Large-Scale Radio and X-ray Jets in the Highest Redshift Quasars

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We describe our program to search for and study the kilo-parsec scale radio jets in a sample of high-redshift (greater than 3.4), flat spectrum quasars using new and archival VLA data. Two of these radio jets have been imaged with Chandra, and have X-ray counterparts and are briefly discussed. These high-redshift sources are important targets for testing current X-ray jet emission models for kpc-scale jets and follow-up multi-wavelength observations will shed light on this problem.

1. Kiloparsec-scale X-ray Jets in AGN

Chandra X-ray Observatory and Hubble Space Telescope observations have established that X-ray and optical emission from kpc-scale radio jets in active galactic nuclei (AGN) are common (e.g. Stawarz 2003). In quasars, the X-rays are widely interpreted as inverse Compton (IC) scattered emission off the CMB by electrons in the jet emitting synchrotron radiation at very low radio frequencies (Tavecchio et al. 2000; Celotti et al. 2001). If this is the dominant X-ray production mechanism, it implies quasar jets have large bulk velocities (Lorentz factors, $\Gamma\sim3$–15) on the observed 10's – 100's kpc-scale, so that the electrons in the jet frame see a sufficiently boosted source of seed photons to explain the X-rays.

A natural consequence of the IC/CMB model is that high-z quasars should have prominent X-ray jets (Schwartz 2002a) because of the strong dependence of the CMB energy density on redshift: $f_X/f_r \propto U_{\rm CMB} \propto (1+z)^4$. The recent detection of a bright X-ray jet in the z=4.3 quasar GB 1508+5714 (Yuan et al. 2003, Siemiginowska et al. 2003), with only a faint radio counterpart (§ 2), lends support to this scenario. This jet sees 1–2 orders of magnitude times greater energy density from the CMB than jets at lower redshift ($z \lesssim 2$), so its extreme redshift may account, to first order, for its large X-ray to radio luminosity ratio (Cheung 2004). In the framework of the IC/CMB model, variations in B and jet Doppler factor, δ, can cause significant spread in the observed f_X/f_r (both along a given jet, and source-to-source), and would smear the possible relation with redshift if only a limited redshift-range is studied.

It is important to identify more jets in high-redshift quasars to observe with both Chandra and the VLA in order to compare with lower-redshift examples. Observations of these systems could help to distinguish between the different models proposed to account for the X-ray emission – one would not, for instance, expect a z-dependence in the synchrotron X-ray jets.

Unfortunately, very little is known about the extended radio structure of high-redshift quasars. Recent Chandra imaging of a number of z>4 radio loud quasars do not reveal significant extended X-ray emission (Bassett et al. 2004; Lopez et al. 2004), although there is no pre-existing information on possible radio structures in these samples.

We recently began a program to search for and study kpc-scale radio jets in high-redshift quasars. The overall goal of our work is to compile a comparison sample to the X-ray jet detections at lower-redshift to test for a bulk redshift dependence of f_X/f_r. We do not aim for our sample to be a complete one since the lower-z detections are inhomogenous – we require only that our high-z sample be comparable in radio luminosity and that the jets are beamed (i.e. are flat-spectrum core-dominated quasars). Ongoing work from this program is discussed.

2. The X-ray / Radio "Jet" in the z=4.3 Quasar GB 1508+5714

The Chandra detection of an extended X-ray feature ~2.5" from the z=4.3 quasar GB 1508+5714 (Hook et al. 1995) was reported independently by two groups: Siemiginowska et al. (2003) and Yuan et al. (2003). Subsequently, a faint radio counterpart (1.2 mJy at 1.4 GHz) to the extended X-ray feature was found (Cheung 2004), supporting the previous authors' interpretation of the emission as from a jet associated with the quasar. This makes GB 1508+5714 the most distant quasar with a *kiloparsec-scale* jet detected at any wavelength[1].

