**XMM-NEWTON DETECTION OF X-RAY EMISSION FROM THE COMPACT STEEP-SPECTRUM RADIO GALAXY 3C 303.1**

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**ABSTRACT**

Using *XMM-Newton* we detect faint unresolved X-ray emission from the compact steep-spectrum radio galaxy 3C 303.1. We detect a thermal component at $kT \approx 0.8$ keV, which seems likely to be produced in the interstellar medium (ISM) of the host galaxy. There is evidence for a second component in the spectrum whose nature is currently ambiguous. Plausible hypotheses for the second component include (1) hot gas shocked by the expansion of the radio source, and (2) synchrotron self-Compton emission from the southern radio lobe if the magnetic field is below the equipartition value by a factor of $\sim 3.5$.

**Subject headings:** galaxies: active — galaxies: individual (3C 303.1) — galaxies: jets — X-rays: galaxies

**Online material:** color figures

1. INTRODUCTION

The progenitors of the large-scale powerful classical double (3CR FR II) sources seem likely to be the GHz peaked spectrum (GPS) and compact steep-spectrum (CSS) radio sources (e.g., O’Dea et al. 1991; Fanti et al. 1990, 1995; Readhead et al. 1996a, 1996b; O’Dea & Baum 1997; for a review see O’Dea 1998). The GPS and CSS sources have generally simple and convex radio spectra with peaks near 1 GHz and 100 MHz, respectively.

Models for the evolution of powerful radio galaxies (Fanti et al. 1995; Begelman 1996; Readhead et al. 1996a; O’Dea & Baum 1997; De Young 1997; Kaiser & Alexander 1997; Kaiser et al. 1997; Blundell et al. 1999; and cf., Snellen et al. 2000) are generally consistent with a scenario in which these sources propagate from the $\sim 10$ pc to Mpc scales at roughly constant velocity through an ambient medium that declines in density while the sources decline in radio luminosity.

There is increasing evidence that the GPS and CSS sources interact with the host galaxy as they propagate through it. Broad- and narrow-band *Hubble Space Telescope (HST)* imaging of CSS radio sources (de Vries et al. 1997, 1999; Axon et al. 2000) have shown that CSS radio galaxies at all redshifts exhibit emission-line gas, which is strongly aligned with the radio source. The alignment is much stronger than seen in low-redshift large-scale radio galaxies and is similar to that seen in high-redshift ($z \gtrsim 0.6$) radio galaxies. The close association between the gas and the radio source suggests that the latter interacts strongly with the ambient medium as it propagates through the ISM.

In 3C 303.1 cooling-time arguments (e.g., Pedlar et al. 1985; Taylor et al. 1992) applied to the gap between the radio hot spots and the onset of bright emission-line gas are consistent with lobe expansion velocities $\gtrsim 6000$ km s$^{-1}$ for ambient densities of $n \sim 1$ cm$^{-3}$ (de Vries et al. 1999). The broad and highly structured spatially integrated [O IV] $\lambda 5007$ line widths observed by Gelderman & Whittle (1994) strongly suggest that the radio source is dominating the emission-line kinematics. *HST* Space Telescope Imaging Spectrograph (STIS) long-slit medium-dispersion spectroscopy of the aligned emission-line gas has shown that the kinematics of the gas are consistent with cloud motions driven by interaction with the expanding radio source (O’Dea et al. 2002). Constraints on the bow-shock velocity from lifetime and cooling arguments are in the range of a few $\times 10^3$ to a few $\times 10^4$ km s$^{-1}$ (O’Dea et al. 2002). Analysis of the low-dispersion STIS spectra reveals that the ionization diagnostics are consistent with strong contributions from shocked gas (Labiano et al. 2005). *HST* UV imaging shows a clear detection of UV continuum light tightly aligned with the radio source (Labiano et al. 2006). These observations are all consistent with the radio source in 3C 303.1 interacting with gas clouds in its environment, shocking them and triggering star formation.

