Deep X-ray and Optical Observations of Quasar Jets

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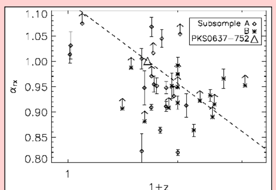
We are conducting multi-wavelength follow-up observations for a few of the more interesting systems discovered as part of our Chandra snapshot survey of quasar jet systems. What follows is an update on several of these sources, which to varying degrees are all works in progress.

Introduction: the snapshot survey

We have defined a sample of 56 flat radio spectrum* sources, selected by their extended (> 2") radio flux. To date, 37 have been observed by Chandra with short ACIS-S exposures (typically 5-10 ks).

- We find X-ray bright jets or jet knots in 2/3 of the systems (22 out of 37 so far).
- A problem for IC-CMB? The X-ray fluxes do not show evidence of the $(1+z)^4$ enhancement expected for inverse Compton scattering of the CMB (below), indicating that either a different process dominates or that there is enough scatter in the intrinsic jet properties to hide any correlation amongst our sources.
- From these we identify interesting or unusual systems for follow-up study.

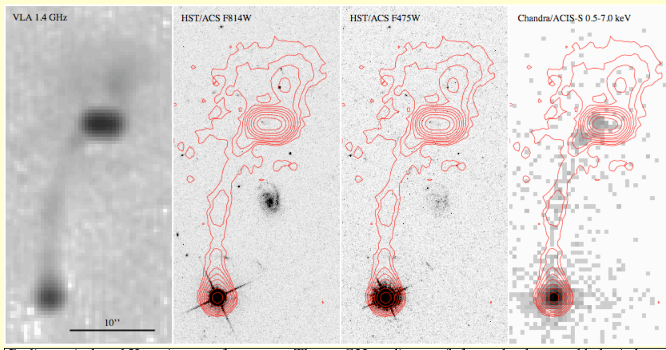
For more on the survey, see Marshall et al. 2005 (ApJS 156, 13).



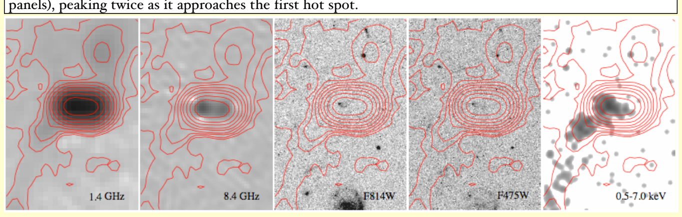
If IC-CMB dominates the X-ray emission, then the α_{rx} values would be expected to decrease with increasing z parallel to the dashed line.

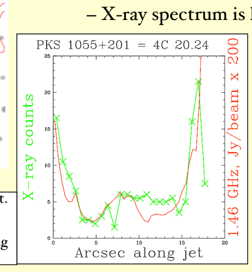
*A flat radio spectrum is defined by $\alpha < 0.5$, where $S_\nu \propto \nu^{-\alpha}$.

PKS 1055+201



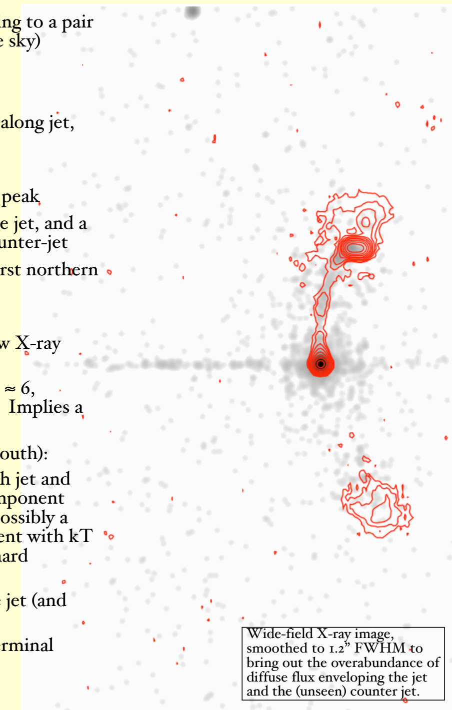
Radio, optical, and X-ray images of 1055+201. The 1.4 GHz radio map (left panels, above and below) shows an arcing jet that reaches a hot spot 21" from the core; 1.4 GHz contours are superimposed on all other images for reference. Higher radio frequencies (below, 2nd from left) resolve the northern hot spot into two peaks about 2" apart. The HST images (middle pair above; 3rd and 4th image below) reveal an extended source coincident with the first (eastern) hot spot. X-ray flux is detected throughout the long jet (right panels), peaking twice as it approaches the first hot spot.





