Chandra Observations of Relativistic AGN Jets

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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
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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. Interpretation as IC/CMB
   - Energy densities: $B^2$ vs. $kT(1+z)^4$
   - Broadband SED
   - Morphology
   - $f_x/f_r$ Profiles

2. Parameters and Implications
Outline

1. Interpretation as IC/CMB

2. Parameters and Implications
   - $B$, $\delta$, $\gamma_{\text{min}}$
   - Kinetic Flux
   - Beacons at Large Redshift

Siemiginowska et al., 2003ApJ...598L..15S
A Radio Selected Jet Sample

• Flat Spectrum Quasars. Two Samples: $S_{5\text{GHz}} > 1\text{Jy}$\textsuperscript{a} or $S_{2.7\text{GHz}} > 0.34 \text{ Jy}$\textsuperscript{b}

• Radio Maps with $< 2''$ resolution have jets $>2''$ with detection expected by analogy to PKS 0637-752.

• Detected 17 of the first 30 Observed.

\textsuperscript{a}Murphy, Browne & Perley 1993
\textsuperscript{b}Lovell 1997
A Survey for X-ray Jets – Cycle 5

- PKS 2255-282
- 0820+225
- 1055+201 = 4C20.24
- 1251-713
- PKSB1116-462
- 2123-463
- 0454-463
- 2326-477
- 0234+285

- 0234+285
Synchrotron vs. IC/CMB

Magnetic Field ($\mu$Gauss)

REDSHIFT

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

Magnetic Field ($\mu$Gauss) vs. REDSHIFT
Synchrotron vs. IC/CMB

Gamma = \frac{5}{1}

Magnetic Field (\mu Gauss)

\text{B}_{\text{radio}}

\text{B}_{\text{IC/CMB}}

REDSHIFT
PKS 1202-262

HST F814W

HST f475w

z = 0.789

5° = 40.3 kpc

8.6 GHz
Spectral Energy Distribution often indicates against Synchrotron X-rays
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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 kpc scale jets may be detectable by GLAST, at \(10^{-13}\) to \(10^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\)
PKS 0637-752 Jet Spectrum

Electron Spectrum

$\gamma_{\text{min}} \leq 80$  
$\gamma^{-2.6}$

channel energy (keV)
PKS 0637-752

0.5-7 keV X-rays

z=0.653

8.6 GHz

K1 K2 K3 K4

11" = 76 kpc
PKS 0637-752

z = 0.653

0.5-7 keV X-rays

8.6 GHz

11" = 76 kpc
PKS 0637–752

$\nu f_\nu [\text{Jy} \cdot \text{Hz}]$ per arcsec

Distance [kpc]

$67$ $200$ $466$ $10$

Arcsec along jet
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

X-ray Counts

Distance (kpc)

1.6 GHz, Scaled

Distance along jet, arcsec

Naive Models

Synchrotron X-ray

Relative flux density

Distance (kpc)

IC/CMB X-rays

Relative flux density

Distance (kpc)
Confront IC/CMB with Morphology

Siemiginowska et al. 2002 ApJ...570..543S
PKS 1127-145 at z=1.187
$4C19.44$ (=$PKS1354+19$)

$X$-ray counts

Arcsec along jet

4.8 GHz, Jy/beam $\times 30$
Morphology Summary

• Roughly constant $f_x/f_r$ (within $\times 2$).
  X-rays end when radio makes sharp bend.

• X-ray profile decreases, Radio profile increases,
  $f_x/f_r$ changes more than $\times 10$.