The interaction of the radio source with its environment may also produce observable signatures in the X-ray. Heinz et al. (1998) suggested that compact evolving radio galaxies might create shells of hot shocked gas as they expand into the ambient medium. X-ray observations have found examples of both hotter (e.g., Kraft et al. 2003; Wilson et al. 2006) and cooler (e.g., Nulsen et al. 2005; Soker et al. 2002; Blanton et al. 2001) shells of ambient gas swept up by expanding radio galaxies.

In this paper we present *XMM-Newton* X-ray observations of the CSS radio galaxy 3C 303.1. We discuss the results and their implications for our understanding of CSS radio sources.

2. THE XMM-NEWTON OBSERVATIONS AND RESULTS

The properties of the source are given in Table 1. We observed 3C 303.1 with *XMM-Newton* for about 40 ks on 2003 August 18.

Three EPIC cameras, MOS 1, MOS 2, and pn, were operated with medium optical blocking filters in “Prime Full Window” mode, which covers the full field of view (FOV) of 30’ diameter. Because a fraction of the flux collected by the telescopes hosting the MOS cameras is directed to dispersing grating arrays, the photons collected by each MOS camera are fewer than those collected by the pn camera.

The data were reprocessed using the *XMM-Newton* Science Analysis System (SAS) version 6.1.0. EMCHAIN and EPCHAIN were employed to obtain the photon event lists. Then we used EVESELECT to select single, double, triple, and quadruple events (PATTERN $\leq 12$) for MOS, and single and double events...
XMM-Newton Observations of 3C 303.1

### TABLE 1

| Parameter                        | 3C 303.1 |
|----------------------------------|----------|
| Redshift                         | G        |
| R.A. (J2000.0)                   | 14 43.14.8 |
| Decl. (J2000.0)                  | 77 07.28 |
| Scale (kpc arcsec⁻¹)             | 4.07     |
| Radio power log₁₀P₂ GHz (W Hz⁻¹) | 26.53    |
| Radio source total angular size θ (arcsec) | 1.7 |
| Linear size D (kpc)              | 6.9      |
| Integrated emission-line flux F[(O ν)] 50007) (10⁻¹⁵ ergs s⁻¹ cm⁻²) | 28 |
| Spectral age (yr)                | 1.00     |
| Advance speed (c/c)              | 0.07     |

**Notes:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. We adopt the standard cosmology with H₀ = 71 km s⁻¹ Mpc⁻¹, Ω₀ = 0.3, and Ω₀ = 0.7. The integrated emission-line flux is from Gelderman & Whittle (1994). The spectral age is estimated by fitting a continuous injection model to the integrated radio spectrum and is taken from Murgia et al. (1999). The advance speed is estimated using 2v = linear size/spectral age.

### TABLE 2

| Parameter                        | pn        | MOS 1      | MOS 2      |
|----------------------------------|-----------|------------|------------|
| Net exposure time (ks)           | 25.93     | 32.13      | 32.67      |
| Net count rate (counts s⁻¹)      | 8.15E–3 ± 1.92E–3 | 2.15E–3 ± 7.22E–4 | 1.62E–3 ± 6.97E–4 |
| Total counts                      | 628       | 218        | 191        |
| Total counts 0.4–8 keV           | 483       | 127        | 128        |
| Net count* 0.2–12 keV            | 211       | 69         | 53         |

**Notes:** These numbers are after GTI filtering. Observation date is 2003 August 18.

* Background subtracted.
Arnaud & Evrard 1999). This suggests that we have detected the ISM of the host galaxy or possibly the intragroup medium (if there is a galaxy group).

3.2. Constraints on Shock-Heated Gas

The expanding radio source will run over and shock the ambient gas possibly producing detectable emission (e.g., Heinz et al. 1998). We calculate the expected properties of the shocked gas following Worrall et al. (2005). The sound speed in the 0.8 keV ISM is $c_s \approx 460 \text{ km s}^{-1}$. If the propagation velocity of the radio source is as high as 6000 km s$^{-1}$ as suggested by the cooling-time arguments for the emission-line nebula (de Vries et al. 1999), the Mach number is $M \approx 13$. For such a strong shock the Rankine-Hugoniot conditions give a temperature ratio between shocked and preshocked gas of $T_2/T_1 \approx 54$, which implies $T_2 \approx 43 \text{ keV}$. We note that a two-temperature model with $T_1 = 0.8$ and $T_2 = 45 \text{ keV}$ is permitted by the data (Table 5).