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[1] A similar single jet feature has been disovered recently on smaller (VLBI) scales in the more distant z=5.47 blazar Q0906+6930 by Romani et al. (2004).

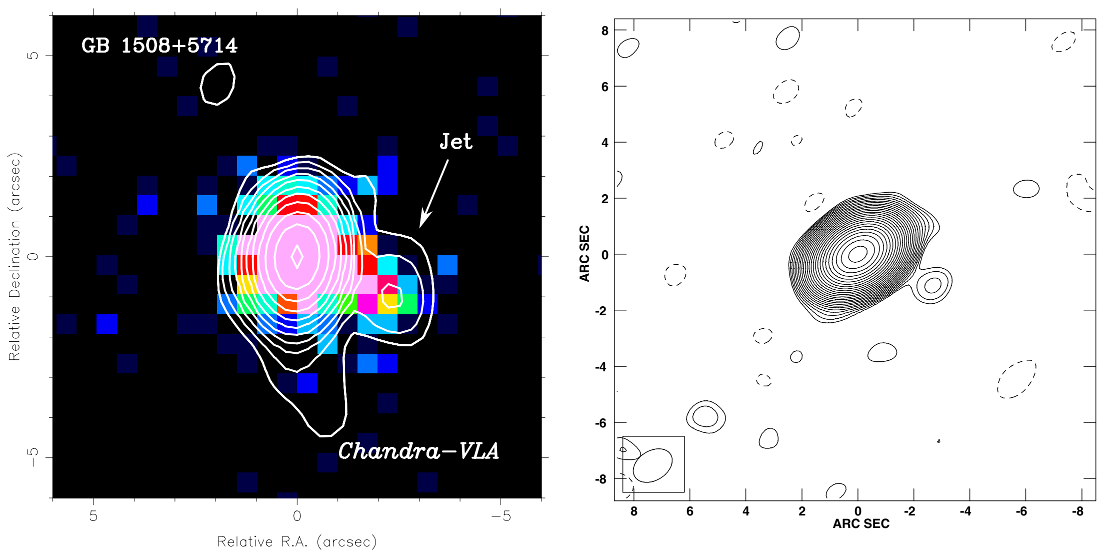

Figure 1: [LEFT] Chandra X-ray image of GB 1508+5714 (color) with VLA 1.4 GHz contours overlaid (taken from Cheung 2004). [RIGHT] New VLA 4.9 GHz map confirming the faint radio/X-ray feature ∼2.5” west of the core (see left panel). The lowest contour level is 67 μJy/bm (2σ), and subsequent ones increase by factors of $\sqrt{2}$ up to a peak of 0.323 Jy per beam (1.50”×1.05” at PA=–57.8 deg).

The jet knot in GB 1508+5714 shows an extremely high monochromatic X-ray to radio luminosity ratio (f_x/f_r=158). This is large in comparison to X-ray jets detected in lower redshift, z $\lesssim$ 2 core-dominated quasars (range of ∼0.2–50). Since this observed ratio is strongly dependent on redshift in the IC/CMB model (e.g. Schwartz 2002a), it suggests that this is an important and presumably a dominant X-ray production mechanism in kiloparsec-scale quasar jets (see Cheung 2004).

2.1. Radio Spectrum of the Jet

We have since obtained exploratory time VLA B-configuration observations of GB 1508+5714 at 4.9 and 8.4 GHz (program AC728). A total of ∼30 minutes integration per frequency was obtained, and the measured off-source rms in the self-calibrated images are within 10% of the theoretical noise level of 0.03 mJy/bm. We measured an inverted radio spectrum (α=–0.5 ±0.1; $F_\nu \propto \nu^{-\alpha}$) for the radio core between 4.9–8.4 GHz at our observation epoch (January 2, 2004).

