RADIO IDENTIFICATION OF THE X-RAY JET IN THE $z = 4.3$ QUASAR GB 1508+5714
C. C. Cheung
Department of Physics, Brandeis University, MS 057, Waltham, MA 02454; ccheung@brandeis.edu
Received 2003 October 25; accepted 2003 November 13; published 2003 December 12

ABSTRACT
The recent discovery of an X-ray jet in the $z = 4.3$ quasar GB 1508+5714 by Yuan et al. and Siemiginowska et al. prompted a search for its radio counterpart. Here, we report the successful discovery of faint radio emission from the jet at 1.4 GHz using archival Very Large Array data. The X-ray emission is best interpreted as inverse Compton (IC) emission off the cosmic microwave background (CMB) as discussed by the previous investigators. In this scenario, its high X-ray–to–radio monochromatic luminosity ratio, compared to previously detected IC/CMB X-ray jets at lower redshift, is a natural consequence of its high redshift.

Subject headings: galaxies: active — galaxies: jets — quasars: general — quasars: individual (GB 1508+5714) — radio continuum: galaxies — X-rays: galaxies

On-line material: color figure

1. BACKGROUND
Since its launch in 1999, the Chandra X-Ray Observatory has been used to detect a large number of X-ray jets in active galactic nuclei, where prominent radio jets were previously known to exist (see, e.g., Harris & Krawczynski 2002 and associated Web site\(^1\)). The recent report (Yuan et al. 2003; Siemiginowska et al. 2003a) of an extended X-ray jet originating from the $z = 4.3$ quasar GB 1508+5714, where previous observations showed no obvious sign of extended radio emission, presents an interesting case. The X-ray feature is strong—well over 100 counts were detected from it in the $\sim$90 ks Chandra observation. An archival Hubble Space Telescope (HST) image helps rule out the possibility that it is due to a foreground galaxy or a gravitationally lensed image of the quasar (Siemiginowska et al. 2003a). On the basis of deep X-ray source counts, it has a low probability of being a random unassociated X-ray field source.

As discussed by the previous authors, such detections of X-ray jets at large redshifts are actually to be expected as a natural consequence of the inverse Compton (IC) emission off the cosmic microwave background (CMB) model (e.g., Tavecchio et al. 2000; Celotti, Ghisellini, & Chiaberge 2001). This is because the $\Gamma = (1+z)^4$ dependence of the CMB energy density compensates for cosmological dimming of radiation, so that IC/CMB X-ray jets should remain detectable out to large cosmological distances (Schwartz 2002a). The model has been successfully applied to account for X-ray jets in many other powerful quasars at more modest redshifts (e.g., Sambruna et al. 2002), requiring that the jets are still highly relativistic on kiloparsec scales, in order that the electrons in the jet frame see an adequately boosted photon source. However, the lack of a detection of the GB 1508+5714 jet at lower frequencies, along with only a rough constraint on the X-ray spectrum, could not rule out a synchrotron origin for the X-rays (Siemiginowska et al. 2003a). A previous search in the radio for a proposed X-ray jet in another high redshift ($z = 5.99$) quasar, SDSS 1306+0356 (Schwartz 2002b), yielded only an upper limit of less than 0.1 mJy at 1.4 GHz (Petric et al. 2003; Schwartz, Cheung, & Wardle 2003).

Distinguishing between the two possible emission processes is important, as they probe different energetic phenomena. In the case of synchrotron X-ray emission, the X-rays mark sites of particle acceleration with electrons accelerated up to $\gamma \sim 10^5$ with very short lifetimes (e.g., M87; Harris et al. 2003). When considered together with minimum energy/equipartition conditions, the IC/CMB model offers important constraints on the beaming, magnetic field, and jet power (Tavecchio et al. 2000; Celotti, Ghisellini, & Chiaberge 2001).

