RADIO AND X-RAY OBSERVATIONS OF 3C303 AND 3C15

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Abstract

We describe the *Chandra* detection of X-ray kpc-scale jet components in 3C303 and 3C15. The X-ray morphology of 3C303 is similar to that of the radio/optical emission with peaks in the X-ray emission found at 5.5″, 9″ and 17″ from the core. In 3C15, the peak of the X-ray emission in the jet is 4.1″ from the core, and coincident with a component previously identified in the radio and optical jets. We construct the spectral energy distributions for components in these sources and find that the X-ray fluxes are well below the extrapolation of the radio-to-optical continuum. We provide interpretations of these observations, and describe planned very long baseline interferometry observations to study the parsec scale jet morphology.

1 Introduction

Ogden Nash (1902–1971) was an American poet known for his light and whimsical verse. A typical example is his poem "The Lama":

The one-l lama,
He's a priest.
The two-l llama,
He's a beast.
And I will bet
A silk pajama
There isn't any
Three-l lllama.

This was the inspiration for the one minute advertisement for the poster presentation of this paper at the conference:

The one-c source,
is in a spelling bee.
Two-c sources are found
a*cc*identally.
But silk pajamas can
be wagered on bets
for 3C sources
with X-ray jets.

2 3C303 (J1443+5201)

3C303 (z = 0.141) is an unusual double radio source with a highly asymmetrical structure. Leahy et al. (1991) describe the source as "bizarre", as the kpc-scale jet terminates in a lobe with two pronounced hotspots in the west, with a fainter single hot spot to the east (Fig. 1). A short (15 ks) *Chandra* exposure in 2001 March resulted in the discovered X-ray emission from the hotspot and kpc-scale jet knots of 3C303 (Kataoka et al., 2003a). The X-ray morphology is similar to that of the radio/optical emission with peaks in the X-ray emission found at 5.5″ (knot B), 9″ (knot C) and 17″ (hotspot A2) from the core of 3C303 (Fig. 2).

The bright nucleus suffers from significant X-ray pile-up. In addition, the nearby faint knots B and C are contaminated by emission from the much brighter core. We thus concentrate on hotspot component A2. We find the X-ray emission is produced via inverse Compton scattering of both synchrotron photons (SSC) and cosmic microwave background photons (ERC/CMB), as shown in Fig. 3. The magnetic field strength, region size, and the maximum energy of electrons for the hotspot are self-consistently determined to be $B \simeq$

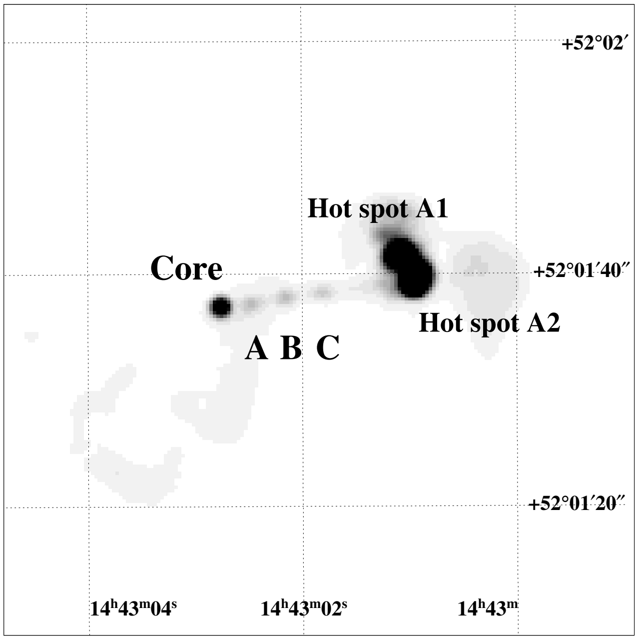

Figure 1: A 1.5 GHz VLA image of 3C303 (Leahy et al., 1991, http://www.jb.man.ac.uk/atlas), adapted from Kataoka et al. (2003a).