Taking into account the uncertainties, Table 5 shows that the normalizations of the heated (shocked) to cool (unshocked) gas is a factor of roughly 0.9–6. The 1 keV normalization is proportional to $n^2 V$, where $n$ is the number density of electrons or protons and $V$ is the volume. Since the Rankine-Hugoniot conditions for a strong shock give $n_{\text{shocked}}/n_{\text{unshocked}} = 4$, the X-ray spectral results are consistent with $V_{\text{shocked}}/V_{\text{unshocked}} \approx 3–18$. What is the volume of the shocked gas? We detect radio emission from the cocoon but not from the hot shocked gas that lies between the cocoon and the bow shock. We use the numerical simulations of Carvalho & O’Dea (2002) as a guide to estimate the ratio of the volumes of hot shocked gas and the cocoon. The estimated ratio is model dependent and varies with the jet density contrast and Mach number. For a light, supersonic jet the numerical simulations suggest a value of about 3 for the ratio of the shocked gas to cocoon volume. Adopting a value of 3 along with the

| TABLE 3 |
|---------|
| **Spectral Fits: Single Thermal Component** |
| Parameter | Value |
| External absorption $n_1 \left( 10^{22} \text{ cm}^{-2} \right)$ | $0.031^a$ |
| Abundance | $1.0^b$ |
| Temperature $kT$ (keV) | $0.82 \pm 0.05$ |
| Luminosity $0.4$–$8.0 \text{ keV} \left( 10^{32} \text{ ergs s}^{-1} \right)$ | $2.4$ |
| 1 keV normalization $\left( 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \right)$ | $7.7 \pm 2.1$ |
| $\chi^2$ | $24.63$ |
| dof | $27$ |

*Notes.—A fit to wabs$^a$(raymond + zwabs$^b$) power law using the energy range 0.4–8.0 keV over 29 bins.

$^a$ Absorption is frozen at the foreground Galactic value.

$^b$ Abundance is frozen at the solar value.

| TABLE 4 |
|---------|
| **Spectral Fits: Thermal Component and Power Law** |
| Parameter | Value |
| External absorption $n_1 \left( 10^{22} \times 10^{23} \text{ cm}^{-2} \right)$ | $0.031^a$ |
| Abundance | $1.0^b$ |
| Temperature $kT$ (keV) | $0.77 \pm 0.09$ |
| Luminosity $0.4$–$8.0 \text{ keV} \left( 10^{32} \text{ ergs s}^{-1} \right)$ | $2.0$ |
| 1 keV normalization $\left( 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \right)$ | $5.9 \pm 4.3$ |
| Absorption towards the PL $n_1 \left( 10^{22} \text{ cm}^{-2} \right)$ | $0.47 \pm 1.38$ |
| Photon index $\Gamma$ | $1.5^c$ |
| 1 keV PL normalization $\left( 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \right)$ | $1.9^{+0.7}_{-0.6}$ |
| Luminosity $0.4$–$8.0 \text{ keV} \left( 10^{32} \text{ ergs s}^{-1} \right)$ | $2.2$ |
| $\chi^2$ | $17.17$ |
| dof | $25$ |

*Notes.—A fit to wabs$^a$(raymond + zwabs$^b$) power law using the energy range 0.4–8.0 keV over 29 bins.

$^a$ Absorption is frozen at the foreground Galactic value.

$^b$ Abundance is frozen at the solar value.

$^c$ The power-law photon index is poorly constrained by our data, so we froze a value of $\Gamma = 1.5$. A value of $\Gamma = 2.0$ produces similar results.
estimates of cocoon volume from the MERLIN observations gives a volume of shocked gas of about 14 kpc$^3$. We find the volume of unshocked gas is large enough to be consistent with a realistic galaxy atmosphere if $V_{\text{unshocked}}/V_{\text{shocked}}$ is toward the upper value permitted by the X-ray spectral fitting. For example, if $V_{\text{unshocked}}/V_{\text{shocked}} = 18$, a spherical galaxy of uniform density would be required to have a radius of about 4 kpc. Such a galaxy has a similar $n^2V$ to one of the same central density modeled with a $\beta$ model of $\beta = 2/3$ and core radius of $\sim 3$ kpc. Chandra measurements of the atmospheres around relatively powerful nearby radio galaxies are fitted to $\beta$ models that typically bracket these parameter values (e.g., Kraft et al. 2005; Worrall & Birkinshaw 2005). High-resolution X-ray imaging spectroscopy would probe the density and temperature structure, and should confirm whether such a high-temperature component exists.

