X-RAY DETECTION OF THE INNER JET IN THE RADIO GALAXY 3C 129

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ABSTRACT

During the course of an investigation of the interaction of the radio galaxy 3C 129 and its ambient cluster gas, we found excess X-ray emission aligned with the northern radio jet. The emission extends from the weak X-ray core of the host galaxy ≈2′′5 to the first resolved radio knot. On a smaller scale, we have also detected a weak radio extension in the same position angle with the VLBA. Although all the evidence suggests that Doppler favoritism augments the emission of the northern jet, it is unlikely that the excess X-ray emission is produced by inverse Compton emission. We find many similarities between the 3C 129 X-ray jet and recent jet detections from Chandra data of low-luminosity radio galaxies. For most of these current detections, synchrotron emission is the favored explanation for the observed X-rays.

Subject headings: galaxies: active — galaxies: individual (3C 129) — galaxies: jets — radiation mechanisms: nonthermal — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

The radio galaxy 3C 129 is a low-luminosity (FR I type) “tailed radio galaxy” seen in projection toward the outer edge of the X-ray emission from the hot gas of a nearby cluster of galaxies (Leahy & Yin 2000; Taylor et al. 2001). Because the cluster lies at low Galactic latitude toward the anticenter, it has not been well studied in the optical.

We obtained Chandra observations in order to study the interaction of the radio structures with the hot intracluster medium (ICM) and that work will be presented elsewhere (an analysis of the ICM properties has been performed by Krawczynski 2002, and a paper on pressure balance is in preparation). In this paper we report on faint X-ray emission detected from the core of the 3C 129 galaxy and from the inner 3 kpc of the northern radio jet. We include the results of “follow-up” observations with the VLBA 1 in § 3.

X-ray emission from radio jets presents us with the problem of identifying the emission process, but once this process is determined, we can then obtain new constraints on physical parameters (Harris & Krawczynski 2002). With the introduction of the relativistic beaming model of Celotti, Ghisellini, & Chiaberge (2001) and Tavecchio et al. (2000), most X-ray emission from jets has been interpreted as indicating either synchrotron emission or inverse Compton scattering off the cosmic microwave background (CMB). For 3C 129, we show that synchrotron emission is the probable process, as has been found for a number of other FR I radio galaxies (Worrall, Birkinshaw, & Hardcastle 2001; Hardcastle, Birkinshaw, & Worrall 2001). The implications of the detected X-ray emission are discussed in § 5.

The redshift of the radio galaxy at the center of the cluster, 3C 129.1 is z = 0.0208 (Spinrad 1975), and we take this for our distance estimate of D_L = 126 Mpc with H_0 = 50 km s^{-1} Mpc^{-1} and q_0 = 0. One arcsecond then corresponds to 0.60 kpc.

2. X-RAY DATA

The X-ray observation was obtained with the ACIS-S detector on the Chandra X-Ray Observatory (observation ID 2218, 2000 December 9). The exposure time was 31.46 ks, and the 3C 129 galaxy was observed with the back-illuminated S3 chip. After standard Chandra pipeline processing (R4CU5UPD12.1 on 2000 December 12), we rejected intervals with excess counting rates (indicative of particle flares) resulting in a live time of 30.405 ks. Events with energies less than 0.3 keV or greater than 8 keV were rejected.

We then binned the data by a factor of 2 to obtain images with pixel size 0′′.123. Various Gaussian smoothing functions were then convolved with the data, and one example is shown in Figure 1, an overlay of the radio image with X-ray contours. While it is clear that there is excess X-ray emission coincident with the first visible radio knot, N2.3, it appears that the X-ray morphology is essentially a projection from the core rather than a completely resolved separate structure. There is also a 1–2 σ excess located at the beginning of the second radio knot, N5.0. All of these features are weak. For a circular aperture of radius 0′′9, we find only 30 net counts in the core and an additional 12 net counts defining the jet. N5.0 contains only 4 net counts.