Both the IC and the synchrotron interpretations of X-ray jet emission usually require a population of relativistic electrons emitting synchrotron radiation at lower (radio) frequencies. On the basis of the X-ray flux and spectrum, the two models give different predictions of the radio component flux and spectrum. Here, we report the detection of such a radio component coincident with the X-ray feature extending from GB 1508+5714 from an analysis of archival Very Large Array (VLA) data. This supports its interpretation as an X-ray jet, and we discuss the X-ray emission in the context of the new 1.4 GHz detection, along with the previously set optical, and a new 8.4 GHz limit. Following Yuan et al. (2003) and Siemiginowska et al. (2003a), $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Spergel et al. 2003) are assumed throughout, so 1" = 6.871 kpc.

2. ARCHIVAL RADIO OBSERVATIONS
Two data sets that utilized the VLA in its highest resolution A configuration were obtained from the NRAO\(^2\) archive. The data were calibrated in the NRAO AIPS package (Bridle & Greisen 1994) and brought into DIFMAP (Shepherd, Pearson, & Taylor 1994) for editing, self-calibration, and imaging. The flux density scale was set on the VLA 1999.2 scale using scans of 3C 286 as outlined in the VLA Calibrator Manual (Perley & Taylor 2003).

The 1.4 GHz data set—a single 5 minute snapshot observation—yielded a 10σ detection of a 1.2 mJy feature extended from the quasar (Fig. 1). This feature is only about 0.5% of the core flux (224±5 mJy), so it is no surprise that the original investigators (Moran & Helfand 1997) simply concluded that the quasar was an unresolved point source from these data. The measured off-source rms of $\lesssim 0.12$ mJy in the image is within 50% of the thermal noise limit expected from

---

\(^1\) See http://hea-www.harvard.edu/XJET.

\(^2\) The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
The jet knot was modeled with an elliptical Gaussian profile in both the $(u,v)$-plane with DIFMAP’s MODELFIT utility and the map plane with the JMFIT task in AIPS. The fits gave consistent measures of the deconvolved size: $1'' \times <1''$, elongated along the jet direction. We note that this is comparable to the beam size for this observation so the source is consistent with being unresolved, and the size should be considered an upper limit. The separation from the core is $2.5$ at a position angle of $-114^\circ$ and is comparable to that measured from the X-ray data. Interestingly, however, the peak in the X-ray jet appears somewhat closer to the nucleus than the radio centroid in the image overlay (Fig. 2), by about 1 Chandra ACIS pixel ($0''.492$ pixel$^{-1}$) or equivalently $\sim 3$ kpc projected distance. The images were aligned by the cores to better than half of a pixel. Siemiginowska et al. (2003a) found the peak in the X-ray jet to be $\sim 2''$ away (see also their subpixel rebinned radial profile published in their Fig. 2), consistent with our qualitative assessment. Yuan et al. (2003) stated the same peak to be $\sim 3''$ distant from the nucleus, although we measured a smaller value off their Figure 1. Much more apparent X-ray/radio offsets are seen in other powerful quasars (e.g., up to $\sim 2''$ in PKS 1127$-$145; Siemiginowska et al. 2002). Most if not all of the X-ray counts from the GB $1508+5714$ jet lie within the outermost radio contour in the VLA image (Fig. 2).

A 10 minute 8.4 GHz observation obtained on 1996 November 3 (program AD388) yielded no detection of the radio jet. The measured off-source rms in the naturally weighted image ($0''.35$ beam) is at about the expected thermal noise limit of 0.045 mJy. In order to judge if the nondetection was a result of the greater resolution in this image compared to the 1.4 GHz map, the 8.4 GHz data set was tapered by different amounts. No outstanding feature appeared above the residual artifacts from the dirty beam. The measured rms at the expected position of the jet in a tapered image restored with a 0.75 beam is 0.3 mJy (3 $\sigma$). This, along with the 1.4 GHz detection, is consistent with an radio spectrum ($F \propto \nu^{\alpha}$), which agrees with the measured X-ray spectral index: $0.9 \pm 0.36$ (Siemiginowska et al. 2003a) and 0.92$^{+0.38}_{-0.33}$ (Yuan et al. 2003).