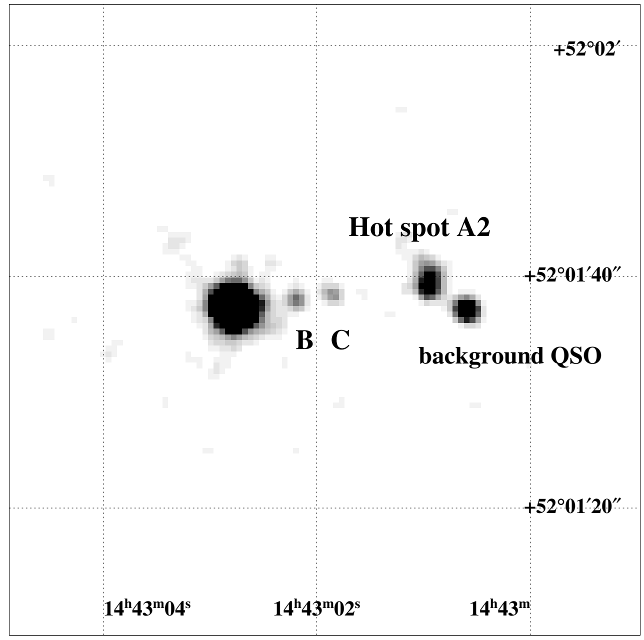

Figure 2: *Chandra* 0.4–8 keV image of 3C303 (Kataoka et al., 2003a). Knot A is swamped by the bright nucleus, and hotspot A1 is only marginally detectable. A background quasar at z = 1.57 is, however, clearly detected at X-ray energies.

4.3 μG, $R \simeq 6.5\times10^{21}$ cm, and $\gamma_{\max} \simeq 1.4\times10^{7}$. This implies a magnetic field strength a factor of $\sim$ 30 below the equipartition value; $B_{\rm eq} \simeq 150\,\mu$G. Equipartition can be restored if the plasma in the hotspot is moving with a mildly relativistic speed ($\Gamma_{BLK} \sim$ 2–3), in which case inverse Compton scattering of CMB photons dominates over that of synchrotron photons.

The electron cooling time, for the parameters used to model the spectral energy distribution (SED), is $t_{\rm cool}(\gamma_{\max})$ = 7.0$\times10^{11}$ s. Thus, the highest energy electrons can travel $d \sim ct_{\rm cool}$ = 6.8 kpc before losing their energy. This is consistent with the size of the hotspot, but smaller than the projected distance from the nucleus (36 kpc), consistent with electrons being accelerated at a single site in the hotspot. However, the uncertainties in fit to the SED preclude this from being firmly established.

Kronberg (1986) studied the polarization properties of the source with the Very Large Array (VLA) at 4.9 GHz and found that the EVPAs (Electric Vector Position Angles) of the core and kpc-scale jet knots were mostly perpendicular to the jet axis. The polarizations of all three jet knots were found to peak slightly closer to the core than the total intensity. A similar phenomena has been observed with *Chandra* for the X-ray knots in some FRI sources (Hardcastle et al., 2001, 2002). If the X-ray emission from the knots is due to synchrotron radiation, then the rapid cooling time of the the X-ray emitting electrons suggests that the shock which accelerates the particles is located upstream (closer to the core), with the radio emitting electrons diffusing downstream from the shock. Although the eastern jet and hotspot structure of 3C303 bears a closer resemblance to an FRII radio galaxy, it is of interest to see whether there is any offset between the peaks of the X-ray and radio emission from the knots. However, the photon statistics in the short X-ray exposure are poor (only $\sim$ 20 photons for each knot) which, combined with the *Chandra* image resolution of $\sim 0.5''$, prevent any conclusion about an offset from being drawn.

Giovannini et al. (2001) observed 3C303 at 5 GHz in September 1997. Their image (Fig. 4) reveals a compact core and a number of jet components up to 15 mas from the core at a PA of $-90°$: there is clearly a moderate (in projection) bend between the two size scales. The jet-to-counter jet ratio and core dominance were used to derive limits for the angle to the line of sight and jet speed of $\theta \leq 40°$, and $\beta \geq 0.7c$.

In 2003 November we observed 3C303 with the Very

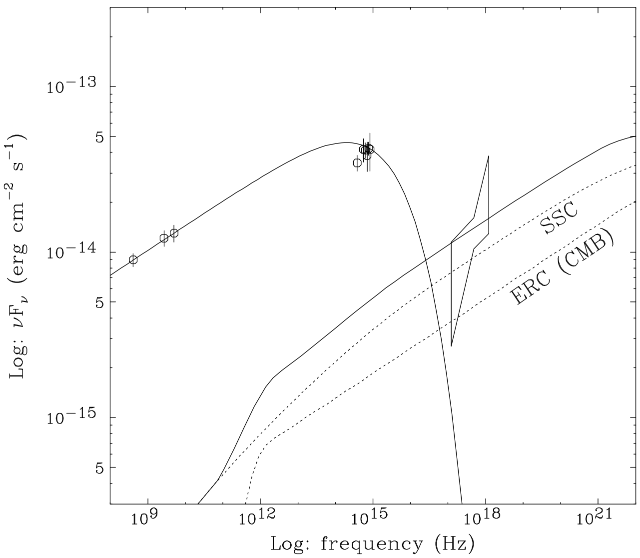

Figure 3: The SED for hotspot component A2 of 3C303 showing the modeled contributions from SSC and ERC processes (Kataoka et al., 2003a).