• Roughly constant $f_x/f_r$ (within $\times 2$).
  X-rays persist beyond radio.
PKS 0637–753 K3

Equipartition $B_{eq}$ assumes:

$\alpha = 0.7$, $\nu_1 = 10^6$, $\nu_2 = 10^{12}$

For this object:

$z = 0.653$, $\nu = 8.64$ GHz

$$B_{eq} \propto \left(\frac{S_\nu}{\theta_1 \theta_2^2 \theta_r}\right)^{2/7}$$

Doppler Factor $\delta$

Magnetic Field [\mu G]
If X-rays are IC/CMB:

\[ B_0 \propto \left[ \frac{S_r(\nu)}{S_x(\nu)} \right]^{1/(1+\alpha)} \]
PKS 0637 K3

Doppler Factor $\delta$

$B_{eq}$ transforms as

$B_{jet} = \frac{B_{eq}}{\delta}$

$B_{IC}$

$B_{eq}$

$B_{jet} \quad [\mu G]$
PKS 0637 K3

$B_{IC} \text{ transforms as } B_{jet} = B_{IC} \times \delta$

Doppler Factor $\delta$

$B_{IC}$

$B_{eq}$

$B_{jet}$ [\(\mu G\)]
The intersection gives a solution for the magnetic field, $B$, in the rest frame, and for the apparent Doppler factor,

$$\delta = (\Gamma(1 - \beta \cos(\theta)))^{-1}.$$
- Determined $B$ and $\delta$ within a factor of 2
Structure of the Jets

Doppler Factor $\delta$

Magnetic Field $\mu$G

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

- $K = \Gamma^2 \pi r^2 \beta c U$
- We take $\Gamma \approx \delta$
  
  \[
  \delta = \left( \frac{1}{\Gamma(1 - \beta \cos(\theta))} \right)^{-1}
  \]
- $\cos(\theta_{\text{max}}) = \frac{\delta - 1/\delta}{\sqrt{\delta^2 - 1}}$
Kinetic Flux

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

\[ K \propto \delta^2 \theta_F^2 \left( 3 \frac{B^2}{8 \pi} \right) \]
Kinetic flux is a significant, even dominant, portion of the accretion energy budget. 

From \[ K = \Gamma^2 \pi r^2 \beta c U, \]

\[ K \propto \delta^2 \theta^2_r (3 B^2/(8 \pi)) \]
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.
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?
Anonymous ROSAT source

GB2 J1713+2148
z=4.011
415 kpc

GB2 J1713+2148
z=4.011
415 kpc
Anonymous ROSAT source

1715+2145 Jet

Quasar 1715+2145

VLA 1.425GHz
Anonymous ROSAT source

Quasar 1715+2145

VLA 1.425GHz

1715+2146 Jet

Northern Brighter X-ray source
probable jet

GB2 1713+2148

z=4.01
An Einstein and ASCA source

3" = 20 kpc

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. Texas Symposium 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 $\gamma \approx 1000/\Gamma$
- $\nu = 4.2 \times 10^{-6} \gamma^2 \text{ Hz}[\mu\text{G}]$
- $\approx 10$ MHz

![Inverse Compton Lifetimes Graph]
There Could Be Radio Quiet X-Ray Jets!

- 1 keV X-rays produced by $\gamma \approx 1000/\Gamma$
- $\nu = 4.2 \times 10^{-6} \gamma^2 \, H[\mu G] \approx 10 \, \text{MHz}$
- Age $\approx 3 \times 10^4 \, \text{years}$?
Correlation of X-ray Jet and Radio Flux Densities

X-ray to radio jet

\[ f_{1\text{keV}}(\text{nJy})/f_{5\text{GHz}}(\text{mJy}) \text{ for Jets} \]

\[ \Gamma = 15 \]

\[ \gamma \]

\[ 3 \]

\[ \text{GB}1508+57 \]

X-ray to core radio

\[ f_{1\text{keV jet}}(\text{nJy})/f_{5\text{GHz core (mJy)}} \]

\[ \Gamma = 15 \]

\[ \gamma \]

\[ 3 \]

\[ \text{GB}1508+57 \]
Significance of the X-ray Emission

1. X-rays dominate power radiated by jet
2. SED through X-ray band provides clues to structure.
   - Acceleration sites
   - Deceleration of bulk motion
   - Proton content
Significance of the X-ray Emission

If emission is inverse Compton on the Cosmic Microwave Background

3. X-rays give the effective Doppler factor, rest frame B, and electron $\gamma_{\text{min}}$

4. X-ray jets will be detectable at arbitrarily large redshift!