3. CONSTRAINTS FROM THE RADIO DATA

The spectral energy distribution of the jet knot in GB $1508+5714$ is shown in Figure 3. If the X-ray and radio emission are drawn from the same population of relativistic electrons emitting synchrotron radiation, the spectral index will be about what is measured between the 1.4 GHz and X-ray (using $1.68 \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV, reported by Siemiginowska et al. 2003a) detections: $\alpha_{\nu} = 0.73$. This is a typical value for the spectrum seen in radio jets (Bridle & Perley 1984) and is consistent with the measured X-ray spectral of $0.9 \pm 0.36$ (Yuan et al. 2003; Siemiginowska et al. 2003a) and our constraint on the radio spectrum of $0.8$ (the modest 8.4 GHz data set does not preclude that the higher frequency radio emission, greater than 40 GHz in the source frame, was actually resolved out). The optical HST limit (3 $\sigma$) from Siemiginowska et al. (2003a) is not useful in this case, as it hovers over the radio–to–X-ray spectrum, and only weaker constraints are available at other optical bands (Yuan et al. 2003).

We can estimate an equipartition magnetic field of $B_{eq} \approx 9.7 \times 10^{-5}$ G, by adopting the observed $\alpha_{\nu}$ value as the optically thin spectral index, and that the particles and field fill a fraction $f$ of a $2.9 \times 10^{57}$ cm$^3$ sphere, corresponding to the size upper limit derived from the radio detection. The factor $\eta$ is the ratio of magnetic field and electron energy densities, and $\gamma_{\text{min}}$ is the lower energy cutoff of a power-law
distribution of relativistic particles. If we further assume \( \eta = 1, f = 1, \) and \( \gamma_{\text{max}} = 10, \) then \( B_{\text{eq}} \approx 7.4 \times 10^{-3} \delta^{-1} \) G, where \( \delta \) is the unknown jet Doppler beaming factor. In this field, electrons emitting the highest energy X-rays detected (\( \sim 5 \) keV; Siemiginowska et al. 2003a) will have \( \gamma \sim 10^8 \) and short lifetimes (\( \sim 50 \) yr)—this would require continuous in situ reacceleration of high-energy particles in order that the X-ray jet not be a transient feature. At this high redshift, the energy density of the CMB already exceeds that of the equipartition field, even without bulk motion (see below), so IC losses will already be dominant. The lifetime of the \( \gamma \sim 10^8 \) electrons calculated above is then a strict upper limit. Taking this evidence together, it is unlikely that the jet X-ray emission is dominated by synchrotron losses.

An IC/CMB origin for this high-redshift X-ray jet is preferred (Yuan et al. 2003; Siemiginowska et al. 2003a) and gives us an additional constraint on the allowed range of magnetic field and jet Doppler factor to the equipartition condition. The following expression is taken from Tavecchio (2002):

\[
B = \delta \left[ \frac{3 c(\alpha)}{2} \frac{1}{\sigma_T c} \frac{v_e^3 F_C(v_e)}{U_{\text{rad}} v_0^2 F_e(v_0)} \right]^{1/(1+\alpha)},
\]