### 3.3. The Power-Law Component

Here we consider the possibility that there is a significant nonthermal power-law component, i.e., the second component in the fit to the spectrum is not due to a hot shocked gas. The lack of a high intrinsic absorbing column toward the PL component suggests that it is not from accretion-disk emission that would be expected to be obscured in this powerful two-sided radio galaxy, and the fact that the nucleus is undetected both at 1.6 GHz (O'Dea et al. 1999) and at 5.0 GHz (Lüdke et al. 1998) disfavors the X-ray emission originating from a small-scale jet. X-ray binaries produce emission that can mimic a hard power law, but the luminosity of $>10^{42}$ ergs s$^{-1}$ is 1 or 2 orders of magnitude more than is typically measured in elliptical galaxies (e.g., Kim & Fabbiano 2004).

The most likely explanation for a power-law component would appear to be inverse Compton emission from the lobes of the radio galaxy. We estimate the expected flux (e.g., Harris & Grindlay 1979; Harris & Krawczynski 2002; Hardcastle et al. 1998) using the MERLIN radio measurements of Sanghera et al. (1995), where at 1.6 GHz the southern lobe contains about 90% of the total radio flux density. We find that, because of the small size of the lobes, synchrotron self-Compton (SSC) dominates the X-ray yield from scattering of the cosmic microwave background radiation.

Results of the SSC calculations are presented in Table 6. In these calculations we adopt a single-component power-law electron spectrum of slope consistent with the observed radio synchrotron spectrum (Sanghera et al. 1995). In order to maximize the SSC output under the equipartition assumptions, we set the minimum electron energy to no lower than is required to produce the radio emission, and we assume that no nonradiating particles (protons) are present. If the magnetic field is at the equipartition strength, the predicted SSC X-ray flux is too low by factors of $\sim 350$ in the northern lobe and $\sim 16$ in the southern lobe. However, if the field is below the equipartition level by factors of $\sim 16$ and $\sim 3.5$, in the northern and southern lobes, respectively, the predicted flux is comparable to that in the measured PL component. There is some evidence that the magnetic fields in some radio lobes are indeed about 1/3 of the equipartition strength (e.g., Carilli et al. 1994; Wellman et al. 1997; Croston et al. 2005), and thus there is additional justification for the PL component arising from SSC emission primarily in the southern lobe of 3C 303.1, with a magnetic field about one-third of the equipartition value. If this is the correct interpretation it suggests that the mechanism for keeping the average B field below equipartition occurs in young radio galaxies and is not just a feature of large FR II radio galaxies.

### 3.4. Comparison with other Radio Galaxies

There are now X-ray observations of a dozen GPS radio galaxies (O’Dea et al. 1996, 2000; Iwasawa et al. 1999; Guainazzi et al. 2004, 2006; Vink et al. 2006). 4C +55.16 appears to be in a cluster with a cooling flow (Iwasawa et al. 1999). The others are dominated by a power-law component with intrinsic absorption of $N(H) \sim 10^{22}$ to $10^{24}$ cm$^{-2}$ (Guainazzi et al. 2006; Vink et al. 2006). This intrinsic absorption is larger than the H I absorption along the line of sight to the radio emission in the small number of cases where the radio measurements have been made (Vink et al. 2006), thus suggesting that the absorbed X-ray emission arises from the vicinity of an accretion disk.

