Chandra Observations of Relativistic AGN Jets

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TEXAS AT STANFORD
2004 December 15
Observations of Extragalactic X-ray Jets

BC: 3 Clear Detections

Chandra Launched: Jets start rolling in.

CE: 3 Fields of Investigation

- Interactions with gas in Seyferts, radio galaxies, clusters.
- FR I and BL Lac jets.
- Quasars, Powerful Radio Sources, and Cosmology.
Observations of Extragalactic X-ray Jets

BC: 3 Clear Detections

Chandra Launched: Jets start rolling in.

WHY?

Angular Resolution!

3C 273

10" = 29 kpc

0.5 to 7 keV

10" = 27 kpc
INTRODUCTION

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

• What Do Jets Do?
  – Carry large quantities of energy, to feed radio lobes
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• 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
Outline

1. Spatially resolved analysis
   • Broadband SED
   • Interpret X-rays as IC/CMB
     – $B$, $\delta$, $\gamma_{\text{min}}$
   • Kinetic flux and efficiency

2. Morphology

3. Jets at Large Redshift

Outline

1. Spatially resolved analysis

2. Morphology
   - Profiles
   - X-ray vs Radio Brightness
   - Bends and curvature
   - X-ray vs Radio Polarization

3. Jets at Large Redshift

PKS0637-752 at $z=0.653$

PKS 1127-145 at $z=1.187$

Siemiginowska et al. 2002
Outline

1. Spatially resolved analysis

2. Morphology

3. Jets at Large Redshift
   • Radio quiet X-ray jets?
   • Beacons to Large Redshift?

J0841
30" = 273 kpc
Schwartz et al., 2004ApJ...605L.105S
z=1.866

GB 1508+5714
3" = 20 kpc
Siemiginowska et al., 2003ApJ...598L..15S
z=4.3
PKS 0637-752

$z=0.653$

0.5-7 keV X-rays

8.6 GHz

11" = 76 kpc

K1  K2  K3  K4
0.5-7 keV X-rays

PKS 0637-752

z=0.653

8.6 GHz

11"=76 kpc
Spectral Energy Distribution often indicates against Synchrotron X-rays

PKS 0208-512 Jet

PKS 0920-397 Jet

PKS 1030-357 Jet

PKS 1202-262 Jet
Spectral Energy Distribution often indicates against Synchrotron X-rays

Sambruna et al., 2002ApJ...571..206S
Spectral Energy Distribution often indicates against Synchrotron X-rays

Inverse Compton X-rays from the CMB:
\[ \gamma_x \approx 10^{2-3} \]
\[ \gamma_r \approx 10^{4-5} \]

Some jets may be detectable by GLAST, at \(10^{-13}\) to \(10^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\)

Sambruna et al., 2002ApJ...571..206S
PKS 0637-752 Jet Spectrum

![Graph showing the spectrum of electron energy distribution with a log-log scale. The inset graph shows a power law distribution with minimum energy and index.](image-url)
Confront IC/CMB with Morphology

3C 273 Jet

X-ray Counts

Distance (kpc)

Distance along jet, arcsec

1.6 GHz, Scaled
Confront IC/CMB with Morphology

3C 273 Jet

Naive Models

X-ray Counts

Distance (kpc)

1.6 GHz, Scaled

Distance along jet, arcsec

Synchrotron X-ray

Radio Profile

X-ray Profile

IC/CMB X-rays

Radio Profile, z=1

X-ray Profile

Radio Profile, z=5
Confront IC/CMB with Morphology

Naive Models

Siemiginowska et al. 2002 ApJ...570..543S
PKS 1127-145 at z=1.187
PKS 1421-490 Images
Gelbord et al.

a) ATCA 20 GHz
b) Magellan i'
c) Chandra 0.5 – 7 keV
PKS 1421-490 Spectra
Gelbord et al.