The extended ∼2.5” radio feature is confirmed at 5 GHz, where we found a very faint counterpart (0.2 ±0.04 mJy, a 5σ detection; Figure 1). With the previous 1.4 GHz detection, the 1.4–5 GHz radio spectral index is 1.4±0.2, which is very steep in comparison to other radio jet features (e.g. Bridle & Perley 1984). Extrapolating this spectrum to 8.4 GHz, the expected flux density is ∼0.1 mJy, consistent with our previous limit at this frequency from archival data (Cheung 2004), and non-detection in the new observation (5σ=0.2 mJy at the position of the jet). The steep observed radio spectrum is probably due to the fact that we are sampling both higher rest-frame energies (up to 44 GHz for the 8.4 GHz limit) and the increased efficiency of radiative losses due to inverse Compton scattering on the cosmic microwave background at this high-redshift.

2.2. Reconstructing the Electron Energy Spectrum in a One-zone Model

Our new measurement of the jet radio spectrum allow us to rule out a single power-law extrapolation of the radio data into the X-ray band, since $\alpha_{\rm r} > \alpha_{\rm rx}$ (=0.73), as would be expected in canonical synchrotron models. If we assume the radio and X-ray emission are produced co-spatially, we can apply a ”one-zone” synchrotron (radio) and IC/CMB (X-ray) model (Tavecchio et al. 2000) as done previously for this jet (§2). Assuming also equipartition between the relativistic particles and magnetic field, we can solve for the Doppler factor, δ ∼4, and magnetic field, B ∼25 μG assuming α=0.9, the measured X-ray spectral index (Cheung 2004).

This interpretation then demands that we (or allows us to, depending on one’s vantage point) reconstruct the underlying electron energy spectrum in some detail as follows:

- The radio spectrum is steeper than the X-ray one ($\alpha_{\rm x}$ ∼0.9±0.3; Siemiginowska et al. 2003, Yuan et al. 2003) implying a break in the electron energy spectrum of ∼0.5±0.4.
- The detected IC/CMB X-ray emission is produced

by electrons with energy $\gamma \sim$ 100-1000 (0.3–5 keV) which emit synchrotron radiation at (unobservable) radio frequencies of 40 MHz and below.

• The X-ray spectral index of 0.9 reveals the intrinsic index of the relativistic electron population before the spectrum drops steeply in the cm-band ($\gamma \sim 6\times10^3$ to 10^4 for 1.4 and 5 GHz).

The overall picture is that electrons with energies $\gamma \sim 100$ to at least 10^4 are present, and a break in the spectrum occurs between $\gamma \sim$1000–6000. This has important implications for prospects of future multi-wavelength studies of kpc-scale jets:

• The lowest energy electrons Comptonize CMB photons into the optical band ($\gamma \sim$10). These electrons dominate the total energy density in the jet and deep HST observations offer a possible probe of their emission which would otherwise be unobservable at sub-MHz frequencies.

• The expected flux density of the jet at low radio frequencies – e.g. 74 MHz – is 17 mJy (if the spectrum breaks at 1.4 GHz) and up to 74 mJy (break at or below 74 MHz). This level of emission will be detectable by the proposed Long Wavelength Array (LWA) which will offer arcsecond-resolution at MHz frequencies (Harris 2005). Current VLA 74 MHz observations provide an integrated flux limit from GB 1508+5714 of $\sim$100 mJy (1σ) measured from the FITS map obtained by the VLSS survey (Cohen et al. 2004). The integrated low-frequency radio emission may well be dominated by the kpc-scale jet as radio core spectra are typically flat or inverted (§ 2.1), and its emission is expected to be mostly self-absorbed in the LWA-bands. If there is "contaminating" emission from the radio core and/or sub-arcsecond scale jet, astrometric uncertainties of order 1" or less in the LWA observations are then necessary to distinguish emission from the different components.

