A Multi-wavelength study of nuclear activity and environment of low power radio galaxy CTD 86

M. B. Pandge¹, G. C. Dewangan², K. P. Singh³, M. K. Patil¹*

¹Swami Ramanand Teerth Marathwada University Nanded 431606, India
²Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411007, India
³Tata Institute of Fundamental Research, Mumbai 400005, India.

6 May 2014

ABSTRACT
We present an X-ray study of the nuclear and extended emission of a nearby Fanaroff & Riley class I (FR-I) radio galaxy CTD 86 based on the XMM-Newton observations. Two different components observed are: diffuse thermal emission from hot gas ($kT \sim 0.79$ keV, $n_e \sim 10^{-3}$ cm$^{-3}$, $L_X \sim 5 \times 10^{42}$ erg s$^{-1}$ extended over $\sim 186$ kpc), and unresolved nuclear emission exhibiting mild activity. The hot gaseous environment of CTD 86 is similar to that found in groups of galaxies or in bright early-type galaxies. No clear signatures of radio-lobe interaction with the diffuse hot gas is evident in this case. X-ray emission from the nucleus is well constrained by an intrinsically absorbed ($N_H \sim 5.9 \times 10^{22}$ cm$^{-2}$) power law ($\Gamma \sim 1.5$) with $2 - 10$ keV luminosity $L_X \sim 2.1 \times 10^{42}$ erg s$^{-1}$. We have measured the stellar velocity dispersion, $\sigma = 182 \pm 8$ km s$^{-1}$, for the CTD 86 and estimated a mass $M_{BH} \sim 9 \times 10^7$ M$_\odot$ with $L_{bol}/L_{Edd} \sim 4 \times 10^{-3}$. The low $L_{bol}/L_{Edd}$ rate and high $L_X/L_{[O~III]}$ ratio suggest that the central engine of CTD 86 consists of a truncated accretion disk lacking a strong ionizing UV radiation and an inner hot flow producing the X-ray emission. The truncated disk is likely to be inclined with $(i \sim 40^\circ - 50^\circ)$ such that our line of sight passes through the outer regions of a putative torus and thus results in high X-ray absorption. We have also identified two bright X-ray sources, SDSS J142452.11+263715.1 and SDSS J142443.78+263616.2, near CTD 86. SDSS J142452.11+263715.1 is a type 1 active galactic nucleus at $z = 0.3761$ and unabsorbed $0.3 - 10$ keV.
X-ray luminosity $L_X \sim 8 \times 10^{43}$ erg s$^{-1}$, while SDSS J142443.78+263616.2 is probably a galaxy with an active nucleus.

**Key words:** galaxies: active; galaxies: elliptical and lenticular, cD; galaxies: nuclei; galaxies: individual: CTD 86; X-rays: galaxies; X-rays: individual: RX J1424.7+2636

1 INTRODUCTION

Optical and X-ray luminosity functions of active galactic nuclei (AGN) are not complete at the faint end of luminosities. Both radio-quiet as well as radio-loud active galaxies are expected to exist at low optical and X-ray luminosities. The nearby low luminosity radio galaxies (LLRGs) are good candidates to study the mild nuclear activity in galaxies. Since LLRGs also represent the parent population of BL Lac objects, therefore, their study can provide an insight into the unification and evolution of radio galaxies. The LLRGs are members of Fanaroff-Riley class 1 (FR-I) (Fanaroff & Riley 1974), where one finds a variety of sources in terms of power and radio morphology. Apart from having radio power $\lesssim 5 \times 10^{25}$ W Hz$^{-1}$ at a frequency of 1.4 GHz, FR-I sources have only one feature in common: hot spots at the outer edge of lobes are never seen. Naked radio jets occur preferably at the very low end of radio power ($< 10^{23}$ W Hz$^{-1}$), while at the upper end ($\sim 10^{25}$ W Hz$^{-1}$) one sided jets and hot spots in the middle of the lobes are seen. The radio emission is thought to arise from the synchrotron radiation mechanism and is a manifestation of nuclear activity.

