Deep X-Ray and Optical Observations of Quasar Jets

A status report on our survey and follow-up work

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A status report on our survey and follow-up work

Outline:
• Motivation: the case of PKS 0637-752
• Our multiwavelength survey
• Some follow-up targets:
  – PKS B1421-490
  – PKS 1055+201
  – PKS 2101-490
Early X-ray Jet Detections

• Before Chandra, few X-ray jets were known

• X-rays thought to originate as either synchrotron emission or inverse Compton scattering of radio synchrotron photons (synchrotron self-Compton, SSC)
Early X-ray Jet Detections

• M87: knots A & B consistent with continuation of synchrotron spectrum
Early X-ray Jet Detections

- Optical data too low for synchrotron spectrum
- SSC can describe data

Rosat contours over 327 MHz radio map of Cygnus A
(Harris et al. 1994, Nature 367, 713)

SEDs of Cyg A hot spots
PKS 0637-752

- First celestial target for Chandra
- Chosen as a point source to refine focus
- X-ray jet discovered
- Optical knots found with HST

PKS 0637-752

- Optical flux too low for simple synchrotron models
- SSC model requires severely non-equipartition magnetic field and fine-tuned parameters
- Inverse Compton scattering of CMB (IC-CMB) can fit the SED, using $\Gamma \sim 10$, $B \sim 15$ $\mu$G, and $\gamma_{\text{min}} \sim 10$. Parameters consistent with VLBI jet in core.

Our Chandra survey

Some motivating questions:
• Is PKS 0637-752 typical of high power (FRII) quasars?
• What fraction of radio jets have strong X-ray emission?
• What processes dominate this emission?
• What are the physical conditions within the jets?
Our multiwavelength survey

- Sample of 56 flat-spectrum radio sources selected by extended (>2") flux at 5 GHz
  - Subsample A is flux selected: highest predicted X-ray flux assuming $S_x/S_r$ ratio of PKS 0637-752
  - Subsample B is morphologically selected: one-sided, linear radio structure
- 5ks ACIS-S snapshots to detect strong X-ray jets
- New optical and radio observations
- Sources selected for follow-up study
Our multiwavelength survey

- Results on first 20 Chandra targets published this year (Marshall et al., 2005, ApJS 156, 13)
- 12/20 jet detections (9/10 A, 9/16 B)
- All X-ray jets are one-sided; varied morphologies
- IC-CMB implies B ~ 1-10 µG ($\Gamma = 10$ assumed)
- Insufficient data to rule out alternative models

Gelbord et al.: Deep Observations of Quasar Jets

Ultra Relativisitc Jets in Astrophysics, Banff, July 2005
Our multiwavelength survey

- Now have 37 Chandra observations
- 22/37 jet detections
- Finding more unusual systems
- Trouble for IC-CMB? $S_I/S_x$ should decrease with increasing $z$...

Marshall et al., in prep.;
See Marshall et al. poster for more
Our multiwavelength survey

- Highest S/N snapshots examined more carefully
- Distinct jet regions compared
  - Less blending of disparate regions
  - Test for evolution along jets

Our multiwavelength survey

- Low optical fluxes generally rule out synchrotron X-rays from a single e⁻ distribution
- IC-CMB models yield $B \sim 10 \, \mu G$, $\delta \sim 5-10$, $\theta < 10^\circ$, $\gamma_{\text{min}} \sim 50$; radiative efficiency $\sim 10^4$
- Some evidence of deceleration along jets

Follow-up observations

- Sources selected from our snapshot survey
- New Chandra observations $\sim 10 \times$ deeper
- HST and ground-based optical observations
- New radio maps
Follow-up target: PKS 1421-490

- Strong radio source
- Our only sample member without a prior identification
- Low Galactic latitude (10.9°)
PKS 1421-490

- Magellan g’-r’-i’ true-color image
- g’=24.2, i’=23.0 source at coordinates of A
- Radio source B coincides with g’=17.8, i’=17.2 object
PKS 1421-490

- Magellan g’-r’-i’ true-color image
- g’=24.2, i’=23.0 source at coordinates of A
- Radio source B coincides with g’=17.8, i’=17.2 object
PKS 1421-490 observations

- 20 GHz radio map shows structure:
  - Strongest component is unresolved (A1) with a ~1” extension (A2)
  - Component B lies 6” SW of A; it is slightly extended
  - Component C is 12” SW of A; it is clearly extended
PKS 1421-490 observations

• Optical image (SDSS i’ filter):
  – A (i’ = 23) and B (i’ = 17) are both detected; unresolved
  – B/A flux ratio is ~300
  – C is undetected
PKS 1421-490 observations

- 0.5-7.0 keV X-ray image:
  - A and B are both detected; unresolved
  - B/A flux ratio is 3.7
  - C is undetected
PKS 1421-490 components