• The break in the electron spectrum constrains the peak of the Compton component to a narrow range (formally between 5 and 160 keV). The steep cm-wave spectrum we have measured implies that IC/CMB emission from the highest-redshift jets may be minimal in the GLAST bands (>10 MeV). If these steep cm-wave spectra persist in other high-z jets, GLAST[2] studies of IC/CMB X-ray jets may be restricted to lower-redshift targets with detected optical synchrotron jets (e.g. Sambruna et al. 2004).

[2]The main limiting factor of GLAST studies of kpc-scale jets will be its inability to separate the expected gamma-ray emission from their small-scale jets with its course angular resolution.

2.3. Fast-jets or sub-Equipartition Magnetic Field Strengths?

The one-zone synchrotron+IC/CMB model invokes relativistic motion on the observed kpc-scales in order to preserve equipartition (i.e. avoid very large total energies). This appears at odds with previous radio jet asymmetry studies which set upper limits on the jet speed of order $\Gamma \sim$3 (Bridle et al. 1994; Wardle & Aaron 1997; Hardcastle et al. 1999). Although the bulk beaming factor necessary to explain the level of X-ray emission in the GB 1508+5714 jet is not very large, other known examples show that Γ's up to $\sim$25 are necessary (e.g. Harris & Krawcynski 2002; Kataoka & Stawarz 2005). One way to relax the speeds invoked is to assume that kpc-scale quasar jets are not in equipartition as discussed recently in Kataoka & Stawarz (2005). In this scenario, the jets are characterized by sub-equipartition field and are particle dominated. This leads to quite unfavorably larger total energy requirements and synchrotron models may provide a better solution (e.g. Atoyan & Dermer 2004).

2.4. X-ray Emission from Doppler-hidden beams?

To maintain both equipartition and to accommodate radio studies which inferred slower jet speeds than in the one-zone synchrotron+IC/CMB model, one can invoke additional structure in the jet. Such "two-fluid" jet models have in fact been discussed for some time. Early radio studies advocated "transverse" velocity structures with the observed radio emission originating from a slower moving outer sheath which hides emission from a faster moving spine (see summary by Bridle 1996).

In powerful radio-galaxies and lobe-dominated quasars, we are preferentially viewing the slower-moving outer radio-emitting jet layer whose beaming cone is wide. In this case, the IC/CMB X-rays viewed by us originate predominantly from the same observed radio emission and the one-zone synchrotron+IC/CMB model is a good approximation – Chandra/radio observations of these jets may truly be telling us about their physical conditions.

In this picture, the X-rays "reveal" the faster jet spine in the core-dominated quasars which is responsible for most, if not all of the IC/CMB emission (Celotti et al. 2001). With additional transverse velocity structures come naturally other sources of high-energy emission such as turbulent interactions between the spine-sheath layers (Stawarz & Ostrowski 2002). In the IC/CMB scenario, the outer portion of the jet producing most of the observed radio emission will certainly emit IC/CMB radiation also, especially at high-redshift. The key is not whether there are IC/CMB X-rays, it is to consider also how much is being produced by the hypothetical fast spine-layer (Jorstad & Marscher 2004), and if its radio luminosity is only a fraction of the observed, how do we use the X-rays observations to tell us something useful about its physical properties?

In several kpc-scale jets in core-dominated quasars, the X-ray emission terminates abruptly, while the radio emission continues on for 10's kpc or more (e.g. 0827+243, Jorstad & Marscher 2004; PKS 0605–085, PKS 1510–089, and 1642+690, Sambruna et al. 2004). Do these mark the decollimation points of the fast spines? One can indeed find other core-dominated quasars where there is roughly 1-1 correspondence between the radio and X-ray emissions throughout the jets (e.g. Sambruna et al. 2004; Marshall et al. 2005), and lobe-dominated quasars whose X-ray jets do not persist to the terminal radio features (e.g. PKS 1136–135, Sambruna et al. 2004). This may be a resolution dependent effect, as two of the largest angular-size jets (∼30") show multi-wavelength offsets in the terminal features (PKS 1127–145, Siemiginowska et al. 2002; PKS 1354+195, Sambruna et al. 2004) with the X-rays leading the radio.