The nuclear activity is also inferred from other independent means such as optical and X-ray emission. Supermassive black holes, accretion discs, broad line regions (BLRs), narrow line regions (NLRs) etc., all are thought to be associated with low luminosity radio galaxies (LLRGs). Therefore, X-ray and optical studies of LLRGs are useful to estimate some of the basic parameters, e.g., black hole mass, accretion rate, velocity of BLRs and NLRs etc., governing the overall appearance of these galaxies. Donato et al. (2004) found central compact X-ray cores in 13 systems out of 25 FR-I radio galaxies from the 3CRR (Third Cambridge Catalogue of Radio Sources) (Spinrad et al. 1985) and B2 (Second Bologna Catalog of radio sources) (Colla et al. 1975; Fanti et al. 1978) catalogs. From flux—flux and luminosity—luminosity core X-ray/radio correlations Canosa et al. (1999) and Donato et al. (2004) found a physical relationship between the soft X-ray emission of radio galaxies and

* E-mail: patil@iucaa.ernet.in
the jet-generated radio core emission, suggesting that at least some of the X-ray emission is related to the nuclear jet. Donato et al. (2004) also reported small Eddington ratios, \( \frac{L_{\text{bol}}}{L_{\text{Edd}}} \sim 10^{-3} - 10^{-8} \) and failed to confirm strong X-ray absorption; thus implying that their sample of FR-I galaxies generally lack a standard torus. Since the Eddington ratios of FR-I galaxies are very small compared to those of Seyfert 1 galaxies and quasars, it is possible that the central engine of FR I galaxies is different from that of other AGN with high Eddington ratios. Therefore, multiwavelength study of central compact core of FR-I galaxies is required to make any progress in our understanding of their central engines.

The massive elliptical host galaxies, many of which contain radio-loud AGN, are associated with large amount of hot gas with temperatures of \( 10^6 - 10^8 \) K (Sarazin 1986; Mulchaey 2000; Mathews & Brighenti 2003; Hardcastle 2005). The gas is heated in the deep gravitation potential wells of the massive elliptical galaxies or the associated groups or clusters of galaxies. It is now well known that the radio lobes and jets of radio-loud AGN interact with the environment and can efficiently heat the surrounding medium and thus prevent the accumulation of large amount of cool gas in the central regions (Hardcastle 2005, and references therein).

Here, we present results based on the X-ray observations (XMM-Newton, Jansen et al. 2001) and compare it with the optical (SDSS, Sloan Digital Sky Survey) and radio (FIRST, Faint Images of the Radio Sky at Twenty Centimeters; Becker et al. 1994) data of the FR-I radio galaxy CTD 86 (CalTech list D of radio sources), also known as (B2 1422+26). CTD 86 is a low-power radio galaxy (Parma et al. 1987; Canosa et al. 1999) with radio power \( 1.9 \times 10^{24} \) WHz\(^{-1} \) at 1.4 GHz, photometric B band magnitude of 15.62 and is located at a distance of about 161 Mpc (\( H_0 = 73 \) km s\(^{-1}\)Mpc\(^{-1} \), \( z=0.037 \). CTD 86 is an elliptical (E2-type) radio galaxy and belongs to the poor cluster AWM 3 (Beers et al. 1984) with \( \sim 44 \) members at a redshift of \( cz = 4495 \) km s\(^{-1} \). The global parameters of CTD 86 are summarized in Table 1. The radio source B2 1422+26B (observed with the Effelsberg 100-m telescope (Mack et al. 1994)) associated with CTD 86 shows a symmetric double lobed structure and is extended up to about 75 kpc from the optical center of the galaxy. At the outer edges of the lobes, symmetrical ring like structures are also evident. The structure of this paper is as follows. Section 2 describes the X-ray data analysis and presents X-ray images and spectra obtained. Section 3 provides a discussion on the results, and is followed by conclusions in Section 4.
Table 1. Global parameters of CTD 86

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| α (J2000); δ (J2000)      | 14:24:40.5; +26:37:31       |
| Morphological type         | E2                         |
| Magnitude (B)              | 15.62                      |
| Size                       | 0’.96×0’.66                |
| Distance (Mpc)             | 161                        |
| z                          | 0.037152                   |
| Radio core flux density    | 25mJy                      |