Large narrow-emission-line FR II radio galaxies generally have two nuclear X-ray components (Belsole et al. 2006). One has intrinsic absorption similar to that measured for most GPS sources and is interpreted as accretion related, and the other is unabsorbed and identified as arising from jet emission within the radio core. Our X-ray measurements of the CSS radio galaxy 3C 303.1 find no evidence for absorbed emission; it is either absent or very weak. If absent, it may suggest that the central engine of 3C 303.1 is more similar to that of an FR I radio galaxy, where

### Table 5

**Spectral Fits: Warm and Hot Thermal Components**

| Parameter | Value |
|-----------|-------|
| External absorption $n_0$ ($\times 10^{22}$ cm$^{-2}$) | $0.03 \pm 4$ |
| Abundance | 1.0$^a$ |
| Temperature $kT$ (keV) | $0.8^b$ |
| Luminosity 0.4–8.0 keV (10$^{42}$ ergs s$^{-1}$) | 1.7 |
| 1 keV normalization (10$^{-6}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) | 5.3 ± 1.7 |
| Temperature $kT$ (keV) | 45$^c$ |
| 1 keV normalization (10$^{-6}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) | 13.6 ± 7.6 |
| Luminosity 0.4–8.0 keV (10$^{42}$ ergs s$^{-1}$) | 2.8 |
| $\chi^2$ | 18.77 |
| dof | 27 |

**Notes.**—A fit to wabs(raymond + raymond) using the energy range 0.4–8.0 keV over 29 bins.

$^a$ Absorption is frozen at the foreground Galactic value.

$^b$ Abundance is frozen at the solar value.

$^c$ Temperature frozen at 0.8 and 45 keV.
absorbed X-ray components are rarely seen (Evans et al. 2006; but note the cases of Cen A [Evans et al. 2004] and NGC 4261 [Zezas et al. 2005]). The radio core of 3C 303.1 is undetected, and if the second X-ray spectral component is indeed nonthermal, then it is much more plausibly associated with the radio lobes than with the radio core.

The alternative hypothesis is that we are seeing shocked gas. In either case this hard emission should be spatially resolved in Chandra observations. It appears that the weak core of 3C 303.1 is an advantage in allowing other X-ray components to be seen more clearly.

4. SUMMARY

Using XMM-Newton we detect faint unresolved X-ray emission from the CSS radio galaxy 3C 303.1. We detect a thermal component at \( kT \approx 0.8 \) keV, which seems likely to be produced in the ISM of the host galaxy. There is evidence for a second component in the spectrum whose nature is currently ambiguous. It does not appear to be related to the core, giving 3C 303.1 the advantage over other GPS/CSS radio galaxies that extended components show up more clearly. Plausible hypotheses include (1) hot gas shocked by the expansion of the radio source, and (2) SSC emission from the southern radio lobe if the magnetic field is below the equipartition value by a factor of about 3.5. In the former case this would be the first detection of strongly shocked gas around an FR II radio source. In the latter case it would be a rare instance of the detection of SSC emission from a radio lobe, as distinct from a small localized hot spot. Deep Chandra observations could confirm the presence of this extended component and improve our understanding of its origin.