The observation was performed with a stage offset (“sim z”) of −5.86 mm (119′′5 or 243 pixels toward the readout edge), a y offset of −1′ to move the target to the center of a node, and a specified roll angle so as to position the 0′′4 radio tail on the ACIS-S array. Because the target position was not the center of the galaxy, this procedure resulted in

1 The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
the core of the 3C 129 galaxy being 90' from the optical axis.

To check on the reality of the jet morphology, a 1.49 keV point-spread function (PSF) was generated to match the location off-axis and the pixel size of 0'.123. This PSF image was then smoothed with a 1'' Gaussian. The resulting image has quasi circular contours with radius of 0''66 for the 50% intensity levels. This value can be compared with 0''8 for 3C 129 in directions to the south and southwest (away from the jet) and 1''2 for the 50% contour in the position angle (P.A.) of the jet. If the X-ray jet were to be caused by statistical happenstance, its alignment with the radio jet would be coincidental.

To assess the various emission mechanisms for the X-rays, we need to define areas (and their implied emitting volumes) and measure intensities. These regions were selected on the basis of the smoothed map (Fig. 1), but the measurements were made on the event file. Mindful of the paucity of X-ray photons, we are content with order-of-magnitude estimates.

For the core, we have taken a circle of radius 0''95; for the X-ray jet, we use a rotated box of dimensions 2''03 x 1''63; for the N5.0 feature we use a small circle of radius 0''92. These regions are shown in Figure 2.

Using the PIMMS tool and XSPEC/fakeit with a power-law spectrum, we find a conversion value for 1 count s⁻¹ (0.3–8 keV) to unabsorbed flux, $f_X(0.5–5$ keV) of 1.11 ($\alpha = 0.5$), 1.16 ($\alpha = 1.0$), and 1.27 ($\alpha = 1.5$) x 10⁻¹¹ ergs cm⁻² s⁻¹. This allows us to determine rough fluxes for the features measured.

3. RADIO DATA

The VLA data used in this paper are those described in Taylor et al. (2001). However, we mainly used the 8 GHz data at their inherent resolution of 0''83 FWHM rather than the versions previously published, which were smoothed to larger beams so as to match lower frequency data. This beam size is quite close to what we obtained with Chandra, so it meets the need for obtaining comparative morphologies and corresponding flux densities.

To obtain some sense of what role Doppler boosting might play near the radio core of 3C 129, on 2001 December 16 we observed the core at 4.986 GHz with the 10 element VLBA. Because of inclement weather, no data were obtained from the VLBA antenna at Mauna Kea. A total bandwidth of 32 MHz was recorded in left circular polarization only using 2 bit sampling. The VLBA correlator produced 16 frequency channels across each 8 MHz wide IF during every 2 s integration. Amplitude calibration for each antenna was derived from measurements of the antenna gain and system temperatures during each run. Delays, rates, and phases were derived from the nearby (2''79 distant) calibrator J0440+4244 and transferred to 3C 129. A 3 minute cycle of 120 s on target, 60 s calibrator was used. To check the quality of the phase referencing, the calibrator J0427+4133 was observed five times during the 4 hr run. The coherence on J0427+4133 (2''58 distant from J0440+4244) was found to be ~85%.

Once delay and rate solutions were applied, the data were averaged in frequency over 32 MHz. The data from all sources were edited and averaged over 20 s intervals using DIFMAP (Shepherd, Pearson, & Taylor 1995) and then were subsequently self-calibrated and imaged. The final image is

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2 We thank W. Joye for his work on the imaging tool, ds9, which allows us to make high-quality figures with minimal effort.
shown in Figure 3. The position of the core of 3C 129 derived from model fitting with DIFMAP is (J2000.0) R.A. = 4h49m39s06396, decl. = +45°00′39″342. Based on the observed offset of J0427+4133, the accuracy of this position should be ~0.35 mas. The peak flux density is \( \approx 2 \) that obtained some years earlier with a 1.8 beam (Taylor et al. 2001).