1 NED: NASA/IPAC EXTRA GALACTIC DATABASE ; 2 Merkelijn (1968); 3 (Parma et al. 1987; Canosa et al. 1999); 4 Miller et al. (2002); 5 Giovannini et al. (1991)

Figure 1. XMM-Newton tri-color image of CTD 86 and its environment. The soft (0.3–1 keV) band is shown in red, the intermediate (1–2 keV) band in green and the hard (2–10 keV) band is shown in blue. One arcmin corresponds to a linear size of 43.7 kpc at the red shift of CTD 86 (z = 0.037216). The unresolved source marked “1” is SDSS 142452.11+263715.1 and the source “2” is SDSS J142443.78+263616.2. Source “1” shows broad emission lines in its optical spectrum and is classified as a quasar at z = 0.3761. Source “2” is also most likely an AGN.

2 THE XMM-Newton DATA

CTD 86 was observed twice with XMM-Newton, on 2010 June 21 (obsid: 0652720101; hereafter Obs.I) and 2010 August 02 (obsid: 0652720201; hereafter Obs.II), with effective exposure times of 33.9 ks and 32.4 ks, respectively. In both the observations, all the three EPIC cameras were operated in the full frame mode using the “thin” filter for the EPIC-pn (Strüder et al. 2001) and the “medium” filter for the two MOS cameras (Turner et al. 2001). We have made use of both the data sets on CTD 86 available in the archive of the HEASARC. The observation data files (ODF) for CTD 86 obtained from the XMM-Newton archive, were processed using the Science Analysis Software (SAS) version 11. Examination of the background rate above 10 keV revealed that the data were partly affected by the
Figure 2. Composite soft (0.3–1 keV) band X-ray (blue), SDSS optical (red) and FIRST radio (green) image of CTD 86 and its environment. The unresolved source marked “1” is SDSS 142452.11+263715.1 and the source “2” is SDSS J142443.78+263616.2. Optical counterparts of the point sources are clearly evident.

Figure 3. The azimuthally averaged, background subtracted radial surface brightness profile of CTD 86 in the 0.3 – 2.5 keV energy band. The red continuous line shows the best fitted 1d-β model and black points are the extracted photons from each of the annulus.

flaring particle background. Time intervals with the count rates greater than 0.6 counts s$^{-1}$ for the EPIC-pn and 0.175 counts s$^{-1}$ for MOS1 and MOS2 detectors were identified as background flares and were neglected during further analysis. Only events corresponding to patterns 0–4 for the EPIC-pn and 0–12 for the MOS detectors were retained and used for further analysis. The resulting net EPIC-pn, MOS1 and MOS2 exposure times for Obs.I are 30 ks, 30.1 ks and 25 ks and for Obs.II are 27.81 ks, 27.12 ks, 27.12 ks, respectively.
We have a composite (PN+MOS1+MOS2) mosaic image from the Obs.I dataset by combining the EPIC-pn, MOS1 and MOS2 event files in the soft (0.3 – 1 keV), intermediate (1 – 2 keV) and hard (2 – 10 keV) bands. These images were smoothed with a Gaussian kernel of radius 10″ and were then combined to form a single image in color coded form Figure 1. This figure shows the tri-color X-ray image of CTD 86 and its environment and confirms the presence of diffuse soft X-ray emission surrounding CTD 86 reported previously by Canosa et al. (1999). Two unresolved X-ray sources near CTD 86 are also evident in this figure and were reported previously with ROSAT Canosa et al. (1999). In addition, this figure revealed an unresolved X-ray core at the center of the CTD 86. We also made a composite X-ray (0.3 – 1.0) keV band (blue), SDSS optical (red) and radio FIRST (green) image for CTD 86 and is shown in Figure 2. This figure clearly shows an unresolved X-ray core at the center of the CTD 86. Thus, hard X-rays from the central part of overall X-ray emission most likely represents the active nucleus of CTD 86. The radio-lobes of CTD 86 are embedded in the diffuse X-ray emission surrounding the nucleus. Our analysis failed to detect X-ray cavities formed due to the interaction of radio-lobes with the surrounding hot gas (Pandge et al. 2012).