How fast can the spine-beams be? Presumably from the observed X-ray emission, one can deduce physical properties of the spines with the usual machinery (section 2.2), as a function of fraction, f, of the detected radio emission. As an analog to past studies of jet interaction with the accretion disk photon field (e.g. Phinney 1987, Melia & Königl 1989), the implied beaming factors should not be so high as to avoid Compton drag by the CMB photons, although this may be a way to explain the widely observed declining X-ray to radio flux ratios observed in many jets, which can be interpreted as jet-deceleration on the observed kpc-scales (Georganopoulos & Kazanas 2004). If also the beaming cones are made too narrow ($\sim 1/\Gamma$), one has to explain why we are finding X-ray emission from the majority of prominent radio jets in core-dominated quasars[3].

3. Searching for the Highest-Redshift Radio Jets with the VLA

Most Chandra studies of quasar jets have so far targeted *known* arcsecond-scale radio jets (e.g. Sambruna et al. 2004, Marshall et al. 2005), and most are found at z<2 (Liu & Zhang 2002). In fact, not many z>2 radio jets (kpc-scale) are known. The most extensive radio imaging studies of high-redshift quasars to date are VLA snapshot observations (few min. scans) of quasars at redshifts of up to only ∼3 (Taylor et al. 1996; Barthel et al. 2000, and refs. therein). From these studies, only a handful of arcsecond-scale jets are extended enough to be imaged with Chandra.

[3]See http://hea-www.harvard.edu/XJET/ for a list.

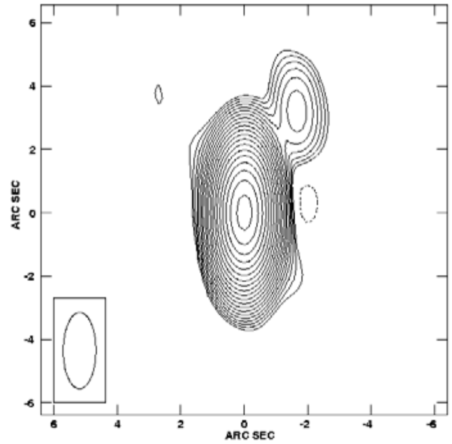

Figure 2: VLA 1.4 GHz contour image of the z=3.78 quasar PKS 2000-330 showing an extended radio feature to the northwest of the quasar. The contours begin at 0.5 mJy/bm and increase by increments of $\sqrt{2}$. The beam is 2.41 × 1.03" at a PA of –0.2 deg.

The majority of z>3 flat-spectrum radio quasars have only been discovered over the last few years from large surveys (e.g. Hook et al. 2002 and references therein), and systematic radio imaging studies have yet been carried out – we are aiming to remedy this deficiency with a VLA imaging survey.

3.1. Target Selection

We used NED[4] to help compile a sample to search for extended radio jets with the VLA with the aim of followup Chandra imaging. For an initial sample, we selected objects with redshifts of 3.4 and greater, and radio fluxes $\gtrsim 100$ mJy at 1.4 and/or 5 GHz. We excluded known radio galaxies and steep spectrum sources (e.g. van Breugel et al. 1999; De Breuck et al. 2001) and focused on the flat-spectrum ones (a first order proxy for high beaming) to facilitate a comparison with the known z $\lesssim$ 2 X-ray jets in core-dominated quasars. Our goal was to compile the best candidates to be imaged with the VLA in order to determine how common large-scale jets are at high-redshift, rather than to create a complete sample. Imaging the fainter objects and extending to lower redshifts (z∼3–3.4) are obvious extensions to our work and this is planned.

[4]This research has made use of the NASA/IPAC Extragalactic Database which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the NASA.