- Properties of A:
  - Flat radio spectrum: $\alpha_r = 0.448 \pm 0.005$ (where $S_\nu \propto \nu^{-\alpha}$)
  - A1 and A2 resemble a core + jet; $\alpha_t$ of A2 is steeper than that of A1
  - VLBI: formally unresolved (< 24 mas) at 8.425 GHz; provides 35% of overall flux (35% of blend of A1, A2, and any diffuse flux at 8.5 GHz)
  - Bluer than stars in surrounding field ($g'-i' = 0.76; \alpha_6 = 1.5 \pm 0.7$)
### PKS 1421-490 components

<table>
<thead>
<tr>
<th>ATCA</th>
<th>Magellan</th>
<th>Chandra</th>
</tr>
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<tbody>
<tr>
<td>![ATCA Image]</td>
<td>![Magellan Image]</td>
<td>![Chandra Image]</td>
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#### Properties of B:
- Even flatter radio spectrum: $\alpha_r = 0.05 \pm 0.10$
- Resolved in radio band; no VLBI data (yet)
- Optically-dominated SED: $\alpha_{ro} = 0.20$ $\alpha_{ox} = 1.62$
- Flat optical spectrum lacking strong lines ($\alpha_o = 0.22 \pm 0.23$; $g'-i' = 0.11$)
Magellanic spectrum of 1421-490B

- No strong lines in optical spectrum of B (S/N ~ 8)
- The presence of a Lyman forest below $\lambda > 4370$ Å is ruled out, requiring that B have $z < 2.6$

Legend:
- “?” = Tentative absorption feature at 5825 Å
- “⊕” = telluric residuals
- “▼” = cosmic ray residuals
- “×” = a bad column

From the top down, spectra are shifted by 2100, 1400, 700, & 0 Å; 6, 4, 2, & 0 mJy
• Properties of B:
  – Even flatter radio spectrum: $\alpha_r = 0.05 \pm 0.10$
  – Resolved in radio band; no VLBI data (yet)
  – Optically-dominated SED: $\alpha_{ro} = 0.20 \; \alpha_{ox} = 1.62$
  – Flat optical spectrum lacking strong lines ($\alpha_o = 0.22 \pm 0.23; \; g’-i’ = 0.11$)
PKS 1421-490 components

• Properties of C:
  – Steep radio spectrum: $\alpha_{xy} = 1.15 \pm 0.03$
  – Well-resolved radio structure
  – No optical or X-ray emission
PKS 1421-490 interpretations

- Possibly a one-sided core-jet system:
  - core at VLBI component within A1
  - jet through A2
  - jet knot at B - a very unusual knot…
  - terminal hot spot at C
• Possibly a one-sided core-jet system:
  – Pros: VLBI hints at core-jet morphology within A1; explains flat radio spectrum at A1, steeper spectrum at A2; predicts featureless optical spectrum at B
  – Cons: knot B with optically-dominated, flat spectrum is unprecedented; optical knot-to-core ratio ~ 300 would be unique
**PKS 1421-490 interpretations**

- **Alternative interpretation:** core at B, hotspots at A & C
  - **Pros:** radio spectrum, strong optical emission of B more like a core
  - **Cons:** trades a problem at B (knot with very flat spectrum) with multiple problems at A (flat spectrum at hot spot A; >1/3 of lobe flux in core-like VLBI component) and problem of ID of B (no evidence of host galaxy in optical spectrum; possible contradiction betw. spectrum & photometric z)
• Alternative interpretation: A & B are distinct objects
  – If B is entirely unrelated to A and C…
    • Featureless optical spectrum rules out stars, normal galaxies, most AGN
    • Not a white dwarf (wrong optical colors; proper motion < 8 mas/yr)
    • BL Lac or weak-lined quasar not ruled out, but such objects are rare and
      SED properties are extreme for a BL Lac
PKS 1421-490 interpretations

- Alternative interpretation: A & B are distinct objects
  - If B is entirely unrelated to A and C…
    - Chance proximity of $F_x > 4\times10^{-13}$ erg/s/cm$^2$ source improbable (<0.1%); alignment with jet even less likely
  - …but B might not be entirely unrelated
    - A neighbor within a group or cluster?
    - Still must not have strong spectral features…
• SED of A is typical of cores
• SED of B is rather core-like, but flat optical spectrum is hard to understand
• SED of C is steeper, typical of terminal hot spots
**PKS 1421-490 interpretations**