2.1 Surface Brightness profile of Diffuse X-ray Emission

We derived azimuthally averaged, background subtracted, 0.3-2.5 keV radial surface brightness profile by extracting X-ray photons from 35 concentric circular annuli extending up to 360″ centered on the CTD 86 using the task funtool available in ds9. To avoid any contamination due to the central source, we excluded the central 15″ region during the analysis. The width of the annuli, particularly in the outer parts, were adjusted so as to achieve roughly the same signal-to-noise ratio. The radial surface brightness profile thus derived is shown in Figure 3. From this figure it is apparent that the extended emission is detectable up to a radius of ~250″ (~186 kpc). This profile was fitted with a single 1-d β model (King 1962) that resulted in the best fit core radius $r_c = 46.12 \pm 4.46$ kpc and the slope parameter $\beta = 0.61 \pm 0.03$. The errors given here are at 68% confidence level.

2.2 X-ray Spectral Analysis

Exposure-corrected, 3″ Gaussian smoothed image of XMM-Newton is shown in Figure 4. We extracted EPIC-pn, MOS1 and MOS2 spectra of the hot diffuse gas around CTD 86
using a circular region with radius 100'' but excluding two circular regions one of radius 30'' centered on CTD 86 and another of radius of 40'' centered on the nearby source SDSS J142443.78+263616.2 (figure 4). We also extracted the EPIC spectra of the nuclear source using a circular region with a radius of 30'' centered at the position of CTD 86. The background spectra were extracted from the source-free regions. Spectra for both the bright X-ray sources SDSS J142443.78+263616.2 and SDSS J142452.11+263715.1 were also extracted using circular regions of radii 40'' centered on their peak positions. Ancillary response files (ARF) and redistribution matrix files (RMF) were generated for each of the extracted spectrum using the SAS tasks rmfgen and arfgen, respectively. The resulting spectra were binned to a minimum of 30 counts per bin for CTD 86 and SDSS J142443.78+263616.2, and 20 counts per bin for SDSS J142452.11+263715.1. We used the X-ray spectral analysis package XSPEC v12.6.0 (Arnaud 1996).

We analyzed the EPIC-pn, MOS1 and MOS2 spectral data jointly for each of the three sources. Several models, discussed in § 2.2.1, were used along with a constant component in order to account for possible differences in the relative normalizations of the three instruments. The constant component was fixed at unity (1) for the EPIC-pn data and varied for the MOS1 and MOS2 data. The best fit parameters were derived using $\chi^2$ minimisation.
technique and the errors were derived for the 90% confidence level. The details of the models fitted and the resulting parameters along with their errors are given below.