Core Model
Radio–Optical: Synchrotron Equipartition
\( B = 13 \text{mG}, \Gamma = 20, \theta = 2.9^\circ \)
\( 20 \leq \gamma \leq 10^4 \)
\( \gamma_{\text{break}} = 10^3 \)
X-ray: SSC

Jet Model
Radio–Optical: Synchrotron Equipartition
\( B = 85 \text{mG} \)
\( 10^4 \leq \gamma \leq 2 \times 10^6 \)
X-ray: Upstream Comptonization?
• Determined $B$ and $\delta$ within a factor of 2

• Kinetic flux is $\propto (B\delta)^2$, for equipartition
Structure of the Jets

- PKS 0208-512
- PKS 0920-397
- PKS 1030-357
- PKS 1202-262
- PKS 0637-752

Doppler Factor $\delta$

Magnetic Field $\mu G$
Kinetic Flux

- $K = \Gamma^2 \pi r^2 \beta c U$
- $U$ is total internal energy density, $U_B + U_e + U_p$
- For equipartition,
  $U = \frac{B^2}{8\pi}(2 + k)$
- NOTE: $K$ constant $\Rightarrow (B \Gamma)^2 = \text{constant}$
Kinetic Flux

- \( K = \Gamma^2 \pi r^2 \beta c U \)
- \( U \) is total internal energy density, \( U_B + U_e + U_p \)
- For equipartition,
  \[ U = \frac{B^2}{8\pi}(2 + k) \]
- NOTE: \( K \) constant \( \Rightarrow \)
  \[ (B \Gamma)^2 = \text{constant} \]
- We take \( \Gamma \approx \delta \)
  \[ \delta = (\Gamma(1 - \beta \cos(\theta)))^{-1} \]
- \( \cos(\theta_{\text{max}}) = \frac{\delta^{-1}/\delta}{\sqrt{\delta^2-1}} \)
Kinetic Flux

From \( K = \Gamma^2 \pi r^2 \beta c U, \)

\[ K \propto \delta^2 \theta_\Gamma^2 \left( 3 B^2 / (8 \pi) \right) \]
Kinetic Flux

From $K = \Gamma^2 \pi r^2 \beta U$,

$K \propto \delta^2 \theta_r^2 \left( \frac{3 B^2}{8 \pi} \right)$

Kinetic flux is a significant, even dominant, portion of the accretion energy budget.
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.
Synchrotron vs. IC/CMB

Magnetic Field ($\mu$Gauss)

REDSHIFT

$B_{\text{radio}}$
Synchrotron vs. IC/CMB

Magnetic Field ($\mu$Gauss)

REDSHIFT

$B_{\text{radio}}$

$B_{\text{IC/CMB}}$
Where ARE the bright X-ray Jets at High Redshift?

• Unidentified ROSAT sources?

• Bright ROSAT, ASCA, EINSTEIN quasar identifications?

• Extreme X-ray/Optical sources (Koekemoer et al. 2004ApJ...600L.123K) in Chandra Deep Surveys?
Where ARE the bright X-ray Jets at High Redshift?

3" = 20kpc

GB 1508+5714
z=4.3

Siemiginowska et al. 2003ApJ...598L..15S

Cheung, 2004ApJ...600L..23C
Two more High Redshift X-ray Jets: Cheung et al. Poster 1613

Quasar 1745+624 = 4C +62.29 at z=3.889

PMN J2219-2719 at z=3.634
There Could Be Radio Quiet X-Ray Jets!

- 1 keV X-rays produced by $\gamma \approx 1000/\Gamma$
- $\nu = 4.2 \times 10^{-6} \gamma^2 \text{ H}[^{\mu}\text{G}]$
  $\approx 10$ MHz
There Could Be Radio Quiet X-Ray Jets!

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Cheung, 2004 ApJ... 600L..23C
A Radio Quiet X-Ray Jet?

EMSS 0841+1314

$30'' = 273$ kpc

$f_{8.6GHz} \leq 100\mu$Jy
Correlation of X-ray Jet and Radio Flux Densities

$X$-ray to radio jet

$X$-ray to core radio

$\frac{f_{\text{1keV}}(\text{nJy})}{f_{\text{5GHz}}(\text{mJy})}$ for Jets

Redshift

$\frac{f_{\text{1keV jet}}}{f_{\text{5GHz core radio}}}$ (mJy)

Redshift

$\Gamma=15$, $\gamma=3$

J0841+1311

GB1508+57

J2219

J1745

$\Gamma=15$, $\gamma=3$

J1745

GB1508+57

J2219
Significance of the X-ray Emission

1. Jet radiated power dominated by X-rays.
2. SED through X-ray band provides clues to structure.
   - Acceleration sites
   - Deceleration of bulk motion
   - Low energy electron cutoff
   - Hadron content

If emission is inverse Compton on CMB, and emission region is in equipartition:

3. X-rays give the effective Doppler factor and rest frame $B$
4. X-ray jets will be detectable at arbitrarily large redshift