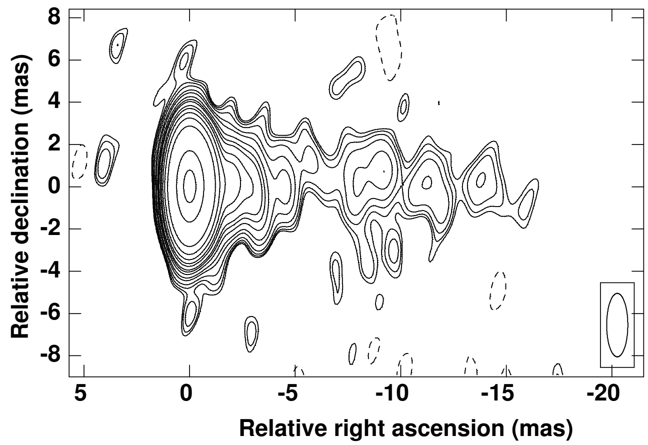

Figure 4: 5 GHz Global VLBI image of 3C303 in September 1997 (Giovannini et al., 2001). Contours levels are −0.1, 0.1, 0.12, 0.15,0.2, 0.3, 0.4, 0.6, 0.8, 1, 1.5, 2, 3, 5, 10, 50, and 100 mJy beam^{-1}.

Long Baseline Array (VLBA) at 5 GHz to study its parsec-scale evolution. We will be comparing this observation with the 1997 data of Giovannini et al., and a September 2002 observation of Taylor and collaborators.

3 3C15 (J0037−0109)

3C15 (z = 0.073) is an unusual radio source with a structure intermediate between Fanaroff-Riley (FR) classes I and II, although its luminosity is above that of a number of sources showing classical FRII structure (Leahy et al., 1997). 3C15 has an optical jet which has been imaged with the *HST* (Martel et al., 1998). The optical morphology of the jet matches the features of the radio jet very well, suggesting that the optical emission is strongly dominated by synchrotron radiation.

The *Chandra* observation of 3C15 in 2000 November (28 ks good data) resulted in the detection of the jet and lobes. The peak of the X-ray emission in the jet is 4.1″ (a projected distance of 5.1 kpc) from the nucleus, and coincident with a component previously identified in the radio and optical jets (Fig. 5).

We find the synchrotron photon energy density is more than a factor of three larger than the CMB photon energy density. We considered four possible models to account for overall SED of knot C, concluding that Synchrotron X-ray emission with moderate cooling best fits the data (Kataoka et al., 2003b). In all four models, however, electrons must be accelerated to $\gamma_{\rm max} \sim 10^7$ in knot C, which corresponds to a travel distance of $ct_{\rm cool} \leq 1.4$ kpc. Comparing this with the projected distance of knot C from the nucleus of 5.1 kpc again implies that re-acceleration is necessary.

The X-ray emission from the nucleus of 3C15 can not be adequately fitted by a simple absorbed power-law model, but needs an additional power-law with heavy absorption ($N_{\rm H} \simeq 10^{22-23}$ cm^{-2}) intrinsic to the source (Fig. 6). Such a high column density is consistent with the *HST* observations, which found no bright, unresolved nucleus in the core of the galaxy (Martel et al., 1998), implying the presence of a dense, dusty torus obscuring the nucleus.

We have undertaken phase-referencing VLBA observations of 3C15 at 1.6, 2.3, 5, 8 and 15 GHz in December 2003 and January 2004 to study the spectral characteristics of the heavily obscured core (and, in turn, probe the absorbing material), and to determine the detectability of the parsec-scale jet. These results will be described elsewhere.