2.2.1 The diffuse emission

Spectral data from the region dominated by diffuse emission around CTD 86, were analyzed using a single component model apec, appropriate for a thermal plasma, modified by the Galactic absorption ($N_{H}^{Gal} = 1.61\times10^{20} \text{ cm}^{-2}$). The best fit resulted in minimum $\chi^2 = 378.06$ for 278 degrees of freedom (dof). The residuals of the fit showed presence of weak excess emission at higher energies and a residual instrumental line at 1.79 keV due to Si Kα. Therefore, we added a power-law to account for the contribution from the large point spread function of the nuclear emission and a Gaussian component to account for the 1.79 keV line. It may also have some contribution from the incorrect subtraction of the background due to soft protons (Snowden et al. 2008; Lakhchaura et al. 2011). The wabs(apec+power1w+Gauss) model improved the fit to $\chi^2/dof = 283.59/274$. The spectral parameters for the powerlaw component were poorly constrained, hence we decided to fix the photon index and performed spectral fitting by keeping it fix at 1.5, the fit results in to $\chi^2/dof = 303.11/275$. This resulted in the best fit temperature of the hot gas $kT = 0.79 \pm 0.02$ keV and elemental abundance $0.29 \pm 0.05$ relative to the solar values. We also performed spectral analysis of the data resulting from the Obs.II and found that the data are well described by a similar model. The spectral analysis resulted in to the $0.3 - 10$ keV X-ray flux of diffuse component to be $15.1 \pm 0.7 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $13.0 \pm 0.6 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ for Obs.I and II, respectively. The best fit values for the elemental abundances for Obs.I and Obs.II are found to be $0.29 \pm 0.05$ Z$_{\odot}$ and $0.31 \pm 0.04$ Z$_{\odot}$, respectively. The $0.3 - 10$ keV X-ray luminosity of the diffuse emission from CTD 86 is thus found to be $4.6 \pm 0.2 \times 10^{42}$ erg s$^{-1}$ and $4.0 \pm 0.2 \times 10^{42}$ erg s$^{-1}$ for Obs.I and II, respectively. The best fit parameters are listed in Table 2 and the spectral data, the best-fit model and the deviations compared to the best fit model are shown in Figure 5. The allowed values of temperature, abundance and $N_{H}^{intr}$ for Obs.I and Obs.II along with their confidence contours at the 68.3%, 90%, and 99% confidence levels are shown in Figure 6. The electron density of the thermal plasma can be calculated from the normalization of apec model,

$$n_{apec} = \frac{10^{-14}}{4\pi[D_A(1+z)]^2} \int n_e n_H dV,$$  \hspace{1cm} (1)
where $D_A$ is the angular diameter distance to the source, $n_e$ and $n_H$ are the electron and proton densities, respectively. For CTD 86, using the best-fit temperature $0.79 \pm 0.02$ keV and assuming the uniform gas density within the central $100'' \sim 74.4$ kpc) and $n_e \approx n_H$, we find the average electron density $n_e \approx 3 \times 10^{-3}$ cm$^{-3}$ and the total diffuse gas mass $M_{\text{gas}} = 1.83 \times 10^{11}$ M$_\odot$.

### 2.2.2 The nuclear X-ray source

X-ray emission from the central part of CTD 86 contains contribution from the nuclear source (AGN) and the hot gas surrounding it. Consequently, we performed spectral analysis of X-ray photons from the central region of CTD 86 using a two component model consisting of an apec, appropriate for a thermal plasma, plus a powerlaw for the central AGN modified by the Galactic absorption ($N_H^{Gal} = 1.6 \times 10^{20}$ cm$^{-2}$). The fit resulted in $\chi^2 = 345.7$ for 167 dof for Obs.I. Examination of the residuals showed a deficit of emission in the $1.5 - 3$ keV band, suggestive of intrinsic absorption of the power-law component. Therefore, we included an additional absorption component zwabs, that improved the fit to $\chi^2/dof = 159.8/164$. We also performed spectral analysis of the data resulting from the Obs.II and found that a similar model was required to fit the data. The best-fit parameters of the fits are listed in Table 2 and the plots are shown in Figure 5. The allowed range of values are shown in Figure 6 as enclosed by confidence contours at the 68.3%, 90%, and 99% confidence levels for temperature, abundance and $N_{H}^{\text{intr}}$ for Obs.I and Obs.II. We note that

The model $\text{wabs}(\text{apec} + \text{zwabs} \times \text{powerlaw})$ provided the intrinsic absorption column $N_H = 5.9^{+0.8}_{-1.0} \times 10^{22}$ cm$^{-2}$ and $5.4^{+1.3}_{-1.0} \times 10^{22}$ cm$^{-2}$ for Obs.I and II, whereas the power law indices ($\Gamma$) derived for Obs.I and II are $1.58^{+0.27}_{-0.25}$, $1.54^{+0.29}_{-0.27}$, respectively. The best fit values for the elemental abundance for the hot gas component for both the observations are found to be $0.15 \pm 0.05$ and $0.14 \pm 0.07$ relative to the solar values. The temperature of the diffuse emission is $0.89 \pm 0.05$ keV, and the corresponding diffuse X-ray flux in the $0.3 - 10$ keV band is $0.66 \pm 0.10 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $0.71 \pm 0.12 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ for Obs.I and II, respectively. This results in to the $0.3 - 10$ keV X-ray luminosities to be $2.1 \pm 0.2 \times 10^{42}$ erg s$^{-1}$ and $1.8 \pm 0.3 \times 10^{42}$ erg s$^{-1}$ for Obs.I and II, respectively. Using the best-fit temperature $0.89 \pm 0.05$ keV, and assuming the uniform gas density within the central region of radius $30'' (\sim 0.22$ kpc), we got $n_e \approx 4.4 \times 10^{-3}$ cm$^{-3}$ and a total gas mass $M_{\text{gas}} = 5.9 \times 10^9$ M$_\odot$. 
Figure 5. X-ray spectral data, best-fit models and the deviations of the data from the best fit models for CTD 86 from two observations: Obs.I (left) & Obs.II (right).