At right: a comparision of the radio (red curve) and X-ray (green curve) fluxes along the northern jet. Midway along the jet, both fluxes peak around 8 arcsec, but the X-ray flux is sustained 5 arcsec beyond where the radio fades. This is consistent with inverse Compoton emission because the X-ray upscattering electrons have lower energies and therefore longer lifetimes than the radio-emitting synchrotron electrons. At the end of the jet the X-rays peak faster than the radio.

- A quasar at z = 1.110 with a long radio jet arcing to a pair of hot spots 170 kpc away (in the plane of the sky)
- The X-ray emission...
  - stretches throughout the northern jet
  - remains strong when radio fades midway along jet, suggestive of inverse Compton process
  - brightens upstream of radio hot spot
  - weakens rapidly after first radio hot spot peak
  - is in a broad swath of emission around the jet, and a similar broad emission around unseen counter-jet
- HST detects an extended optical source at first northern hot spot
- Preliminary spectral modeling:
  - integrated jet is consistent with power law X-ray emission:
    - iC-CMB radiation, with B ≈ 10 μG, δ ≈ 6, oriented about 9° to our line of sight? Implies a deprojected length > 1 Mpc.
  - integrated broad swath (both north and south):
    - X-ray spectrum is harder than the north jet and prefers a two component spectral model, possibly a thermal component with kT ≈ 1.3 keV plus a hard powerlaw tail
    - gas heated by the jet (and counter-jet)?
    - backflow from terminal shock?
    - something else?

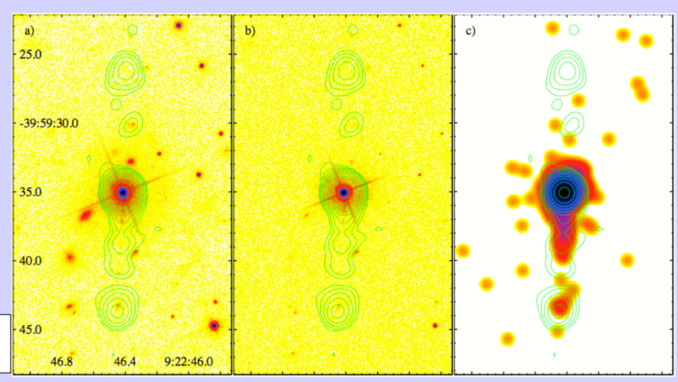


Wide-field X-ray image, smoothed to 1.2" FWHM to bring out the overabundance of diffuse flux enveloping the jet and the (unseen) counter jet.

New observations

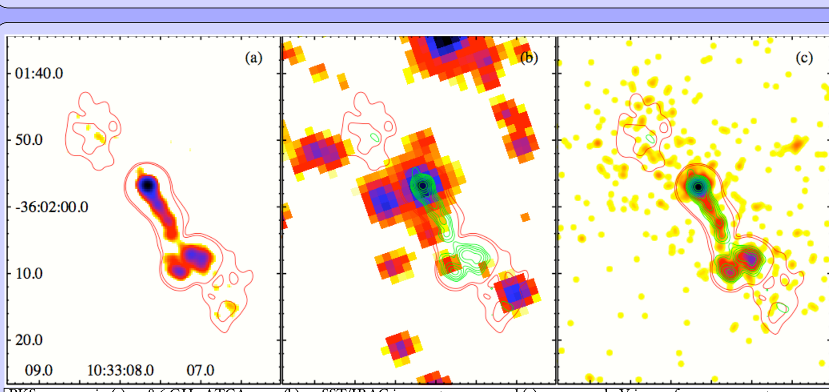
PKS 0920-397

- z = 0.591
- The jet extends 8" to the south without bending
- X-ray emission looks smooth through the first 5" of the jet
- HST resolves a string of knots stretching from 0.5" to 8" from the core. There appear to be faint knots (barely visible in the raw data) making the jet nearly continuous through the first 5-6"
- Both the optical and X-ray terminal hot spots lead the radio peak
- Like 3C 273, the X-ray/radio flux ratio declines with increasing radius
- A deeper ACIS observation is scheduled in a few weeks