The detection of the northern jet extending 6 pc from the core supports the notion that the northern jet is the one coming toward us (in agreement with the VLA morphology) and that Doppler favoritism is operating on the parsec scale. The P.A. of the 6 pc scale feature is 13°, essentially the same as the value measured 630 pc from the core on the VLA map (P.A. \( \approx 14° \)). Thus, we may expect very little bending in the jet up to about 2 kpc (34), and this inner straight segment of the jet is the part that is detected by Chandra.

4. PARAMETERS FOR EMISSION MODELS

To estimate physical parameters associated with various X-ray emission mechanisms, we need to assume values for some unmeasurable parameters such as the spectral index and refine volume estimates. We will also need to estimate the radio flux densities that correspond to the X-ray–emitting volumes, not to the obvious radio features. For the radio spectral index, we use \( \alpha = 0.8 \).

For the jet, we take a cylinder of length 1.8 and radius 0.25. For this volume, we ascribe a flux density of 3 mJy at 8 GHz and \( f_{\text{X}}(0.5–5 \text{ keV}) = 12 \) counts divided by 30,403 s, all multiplied by the conversion factor 1.16 \( \times 10^{-11} = 4.6 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \). Because the X-ray emission is brighter at the downstream end, this is a gross approximation.

4.1. Thermal Bremsstrahlung Emission

The log of the X-ray luminosity (0.5–5 keV) for the jet is 39.967 ergs s\(^{-1}\), and the density required to produce this emission from the cylindrical volume would be 0.7 cm\(^{-3}\).

For a synchrotron X-ray model, we need to extend the radio spectral index between 5 and 8 GHz is in the range 0.35 \( \pm 0.85 \) with a beam size of 1.8; Taylor et al. 2001). In this case, the log of the luminosity would be \( \approx 40.669 \) ergs s\(^{-1}\) and the equipartition field would be 40 \( \mu G \). Although there would be only an insignificant change in the total energy contained in the source, the power-law distribution would have to extend to \( \gamma = 7 \times 10^7 \) with a half-life of some 60 yr for electrons of this energy.

If the morphology difference is real, then the radio flux density to associate with the X-ray jet will be a factor of 2 or 3 less than the 3 mJy found for knot N2.3. However, that would change the values derived above very little, and the only different ingredient would be the natural picture of a quite limited region of shock acceleration capable of producing the high energies required for X-rays, followed by a farther (downstream) segment of the jet, where acceleration of the more common energies continues.

4.2. Synchrotron Emission

At similar resolutions, the X-ray emission decreases monotonically moving away from the core, whereas the radio brightness is low adjacent to the unresolved (0.83 beam) core and then increases to the enhancement we call knot N2.3. Because of this discrepancy in morphology, a simple synchrotron model is not easily constructed.

If the morphology difference arises by a statistical fluctuation from the small number of photons defining the X-ray jet, we may calculate the synchrotron parameters necessary to produce the observed X-rays. For the radio emission from N2.3 (10\(^8–10\(^11\) Hz), the log of the luminosity would be 39.517 ergs s\(^{-1}\) and the equipartition field would be 40 \( \mu G \). For a synchrotron X-ray model, we need to extend the radio spectrum up to 10\(^18\) Hz with the spectral index \( \alpha = 0.9 \) (cf. the radio spectral index between 5 and 8 GHz is in the range 0.55–0.85 with a beam size of 1.8; Taylor et al. 2001). In this case, the log of the luminosity would be 40.669 ergs s\(^{-1}\) and the equipartition field would be 42 \( \mu G \). Although there would be only an insignificant change in the total energy contained in the source, the power-law distribution would have to extend to \( \gamma = 7 \times 10^7 \) with a half-life of some 60 yr for electrons of this energy.

If the morphology difference is real, then the radio flux density to associate with the X-ray jet will be a factor of 2 or 3 less than the 3 mJy found for knot N2.3. However, that would change the values derived above very little, and the only different ingredient would be the natural picture of a quite limited region of shock acceleration capable of producing the high energies required for X-rays, followed by a farther (downstream) segment of the jet, where acceleration of the more common energies continues.