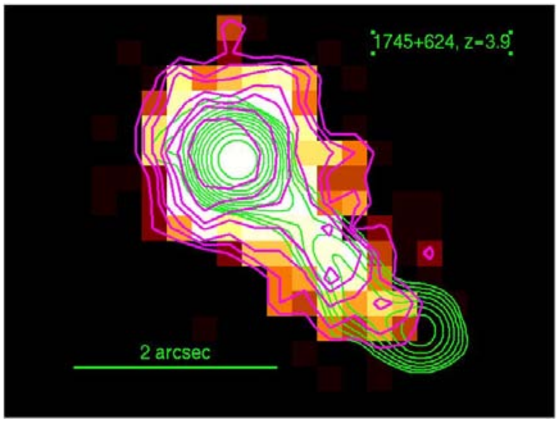

Figure 3: Chandra color (and magenta contours) and VLA 5 GHz (green contours) images of the jet in 1745+624 (4C 62.29) at z=3.9. The X-ray data are taken from the Chandra archive (PI: P. Strub; OBSID 4158). Details can be found in Cheung et al. (in preparation).

We then performed a literature and VLA archive search of the 43 sources in our final sample (z=3.4–4.8): 9 have known radio structures (jets, gravitational lenses), or have sufficient archival VLA data (Table 1). Our final targets were drawn from the remaining 34 objects which did not have suitable VLA data available. Six objects are at declinations of $\lesssim -30°$, so may explain why so little archival VLA data are available for them (see below).

Over nine observing runs in 2004 Oct and Dec, we observed 26 targets with the VLA-A configuration at 1.4 and 5 GHz (resolution 1 and 0.4 arcsec). Since the main goal of this survey was to find jets, we only obtained short snapshots at 5 GHz to estimate spectra relative to the deeper 1.4 GHz images. Archival VLA data exist for a handful of other sources satisfying our criteria and these have been analyzed also. This led to the discovery of a 3.6" long radio jet in one quasar, PKS 2000–330 (Figure 2). Archival Chandra data were available for the z=3.9 quasar 1745+624, which revealed an X-ray counterpart (Figure 3) to its known radio jet (Becker et al. 1992).

The details of this survey will be presented elsewhere. In summary, extended radio features are detected in ∼50% of the sample, although only a handful are extended enough in the z $\gtrsim$ 3.4 sample to be imaged with Chandra's ∼arcsecond resolution. The most distant object we found with a jet is the z=4.72 quasar GB 1428+4217 (Fabian et al. 1997). Proposed X-ray observations will allow us to determine the relative importance of IC/CMB versus synchrotron X-ray emissions at the highest-redshifts, leading to an important test of expectations between the X-ray emission models.

4. Summary

Jets are common features of radio-loud AGN, at radio and X-ray wavelengths, at least locally (z $\lesssim$ 2). Our work suggests that this may be true also at high-redshift (out to z=4.7) at radio wavelengths. Proposed Chandra observations will tell us if this is true also at X-rays. Extending studies to these high-redshifts should help us to distinguish between the competing synchrotron and IC models to determine if there is a redshift dependence in the X-ray jet emission.

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Table I High-redshift (z>3.4) Quasars with (publicly) Known Radio Structures

Name	z	Description [References]
0201+113	3.61	known 4” radio jet [36]
1239+376	3.818	known ∼6” radio jet [40]
1351–018	3.707	VLBI-scale jet [14]
1422+231	3.62	gravitational lens [28]
1508+572	4.301	known ∼2.5” X-ray/radio jet [9, 35, 44, This work]
1630–003	3.424	gravitational lens [43]
1745+624	3.889	VLBI jet [40]; ∼2.5” X-ray/radio jet [4, This work]
2000–330	3.773	VLBI jet [13]; new ∼4” radio jet (This work)
2215+020	3.572	VLBI jet; diffuse 7” radio extension [24] with possible X-ray emission [33]

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