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REFERENCES

Arnaud, M., & Evrard, A. E. 1999, MNRAS, 305, 631
Axon, D. J., Capetti, A., Fanti, R., Morganti, R., Robinson, A., & Spencer, R. 2000, AJ, 120, 2284
Begelman, M. C. 1996, in Proc. of Greenbank Workshop, Cygnus A: Study of a Radio Galaxy, ed. C. L. Carilli & D. E. Harris (Cambridge: Cambridge Univ. Press), 209
Belsese, E., Worrall, D. M., & Hardcastle, M. J. 2006, MNRAS, 366, 339
Blanton, E. L., Sarazin, D. L., McNamara, B. R., & Wise, M. 2001, ApJ, 558, L15
Blundell, K. M., Rawklings, S., & Willott, C. J. 1999, AJ, 117, 677
Carilli, C. L., Perley, R. A., & Harris, D. E. 1994, MNRAS, 270, 173
Carvalho, J., & O’Dea, C. P. 2002, ApJS, 141, 337
Croston, J. H., Hardcastle, M. J., Harris, D. E., Belsese, E., Birkinshaw, M., & Worrall, D. M. 2005, ApJ, 626, 733
de Vries, W. H., O’Dea, C. P., Baum, S. A., & Barthel, P. D. 1999, ApJ, 526, 27 de Vries et al. 1997, ApJS, 110, 191
De Young, D. S. 1997, ApJ, 490, L55
Evans, D. A., Kraft, R. P., Worrall, D. M., Hardcastle, M. J., Jones, C., Forman, W. R., & Murray, S. S. 2004, ApJ, 612, 786
Evans, D. A., Worrall, D. M., Hardcastle, M. J., Kraft, R. P., & Birkinshaw, M. 2006, ApJ, 642, 96
Fanti, C., Fanti, R., Dallacasa, D., Schilizzi, R. T., Spencer, R. E., & Stanghellini, C. 1995, A&A, 302, 317
Fanti, R., Fanti, C., Schilizzi, R. T., Spencer, R. E., Rendong, N., Parma, P., van Breugel, W. J. M., & Venturi, T. 1999, A&A, 321, 333
Gelderman, R., & Whittle, M. 1994, ApJS, 91, 491
Guainazzi, M., Siemiginowska, A., Rodriguez-Pascual, P., & Stanghellini, C. 2004, A&A, 421, 461
Guainazzi, M., Siemiginowska, A., Stanghellini, C., Grandi, P., Piconcelli, E., & Azubike Ugwoke, C. 2006, A&A, 446, 87
Hardcastle, M. J., Birkinshaw, M., & Worrall, D. M. 1998, MNRAS, 294, 615
Harris, D. E., & Grindlay, J. E. 1979, MNRAS, 188, 25

Harris, D. E., & Krawczynski, H. 2002, ApJ, 565, 244
Harvanek, M., Ellingson, E., Stroe, J. T., & Rhee, G. 2001, AJ, 122, 2874
Heinz, S., Reynolds, C. S., & Begelman, M. C. 1998, ApJ, 510, 126
Helsdon, S. F., & Ponman, T. J. 2000, MNRAS, 315, 356
Iwasawa, K., Allen, S. W., Fabian, A. C., Edge, A. C., & Etori, S. 1999, MNRAS, 306, 467
Kaiser, C. R., & Alexander, P. 1997, MNRAS, 286, 215
Kaiser, C. R., Dennett-Thorpe, J., & Alexander, P. 1997, MNRAS, 292, 723
Kim, D.-W., & Fabbiiano, G. 2004, ApJ, 611, 846
Kraft, R. P., Hardcastle, M. J., Worrall, D. M., & Murray, S. S. 2005, ApJ, 622, 149
Kraft, R. P., Vazquez, S. E., Forman, W. R., Jones, C., Murray, S. S., Hardcastle, M. J., Worrall, D. M., & Chuazov, E. 2003, ApJ, 592, 129
Labiano, A., O’Dea, C. P., Barthel, P. D., de Vries, W. H., & Baum, S. A. 2006, A&A, in press
Labiano, A., et al. 2005, A&A, 436, 493
Lüdke, E., Garrington, S. T., Spencer, R. E., Akujor, C. E., Muxlow, T. W. B., Sanghera, H. S., & Fanti, C. 1998, MNRAS, 299, 467
Murgia, M., Fanti, C., Fanti, R., Gregorini, L., Klein, U., Mack, & K.-H., Vigotti, M. 1999, A&A, 345, 769
Nulsen, P. E. J., McNamara, B. R., Wise, M. W., & David, L. P. 2005, ApJ, 628, 629
O’Dea, C. P. 1998, PASP, 110, 493
O’Dea, C. P., & Baum, S. A. 1997, AJ, 113, 148
O’Dea, C. P., Baum, S. A., & Stanghellini, C. 1991, ApJ, 380, 66
O’Dea, C. P., de Vries, W. H., Worrall, D. M., Baum, S. A., & Kookempoer, A. 2000, AJ, 119, 478
O’Dea, C. P., Worrall, D. M., Baum, S. A., & Stanghellini, C. 1996, AJ, 111, 92
O’Dea, C. P., et al. 2002, AJ, 123, 2333
Pedlar, A., Dyson, J. E., & Unger, S. W. 1985, MNRAS, 214, 453
Readhead, A. C. S., Taylor, G. B., Pearson, T. J., & Wilkinson, P. N. 1996a, ApJ, 460, 634