4.3. Inverse Compton Emission

The synchrotron self-Compton model fails because the photon energy density is so low that the predicted flux would be 4 orders of magnitude below that observed (assuming an equipartition field of 40 \( \mu G \)).

IC scattering off the CMB photons would require a magnetic field strength of 0.3 \( \mu G \), more than a factor of 100 below the equipartition field, and the emitting volumes appear not to coincide as expected from IC emission. Even if we invoke relativistic beaming and ignore the disparity in morphology between radio and X-rays, to produce the observed X-ray jet would require an angle between the jet velocity vector and the line of sight of 7° or less and a beaming factor of 8. If there is a difference in morphologies, the beaming parameters become more stringent since the
actual radio flux density arising from the X-ray–emitting volume would be less than that assumed in the calculation above.

These values are inconsistent with estimates from the radio data. From the observed ratio of intensities of the inner radio jets (4.46), the angle between the line of sight and the north jet has to be less than $75^\circ/C_{14}$ and is most likely greater than $30^\circ/C_{14}$ since we see the two sides of the jet nowhere near lying on top of each other. This range in angles corresponds to beaming factors in the range $1.16–1.3$ and jet fluid velocities, $v/c$, in the range $0.3–1$.

5. DISCUSSION

Granted that we are dealing with few photons and thus an insecure morphology, we believe the evidence favors synchrotron emission for the observed X-rays. Undoubtedly, there are bulk relativistic velocities in the jet producing the observed intensity differences between the north and south jets, but with velocity vectors not too far from the plane of the sky, we see only mild boosting, and the parameters for IC/CMB emission are completely at odds with all other evidence.

If the bulk of the detected X-ray emission is in fact upstream of the radio knot N2.3, it would simply indicate that an acceleration region capable of producing $\gamma$ of order $10^7–10^8$ would be followed by a more extensive acceleration region incapable of such high energies but rather producing up to $\gamma \approx 10^4$. Even in weak fields of order 30–50 $\mu$G, the half-life for electrons producing X-rays is so short that they could travel no more than 30 pc from their acceleration region. Thus, the X-rays clearly demarcate that sort of acceleration region.

There are now several detections of X-ray emission from jets in FR I radio galaxies. For M87 (Marshall et al. 2002) the radio, optical, and X-ray morphologies are quite close, if not identical, but upstream offsets of X-ray brightness peaks compared to those of the radio have been documented for 3C 66B (Hardcastle et al. 2001) and 3C 31 (Hardcastle et al. 2002). For these sources the offsets are a few hundred parsecs, slightly smaller than our (uncertain) value of 480 pc for 3C 129. The situation in the jet of Cen A (Kraft et al. 2000) is confused with some features aligning well at radio and X-ray bands, but for others it is not always clear which features correspond at the other wavelength.

In Table 1 we give comparative values of size and luminosities for several FR I detections. It can be seen that the 3C 129 parameters are quite consistent with the others. While we cannot rule out thermal bremsstrahlung as the cause of the X-rays from 3C 129, it seems likely that as for the other FR I detections, synchrotron emission is the favored process.

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**TABLE 1**

| Source       | Scale (kpc arcsec$^{-1}$) | Projected Length (pc) | $L_X(0.5–5$ keV) $(10^{40}$ ergs s$^{-1}$) | References |
|--------------|---------------------------|-----------------------|------------------------------------------|------------|
| 3C 129       | 0.60                      | 1320                  | 0.9                                      | 1          |
| 3C 31        | 0.48                      | 3356                  | 4.9                                      | 2          |
| B2 0206+35   | 1.02                      | 2040                  | 16.0                                     | 3          |
| 3C 66B       | 0.61                      | 4270$^b$              | 13.0                                     | 4          |
| B2 0755+37   | 1.17                      | 2574                  | 39.0                                     | 3          |
| M87          | 0.08                      | 1386                  | 7.8                                      | 5          |
| Cen A        | 0.02                      | 3400                  | 0.3                                      | 6          |

$^a$ For further examples, see http://hea-www.harvard.edu/XJET/.

$^b$ Most of the X-ray intensity is closer than 1220 pc from the core.

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