where \( c(\alpha) \) is a dimensionless function of \( \alpha \) (e.g., Ghisellini, Maraschi, & Treves 1985), \( \sigma_T \) is the Thomson cross section, and \( U_{\text{rad}} = 4.19 \times 10^{-13} (1+z)^2 \) ergs cm\(^{-3}\) Hz for the CMB (e.g., Schwartz 2002a), whose spectrum is peaked near \( v_0 = 1.6 \times 10^{13} (1+z) \) Hz (Harris & Krawczynski 2002). Assuming \( \alpha = 1, \) the observed ratio of the Compton (X-ray) and synchrotron (radio) fluxes \( F_C(v) \) and \( F_e, \) observed at \( v_e \) and \( v_0, \) respectively) allows us to estimate \( B \sim 7.2 \times 10^{-3} \delta^{-1} \) G. The corresponding equipartition calculation gives \( B_{\text{eq}} \sim 10^{-3} \delta^{-1} \) G, making the assumptions as above about \( \eta, f, \) and \( \gamma_{\text{max}}. \) Both estimates of \( B \)-field are reasonably insensitive to the assumed spectral index: up to \( \sim 25\% \) smaller for \( \alpha = 0.9, \) the measured X-ray spectral index. In order to reconcile the differences between the two equations (opposite dependencies of \( B \) on \( \delta \)), a Doppler factor greater than 1 is required. These two constraints bracket a plausible range of solutions around a 30 \( \mu \)G field and \( \delta = 4. \) Siemiginowska et al. (2003a) arrived at similar conditions using slightly different assumptions. The unresolved nucleus is a variable X-ray and (flat spectrum) radio source with a very high X-ray–to–optical luminosity (see Moran & Helfand 1997 and references therein). These observations have been taken as evidence of beaming on smaller scales in the nucleus.

The ratio of the monochromatic X-ray–to–radio luminosities (i.e., \( \nu F_\nu \)) of the GB 1508+5714 jet is 158. This is one of the highest among the known X-ray jets that can be attributed to IC/CMB emission so far. In Figure 4, this ratio is plotted versus redshift along with IC/CMB X-ray jets taken from the literature. The values seem to vary widely over 4 orders of magnitude times greater energy density from the CMB than other jets at lower redshift, so it is tempting to speculate that its extreme redshift may account, to first order, for its large X-ray–to–radio luminosity ratio. This could similarly account for the large X-ray–to–radio ratio limit obtained for the proposed X-ray jet in the \( z = 5.99 \) quasar SDSS 1306+0356 (Schwartz 2002b; Schwartz et al. 2003; Fig. 4).

The observed monochromatic X-ray–to–radio luminosity ratios can be compared to what is expected in the IC/CMB model.
We can obtain an expression for the expected ratio by rearranging equation (1) (and setting $\alpha = 1$):

$$\frac{\nu_c F_c(\nu_c)}{\nu_i F_i(\nu_i)} = 4.19 \times 10^{-11} (1 + z)^4 \left(\frac{B/\delta}{2}\right)^2 / 8\pi.$$  

(2)

The flux ratio is simply proportional to the ratio of the energy densities in the CMB and magnetic field, with a Doppler factor term. This expression is plotted in Figure 4 for several different combinations of $B$ and $\delta$, one of which best suits the observations of GB 1508+5714. It appears that varying $B$ and $\delta$ can account for the large spread of observed X-ray–to–radio luminosity ratios within a given redshift range. Larger $B$-field, or more likely, smaller $\delta$ may account for the low values observed in Q0957+561 ($z = 1.41$; Chartas et al. 2002) and 3C 9 ($z = 2.012$; Fabian, Celotti, & Johnstone 2003), as they are known to have low radio core dominance and weak VLBI structures (Campbell et al. 1995; Hough et al. 2002) compared to the other sources studied here. In all but 3C 179 ($z = 0.846$; Sambruna et al. 2002), where multiple knot regions along the jet can be distinguished, the X-ray–to–radio flux ratio decreases with increasing distance from the nucleus and can similarly be accounted for by varying $B/\delta$. As discussed specifically in the case of 3C 273 ($z = 0.158$; Sambruna et al. 2001), the variations along the jet may indicate deceleration or increasing $B$ along the jet, possibly by compression in strong shocks. Future detections in the redshift range $\sim 2–4$ or higher with large X-ray/radio flux ratios can lend further support to the currently preferred IC/CMB model used to explain the X-ray emission in quasar jets.

The anonymous referee is thanked for making the point that Compton losses are already dominant in the synchrotron X-ray case and several other useful comments. The author is grateful to John Wardle for his advice and encouragement throughout the course of this work and to Dan Harris, Aneta Siemiginowska, Dave Roberts, and Fabrizio Tavecchio for useful discussions. Radio astronomy at Brandeis University is supported by the National Science Foundation through grants AST 98-02708 and AST 00-98608. Additional support by NASA grant GO2-3195C from the Smithsonian Astrophysical Observatory and HST-GO-09122.08-A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555, is acknowledged.