PKS 0920-397 as observed by HST/ACS in the (a) F814W and (b) F475W filters, and (c) a 0.5-7.0 keV Chandra image from our initial snapshot survey (Marshall et al. 2005, ApJS 156, 13), all with 8.6 GHz radio contours overlaid. A series of knots along a narrow line can be seen extending 8" south in both optical images. Both the optical and X-ray jets may be continuous through the first 5".

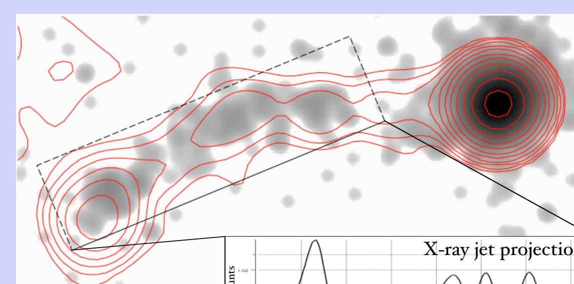
PKS 1030-357



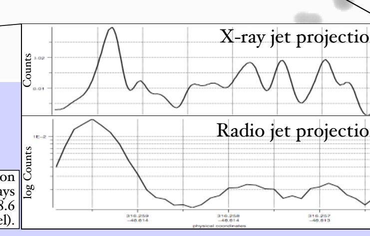
PKS 1030-357 in (a) an 8.6 GHz ATCA map, (b) an SST/IRAC image at 4.5 μm, and (c) an 0.5-7.0 keV image from our recent Chandra/ACIS observation. Two red contours from a lower-resolution 4.8 GHz ATCA map are included to locate the radio lobes. The quasar core and first (eastern) jet knot are detected in the IR; the other Spitzer sources have star-like optical counterparts.

- z = 1.455
- A rare instance in which the X-ray emission remains strong beyond a sharp bend in the radio jet
- Our new Chandra observation makes the inner jet clear (panel c, at left): where previously we had seven counts over 10", we now see a well-defined jet that clearly bends towards the easternmost of the southern knots.
- The first (and so far only) of our Spitzer targets to be observed. There is a clear Spitzer detection coincident with the first jet knot.
- Diffuse X-ray flux is seen around the jet and extending from the core through the coutnerlobe

PKS 2101-490

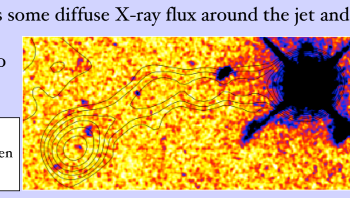


Above: 0.5-7.0 keV X-ray image of the jet smoothed to 0.89" FWHM.



Right: projected emission along the jet in X-rays (upper panel) and 8.6 GHz radio (lower panel).

- PKS 2101-490 is a quasar at z = 1.04 (Gelbord & Marshall, in prep)
- The radio jet extends 7.5" west, bends 30° to the south and continues to a hot spot 12" from the core
- X-ray emission follows the radio jet through the bend to the hot spot, peaking just before the hot spot (see figure above)
- Like 1055+201, there is some diffuse X-ray flux around the jet and the unseen counterjet
- Optical counterpart to the radio and X-ray hot spot (below)

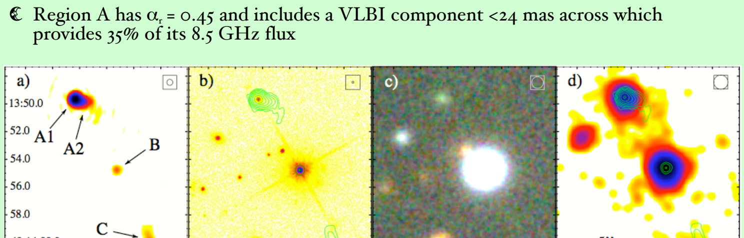


HST/ACS F814W image of PKS 2101-490 with 8.6 GHz radio contours overlaid. Image has been slightly smoothed to bring out weak features.