4 Conclusions

X-ray observations of non-thermal emission allow the energetics and the spectra of the relativistic electrons to be constrained. Our modeling shows that electrons must be accelerated up to $\gamma_{\rm max}$ greater than $\sim 10^7$, suggesting that re-acceleration is necessary in the hotspot of 3C303 and knot C of the 3C15 jet. Our observations confirm that particles are accelerated very

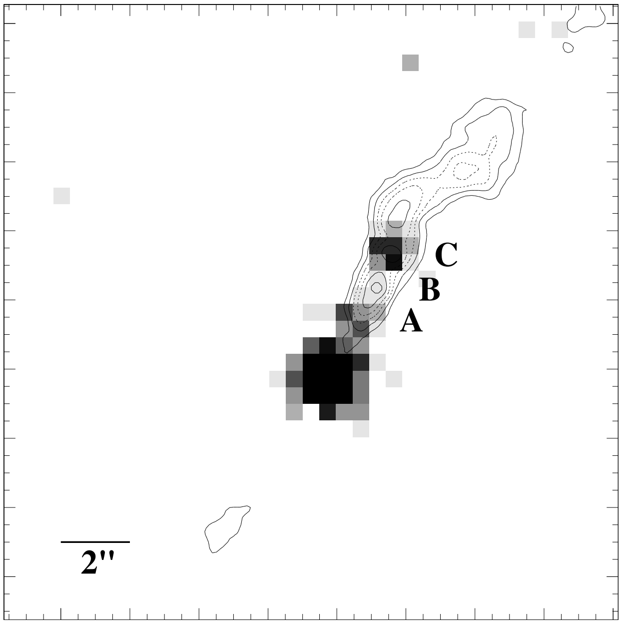

Figure 5: The central 17.4″×17.4″ region of 3C15 (Kataoka et al., 2003b). The image is smoothed with a 0.3″ Gaussian. A, B, and C denote the jet knots as defined in Martel et al. (1998). The VLA contour levels are (0.2, 0.56, 1.6, 4.3, 12) mJy beam^{-1} for a circular 0.34″ beam.

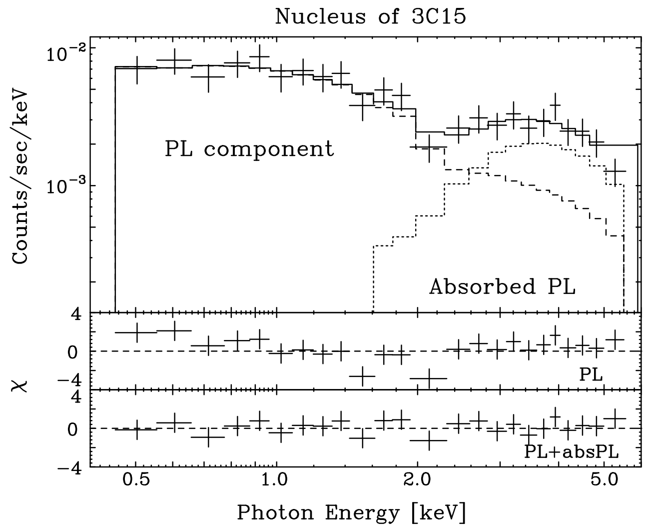

Figure 6: Background-subtracted ACIS spectrum of the nucleus of 3C15. The best-fit model, consisting of two power-law components, is shown with the histograms. The middle panel shows the residuals to a single power-law fit with a differential photon index Γ = 0.5. The bottom panel shows the residuals to the best-fit double power-law model (Kataoka et al., 2003b).

efficiently in radio galaxies.

Acknowledgments

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References

Giovannini, G., Cotton, W. D., Feretti, L., Lara, L., Venturi, T. 2001, ApJ, 552, 508

Hardcastle, M. J., Birkinshaw, M., Worrall, D. M. 2001, MNRAS, 326, 1499

Hardcastle, M. J., Worrall, D. M., Birkinshaw, M., Liang, R. A., Bridle, A. H. 2002, MNRAS, 334, 182

Kronberg, P. P. 1986, Can. J. Phys., 64, 449

Kataoka, J., Edwards, P., Georganopoulos, M., Takahara, F., Wagner, S. 2003a, A&A, 399, 91

Kataoka, J., Leahy, J. P. Edwards, P. G., Kino, M., Takahara, F., Serino, Y., Kawai, N., Martel, A. R. 2003b, A&A, 410, 833

Leahy, J. P., Perley, R. A. 1991, AJ, 102, 537

Leahy, J. P., Black, A. R. S., Dennett-Thorpe, J., et al. 1997, MNRAS, 291, 20

Martel, A. R., Sparks, W. B., Macchetto, D. 1998, ApJ, 496, 203