REFERENCES

Bridle, A. H., & Greisen, E. W. 1994, The NRAO AIPS Project—a Summary (AIPS Memo 87; Charlottesville: NRAO).

Bridle, A. H., Hough, D. H., Lonsdale, C. J., Burns, J. O., & Laing, R. A. 1994, AJ, 108, 766

Bridle, A. H., & Perley, R. A. 1984, ARA&A, 22, 319

Brunetti, G., Bondi, M., Comastri, A., & Setti, G. 2002, A&A, 381, 795

Campbell, R. M., Lehar, J., Corey, B. E., Shapiro, I. I., & Falco, E. E. 1995, AJ, 110, 2566

Celotti, A., Ghisellini, G., & Chiaberge, M. 2001, MNRA, 321, L1

Chartas, G., Gupta, V., Garmire, G., Jones, C., Falco, E. E., Shapiro, I. I., & Tavecchio, F. 2002, ApJ, 565, 96

Chartas, G., et al. 2000, ApJ, 542, 655

Fabian, A. C., Celotti, A., & Johnstone, R. M. 2003, MNRA, 338, L7

Ghisellini, G., Maraschi, L., & Treves, A. 1985, A&A, 146, 204

Harris, D. E., Biretta, J. A., Junor, W., Perlmutter, E. S., Sparks, W. B., & Wilson, A. S. 2003, ApJ, 586, L41

Harris, D. E., & Krawczynski, H. 2002, ApJ, 565, 244

Hough, D. H., Vermeulen, R. C., Readhead, A. C. S., Cross, L. L., Barth, E. L., Yu, L. H., Beyer, P. J., & Phifer, E. M. 2002, AJ, 123, 1258

Moran, E. C., & Helfand, D. J. 1997, ApJ, 484, L95

Perley, R. A., & Taylor, G. B. 2003, VLA Calibrator Manual (Charlottesville: NRAO).

Petric, A. O., Carilli, C. L., Bertoldi, F., Fun, X., Cox, P., Strauss, M. A., Omont, A., & Schneider, D. P. 2003, AJ, 126, 15

Sambruna, R. M., Maraschi, L., Tavecchio, F., Urry, C. M., Cheung, C. C., Chartas, G., Scarpa, R., & Gambill, J. K. 2002, ApJ, 571, 206

Sambruna, R. M., Urry, C. M., Tavecchio, F., Maraschi, L., Scarpa, R., Chartas, G., & Maxlow, T. 2001, ApJ, 549, L161

Schwartz, D. A. 2002a, ApJ, 569, L23

———. 2002b, ApJ, 571, L71

Schwartz, D. A., Cheung, C. C., & Wardle, J. F. C. 2003, in ASP Conf. Ser. 290, Active Galactic Nuclei: From Central Engine to Host Galaxy, ed. S. Collin, F. Combes, & I. Shlosman (San Francisco: ASP), 619

Shepherd, M. C., Pearson, T. J., & Taylor, G. B. 1994, BAAS, 26, 987

Siemiginowska, A., Bechtold, J., Aldcroft, T. L., Elvis, M., Harris, D. E., & Dobrzycki, A. 2002, ApJ, 570, 543

Siemiginowska, A., Smith, R. K., Aldcroft, T. L., Schwartz, D. A., Paerels, F., & Petric, A. O. 2003a, ApJ, 598, L15

Siemiginowska, A., et al. 2003b, ApJ, 595, 643

Spergel, D. N., et al. 2003, ApJS, 148, 175

Tavecchio, F. 2002, Ph.D. thesis, Univ. Milan

Tavecchio, F., Maraschi, L., Sambruna, R. M., & Urry, C. M. 2000, ApJ, 544, L23

Yuan, W., Fabian, A. C., Celotti, A., & Jonker, P. G. 2003, MNRA, 346, L7