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The Highest Redshift Relativistic Jets

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Abstract. We describe our efforts to understand large-scale (10's–100's kpc) relativistic jet systems through observations of the highest-redshift quasars. Results from a VLA survey search for radio jets in ∼30 z>3.4 quasars are described along with new *Chandra* observations of 4 selected targets.

1. Why High-redshift Jets?

It is now well established that X-ray emission is a common feature of kiloparsec-scale radio jets (see Harris & Krawczynski 2006, for a recent review and the associated website, http://hea-www.harvard.edu/XJET/). The spectral energy distributions (SEDs) of the powerful quasar jets are predominantly characterized as "optically faint", with the spectra rising between the optical and X-ray bands. Current models for this 'excess' X-ray emission posit either inverse Compton (IC) scattering off CMB photons in a (still) relativistic kpc-scale jet or an additional high-energy synchrotron emitting component.

In the simplest scenario, such models have diverging predictions at high redshift. Specifically, we expect a strong redshift dependence in the monochromatic flux ratio, $f_X/f_r \propto U_{\rm CMB} \propto (1+z)^4$ for IC/CMB, whereas in synchrotron models, we expect no such dependence, $f_X/f_r \propto (1+z)^0$. As a first order test of this simple idea, our approach is to study the highest-redshift relativistic jets. Such jets probe the physics of the earliest (first ∼1 Gyr of the Universe in the quasars studied) actively accreting supermassive black hole systems and

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are interesting for other reasons. For instance, the ambient medium in these high-redshift galaxies is probably different (e.g., De Young 2006) and this may manifest in jets with different morphologies, increased dissipation, and slower than their lower-redshift counterparts.

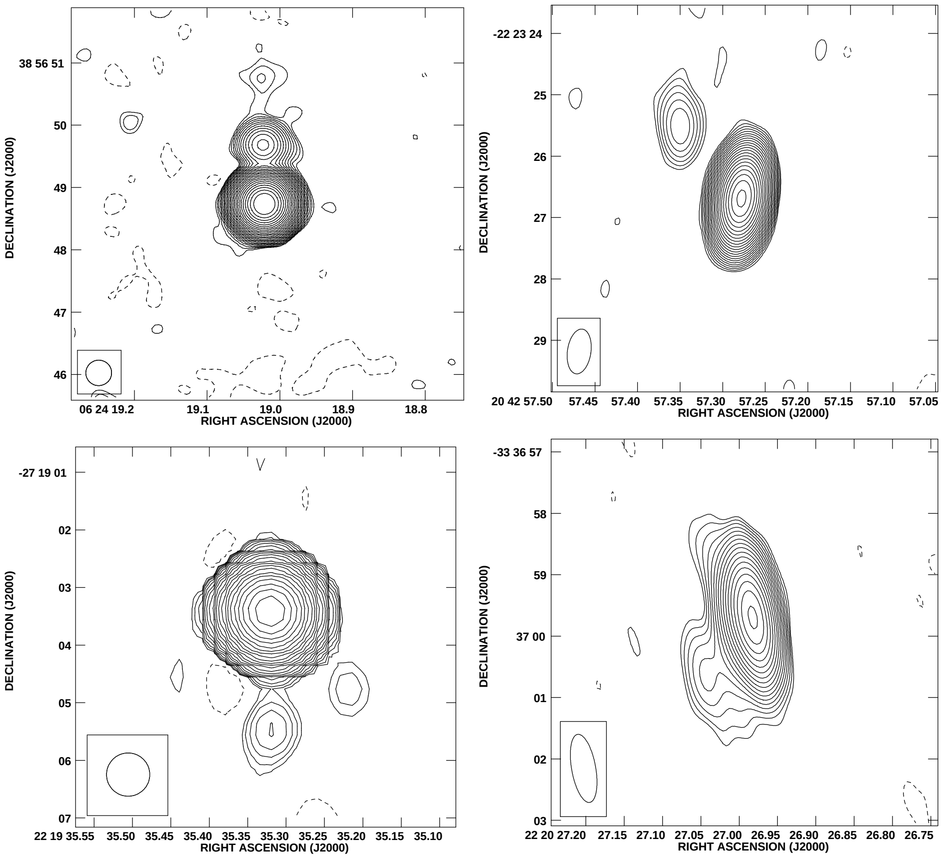

Figure 1. Examples of newly discovered arcsecond-scale radio jets from our VLA observations (§ 2.1.). Clockwise from upper left, the sources are J0624+3856 (z=3.469; Xu et al. 1995), J2042–2223 (z=3.630; Hook et al. 2002), J2220–3336 (z=3.691; Hook et al. 2002), and J2219–2719 (z=3.634; Hook et al. 2002). The J2219–2719 image is at 1.4 GHz while the rest are at 5 GHz. The beam-sizes are $0.41'' \times 0.41''$, $0.73'' \times 0.38''$ at PA=$-8.2°$, $1.13'' \times 0.39''$ at PA=10.2°, and $0.75'' \times 0.75''$ (super-resolved), respectively. The lowest contour levels begin at 0.125 mJy/bm for all images except for J2219–2719 where it is 0.2 mJy/bm, and increase by factors of $\sqrt{2}$.

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), as most known examples are at $z \lesssim 2$ (Liu & Zhang 2002). There are currently only two high-z quasars with well-established kpc-scale X-ray jet detections: GB 1508+5714 at z=4.3 (Siemiginowska et al. 2003; Yuan et al. 2003; Cheung 2004) and 1745+624 at z=3.9 (Cheung et al. 2006). They are observed to have large f_X/f_r values as expected in the IC/CMB model (Schwartz 2002; Cheung 2004), although the small number of high-z detections preclude any definitive statements (Kataoka & Stawarz 2005; Cheung et al. 2006).

