of TeV-emitting blazars

Asca data for Mkn 421

Suzaku observed another TeV blazar, 1218+304, reveals that hard X-rays lag soft X-rays: 20 ks delay of 6 keV vs. 0.6 keV X-rays - clear energy-dependent acceleration time scale? (Sato et al. 2008)

-> Implications on the structure of B-field
Another recent example: Mkn 421 observed with Suzaku

- Broad-band X-ray spectrum measured by Suzaku cannot be described as a simple power law
- Instead, the index steepens with increasing energy
- Assuming constant B field, steepening electron distribution is implied
- Best fitted with power-law electron distribution (index ~ 2.2), with super-exponential cutoff
  (as inferred for some SNR; Tanaka et al. 2008)
- Such a cutoff is predicted in, e.g., radiating relativistic electrons that were accelerated in turbulent B field
  (see, e.g., Stawarz and Petrosian 2008)
- Applicable to many blazars where the X-ray band represents the high-energy tail of the synchrotron peak
  (often the “TeV blazars”)
Clusters of galaxies as particle accelerators

Cluster of galaxies Abell 2029

• Clusters of galaxies are largest gravitationally bound and relaxed structures in the Universe
• They are strong X-ray emitters -> X-rays provide measure of their total mass
• Keeping clusters gravitationally bound requires unknown form of non-baryonic but gravitating material ("dark matter")
• Mass distribution inferred from gravitational lensing data generally (but not always!) agree with the X-ray data
• They are great cosmological probes: their mass/number density as function of cosmic time is an excellent probe of cosmological parameters
The Sunyaev-Zel’dovich Effect

Clusters and the CMB

Abell 2218

HST • WFPC2

Abell 2218 contours are 10% of the peak

X-RAY

MICROWAVE BACKGROUND PHOTON

HOT CLUSTER GAS

ENERGETIC ELECTRON

BLUE SHIFTED MICROWAVE PHOTON

OBSERVER

from L. Van Speybroeck

Abell 1914 \( z=0.17 \)

CL0016+16 \( z=0.54 \)

MS1054-0321 \( z=0.83 \)
Comparison of independent cosmological constraints: cluster $f_{\text{gas}}$ method and supernovae ($\Lambda$CDM)

Color coding:

Cluster $f_{\text{gas}}$ analysis including standard $\Omega_b h^2$, $h$ and $b$ priors (Allen et al. 2004)

CMB data (WMAP +CBI + ACBAR) weak prior

0.3<$h$<1.0

Supernovae data from Tonry et al. (2003)

IMPORTANT: cluster data “orthogonal” to other methods

Figure and analysis from Allen et al. (2004)

More up-to-date results for a larger sample are in Allen+ 2007
Cosmological constraints from X-ray observations of clusters (from Mantz et al. 2007)

- Future observations should provide more and better data – following up on complete samples from S-Z surveys, E-Rosita, ... (but lots of observing time will be needed...)
- It is important that we understand the systematic effects

**Figure 10.** Joint 68.3 and 95.4 per cent confidence constraints on $\Omega_m$ and $w$ for a constant-$w$ model using the luminosity function data (purple) and our standard priors (Table 1). Also shown are independent constraints from CMB data (blue; Spergel et al. 2007), SNIa (green; Davis et al. 2007) and cluster $f_{\text{gas}}$ data (red; Allen et al. 2007).

**Figure 12.** The joint constraints (68.3 and 95.4 per cent confidence) on $\sigma_B$ and $w$ obtained from a combined SNIa+$f_{\text{gas}}$+CMB analysis (blue) and the improved constraints obtained by combining this with the XLF results using importance sampling (gold). No priors on $h$, $\Omega_m h^2$ or $n_s$ are imposed in either analysis.
• Clear relationship between $L_x$ and $T_x$ $\rightarrow$ in principle can get the gas mass and total mass via hydrostatic equilibrium
• Normalization very different for relaxed vs. merging vs. “cooling core” clusters
• Robust mass determination requires knowledge of the dynamical state (“relaxedness”) of the X-ray emitting gas
• Non-thermal processes and bulk gas motion are likely in disturbed clusters…

XMM data:
from
Andersson, Peterson, GM, & Goobar 2008

Blue: cooling-core clusters
Truly disturbed ("bullet") cluster...

Offset between gas and mass peaks $\rightarrow$ Dark Matter exists!
(Clowe et al. 2004)

From Markevitch et al. (X-ray data: 2004, 2005); Clowe et al. (lensing data: 2004), and Bradac et al. 2006 (S+W lensing)

What are details of formaton of clusters? Non-thermal processes? Best studied in hard X-rays: inverse Compton of CMB photons against cluster’s relativistic particles
Radio observations reveal non-thermal particles in clusters

- Clusters are often radio emitters
- Radio emission -> synchrotron (relativistic electrons in $B$ field)
- Cannot easily break the degeneracy between the $B$ field and electron distribution from radio data alone

Cluster of galaxies Abell 2255
X-ray data (Rosat, color) + radio data (contours), from Govoni + 2005
Radio emission is polarized!
Hard X-ray observations as probes of $B$ field in clusters

* Relativistic electrons IC-scatter the Cosmic Microwave Background and produce non-thermal X-ray flux

* Cannot use soft X-ray data – thermal emission dominates in the soft X-ray band

* Comparison of radio and hard X-ray data can break the degeneracy between the B field and distribution of $\gamma_{el}$ and map B-field in clusters

* RXTE as well as the current Suzaku HXD data suggest that the $B$ field is relatively strong ($\sim \mu$Gauss), $\gamma_{el} \sim 1000$

* Particle lifetimes relatively short -> continuous/distributed acceleration needed

* Detailed measurements require X-ray imaging instruments!
• NASA’s Small Explorer mission, led by Caltech (PI F. Harrison), slated to fly in 2011-2012
• Two identical coaligned, multi-layer grazing incidence hard X-ray telescopes + actively shielded solid state CdZnTe pixel detectors
• Extendable mast provides 10-m focal length; energy bandpass 6 – 80 keV