- Emission model for A: synchrotron + beamed SSC
  - Modeled as a jet with $\Gamma = 20$, $\Theta = 2.9^\circ$, $r = 0.5$ mas = 4 pc.
  - Electron distribution with $p = 2.0$ from $20 \leq \gamma \leq 1.6 \times 10^3$; $p = 3.0$ from $1.6 \times 10^3 \leq \gamma \leq 1.6 \times 10^4$.
  - $B_{eq} = 13 \, \mu G$
• B as a knot with synchrotron X-rays?
  - Requires $\gamma \geq 10^8$ electrons, but radio-optical synchrotron model (without beaming) requires $B = 850 \mu G$, $1.6 \times 10^4 \leq \gamma \leq 2 \times 10^6$
  - Narrow $\gamma$ range, a second e\- population, and in situ acceleration?
• B as a knot with inverse Compton X-rays?
  – IC-CMB requires $\Gamma > 60$; core model only has $\Gamma = 20$
  – Upstream Compton instead?
  – Both require $e^{-}$ with $\gamma \leq 100$, but radio model has $\gamma_{\text{min}} \sim 10^4$
  – A second $e^{-}$ population? Self-absorption in a knot??
PKS 1421-490 implications

• Core at A and jet knot at B?
  – Modelling the SED of B is a challenge
  – B likely represents an extreme of jet phenomena
• Core at B and hot spot at A?
  – B must be an unusual, extremely weak-lined AGN
  – Possibly a new type of BL Lac (some similarities to object reported by Londish et al. 2004, MNRAS 352, 903)
• A and B are both cores?
  – Chance alignment highly unlikely
  – Members of same cluster? An interacting system?

More data is needed to determine the right picture.
New 1421-490 data

- New Chandra 54ks exposure
- 0.5-7.0 keV image, convolved to 1.2” FWHM
- Broad bridge of X-ray emission between A & B
- No detailed analysis yet

Also pending:
- VLBI map spanning from A to B
- HST imaging
- Deeper Magellan spectroscopy(?)
Follow-up target: PKS 1055+201

- A.k.a. 4C 20.24; \( z = 1.110 \)
- X-rays throughout 21” (≥170 kpc) north jet
PKS 1055+201: X-ray & radio

- General agreement between radio & X-ray jets; some differences in details
  - Radio peak fades faster than X-ray after 10″: inverse Compton?
  - X-ray peaks faster than radio around 17″
The northern knot of 1055+201

- 8.4 GHz resolves knot
- HST images reveal resolved source
- X-rays strengthen upstream of knot, peak at optical source
PKS 1055+201 jet model

- IC-CMB model can describe integrated jet
- Model parameters: $B \sim 10 \mu G$, $\delta \sim 6$, and $\theta \sim 9^\circ$
PKS 1055+201 envelope

- Extended X-ray emission around north jet, stopping at lobe
- Similar emission between core and south lobe, around unseen counter-jet
- Width: ~15”; length: ~45”
- Direct evidence of the jet heating the surrounding gas
PKS 1055+201 envelope

4C 20.24, Across Jet

X-ray Counts

Arcsec

North
South
Readout Streak

Gelbord et al.: Deep Observations of Quasar Jets
Ultra Relativistic Jets in Astrophysics, Banff, July 2005
Jet X-ray spectrum

Best-fitting model includes a power law with $\Gamma = 1.8$ and a thermal component with $kT = 2.7$ keV.

(244 counts)
Envelope X-ray spectrum

Best-fitting model includes a power law with $\Gamma = 0.7$ and a thermal component with $kT = 1.9$ keV.

(310 counts)
Follow up target: PKS 2101-490

- Quasar at z=1.04 (Gelbord & Marshall, in prep)
- New Chandra and HST observations
Follow up target: PKS 2101-490

- Similarities with PKS 1055+201:
  - Diffuse X-ray flux around unseen counter-jet
  - HST detection at terminal hot spot
Follow up target: PKS 2101-490

- Similarities with PKS 1055+201:
  - Diffuse flux around unseen counter-jet
  - HST detection at (leading edge of) terminal hot spot
Follow up target: PKS 2101-490

X-ray projection

Radio projection

Counts

log Counts

Chandra/ACIS-S 0.5-7.0 keV

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Ultra Relativistic Jets in Astrophysics, Banff, July 2005
Summary (so far…)

• PKS 1421-490…
  – Knot B pushes the boundaries of known jet phenomena
    • a second e- population with \textit{in situ} acceleration?
    • knot emission from compact, self-absorbed clumps?
  – If not a knot, then…
    • …B is a new type of BL Lac
    • …region A pushes the limits of known hot spot phenomena
    • …possibly an interacting system with two nuclei

• PKS 1055+201 & PKS 2101-490
  – Direct evidence of the interaction between the jet and its surroundings?
  – X-ray and optical peak lead radio at terminal hot spot
  – Inverse Compton along the jet?

See \url{http://space.mit.edu/home/jonathan/jets} for updates, preprints, images, etc.