PKS 1421-490

Some observational details (Gelbord et al. 2005, ApJ 632, L75):

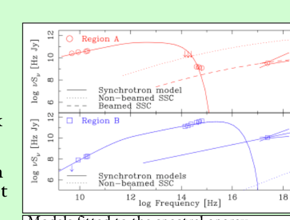
- Previously unidentifed, in a crowded field
- A 24^{th} mag optical source lies at the position of the radio peak A1 (labeled below); with colors resembling quasars at 1 < z < 2
- A 17^{th} mag object coincides with the much weaker radio source B
- Component B is also the strongest X-ray source (see below)
- B has $\alpha_r = 0.05$ and lacks any strong optical spectral features
- Region A has $\alpha_r = 0.45$ and includes a VLBI component <24 mas across which provides 35% of its 8.5 GHz flux



Several views of PKS 1421-490. A 20 GHz ATCA image (a) defines the structure. A new HST/ACS image in the F814W filter (b) shows no structure at all except for A and B, which appear to be pointlike (this needs to be verified). A true-color optical image (c) constructed from SDSS i', r', and g' images taken with Magellan. A 0.5-7.0 keV Chandra ACIS image (d) from our new, deeper (54 ks) observation showing diffuse flux in a wide swath between A and B. The FWHM of the respective PSFs are illustrated within a 1" square box.

How should these features be interpreted?

- Core at A, knot at B?
  - *Pros:* VLBI snapshot hints at core-jet morphology within A1; provides an explanation for the (marginally) flat radio spectrum of A; a jet knot B should have a featureless spectrum
  - *Problems:* Optically-dominated, flat spectrum of B is unprecedented for a knot; the optical knot-to-core flux ratio of B/A (about 300) would be unique
  - *Possibilities:* A second, high energy population of electrons with in situ acceleration to produce synchrotron X-rays, or upstream Comptonization (Georganopoulus & Kazanas 2003, ApJ 589, L5) by a decelerating jet
- Core at B, hot spot at A?
  - *Pros:* A self-absorbed core can explain the flatter spectrum of B; optical core/jet flux ratio more typical
  - *Problems:* VLBI structure at A is more core-like than lobe-like; if A is a lobe, a surprisingly large fraction of its flux comes from a single compact VLBI-scale hot spot; the spectrum of B shows no evidence of AGN or host galaxy features and its broad-band colors are unlike known BL Lacs
  - *Possibilities:* That B is an extremely weak-lined source, possibly a new type of optically-dominated BL Lac akin to the one identified by Londish et al. (2004, MNRAS 352, 903)
- Cores at A and B??
  - *Pros:* Accounts for flat radio spectra of both A and B
  - *Problems:* Probability of any unrelated X-ray source as bright as B so close to radio source at A is < 0.1%
  - *Possibilities:* Two related nuclei– an interacting system?



Models fitted to the spectral energy distributions (SEDs) of regions A and B. The model applied to A is typical of quasar cores: synchrotron emission from a jet with bulk motion of Γ = 20 at 2.9° to the line of sight, radius r = 4 pc, an electron distribution from $\gamma_{min} = 20$ to $\gamma_{max} = 1.3 \times 10^4$ with a break at $\gamma = 1.6 \times 10^3$, and B_{eq} = 13 mG. An SSC model with $B = B_{eq}$ can match the observed X-ray flux if it is relativistically beamed. For region B an assumption of no self-absorption forces us to use a narrow range of electron energies ($1.6 \times 10^4 < \gamma < 2 \times 10^6$), with B_{eq} = 0.85 mG and a r = 0.4 kpc. SSC models fall orders of magnitude below the observed X-ray flux, which may be most readily explained by an ad hoc second population of synchrotron-emitting electrons (Gelbord et al. 2005, ApJ 632, L75).

More information, including preprints, image archives, etc, may be found at our jets web site, http://space.mit.edu/home/jonathan/jets/