We have therefore carried out a VLA survey in search of new radio jets in a sample of high-z quasars (§ 2.1.) and new *Chandra* observations of a small subset (§ 2.2.). This contribution presents some results from these observations. For the redshifts considered, z=3.4 to 4.7, $1''$ corresponds to 7.4 to 6.5 kpc ($H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$).

2. Observations of a High-Redshift Quasar Sample

2.1. VLA Imaging Survey

Using NED, we assembled a sample of z>3.4 flat-spectrum radio quasars for imaging with the VLA. We did not aim for our sample to be a complete one as current samples of lower-z X-ray jets are inhomogenous also. With archival (Lee 2005) and new VLA observations, we find that radio jets in this redshift range are common with a ∼50% detection rate (Cheung et al. 2005, and in preparation). Examples of new radio jets detected from our observations are shown in Figure 1.

2.2. *Chandra* Observations

A small percentage of the radio jets from our radio study (§ 2.1.) are extended enough (>2.5" long) to study with *Chandra*. We observed four of them with short snapshot *Chandra* observations (Figure 2). We detected bright X-ray counterparts to the jets in the quasars J1421–0643 (z=3.689; Ellison et al. 2001) and GB 1428+4217 (z=4.72; Hook & McMahon 1998); the latter detection is currently the highest-redshift kpc-scale radio and X-ray jet known. We did not detect the X-ray counterparts to the radio jets in 1239+376 (z=3.819; Vermeulen et al. 1996) and J1754+6737 (z=3.6; Villani & di Serego Alighieri 1999). The 2/4 X-ray jet detection rate of our high-z sample is comparable to that of lower-z samples (Sambruna et al. 2004; Marshall et al. 2005).

3. Discussion and Summary

Previous *Chandra* imaging studies of a number of z>4 radio loud quasars do not reveal significant extended X-ray emission (Bassett et al. 2004; Lopez et al. 2006). However, in these studies, there were no pre-existing information on possible radio structures in the target objects and any definitive statements regarding the nature of the X-ray emission mechanism in jets at high-redshifts may be premature. In fact, in one case where there was evidence of an extended X-ray structure (J2219–2719; Lopez et al. 2006), our VLA observation revealed a radio counterpart (Figure 1).

In our approach, we began with a VLA survey of a sample of z>3.4 quasars and found radio jets to be relatively common (∼50% detection rate). These jets are quite luminous; with a confident detection of a 1 mJy knot at 1.4 GHz, this corresponds to luminosities of 1.5 $\times 10^{42}$ erg s^{-1} (z=3.4) to 3.1 $\times 10^{42}$ erg s^{-1} (z=4.7).

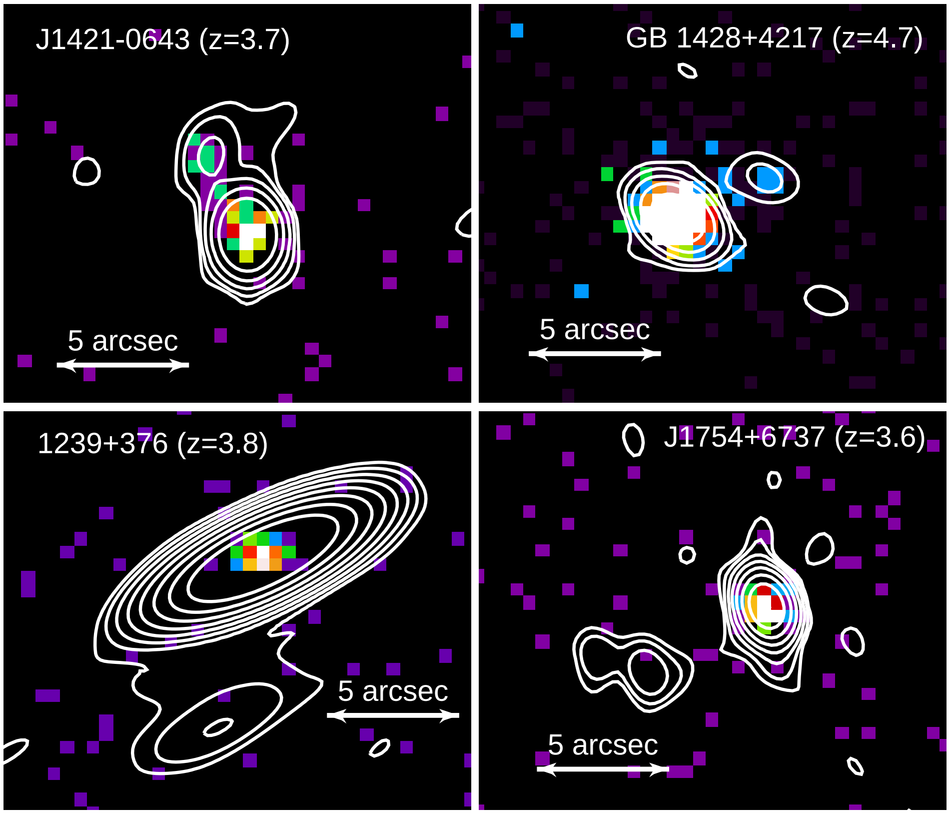

Figure 2. *Chandra* X-ray images (colorscale) with VLA contours overlaid of the four high-z radio jets observed. There are X-ray detections of the top two objects but not of the bottom two (§ 2.2.).

With the radio survey results, we found only a few radio jets to have sufficient angular extent to be imaged with *Chandra*. The detection rate of X-ray counterparts of the high-z radio jets (2/4) is similar to that of lower-z radio jet samples (Sambruna et al. 2004; Marshall et al. 2005). The implications of these observations for models of X-ray emission from large-scale jets will be described in forthcoming publications.

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