Table 2. Results of X-ray spectral analysis of CTD 86 for Obs.I & Obs.II.

| Region                  | Obs.I (21 June 2010) | Obs.II (2 Aug. 2010) | Obs.I (21 June 2010) | Obs.II (2 Aug. 2010) |
|-------------------------|----------------------|----------------------|----------------------|----------------------|
| Model                   | wabs(apec+zwabs×ZPL) | wabs(apec+PL+Gauss)  | wabs(apec+zwabs×ZPL) | wabs(apec+PL+Gauss)  |
| $N_{H}^{wabs}$ (10$^{20}$ cm$^{-2}$) | 1.6(fixed)           | 1.6(fixed)           | 1.6(fixed)           | 1.6(fixed)           |
| $kT_{apec}$ (keV)       | 0.89 ± 0.05          | 0.89 ± 0.07          | 0.79 ± 0.02          | 0.81 ± 0.01          |
| Abundance ($\times$ solar) | 0.15 ± 0.05          | 0.14 ± 0.07          | 0.29 ± 0.05          | 0.31 ± 0.04          |
| $f_{X}^{apec}$ (0.3−10 keV)$^a$ | 0.66 ± 0.10          | 0.71 ± 0.12          | 15.1 ± 0.7           | 13.0 ± 0.6           |
| $N_{H}^{wabs}$ (10$^{22}$ cm$^{-2}$) | 5.9$^{+0.8}_{-0.1}$  | 5.4$^{+1.3}_{-1.0}$  | –                    | –                    |
| $\Gamma$                | 1.58$^{+0.27}_{-0.25}$ | 1.54$^{+0.29}_{-0.27}$ | –                    | –                    |
| $f_{Si K\alpha}$ (keV)  | 1.77 ± 0.03          | 1.77 ± 0.04          | 4.01$\times$10$^{-4}$ | 4.07$\times$10$^{-4}$ |
| $f_{PKL}^{Si K\alpha}$  | 3.82 ± 4.62$\times$10$^{-6}$ | 4.61 ± 3.39$\times$10$^{-6}$ | –                    | –                    |
| $\chi^2$/dof            | 159.8/164            | 134.9/140            | 303.11/275           | 249.38/253           |

$^a$ In units of 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$.

$^b$ Line flux in photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$. 
2.3 Bright X-ray Sources

Two bright X-ray sources: SDSS J142452.11+263715.1 and SDSS J142443.78+263616.2 were evident near CTD 86 at a projected distance of 119 kpc and 64 kpc, respectively from the centre of CTD 86 (see Fig. 1). In the SDSS DR7 and DR8 data, SDSS J142452.11+263715 has been identified as a star and SDSS J142443.78+263616.2 as a galaxy. Based on optical identification and analysis of the SDSS optical spectrum, we find that the star-like object SDSS J142452.11+263715 is in fact a broad emission line quasar with \( z = 0.3761 \) (Pandge et al. 2013 in preparation). The nature of the other source, SDSS J142443.78+263616.2, is not clear as its optical spectrum is not available. This object appears as an extended object in the SDSS image and is likely a galaxy harboring an AGN.

To further examine the nature of these sources, we performed an X-ray spectral analysis of each source. For this, we extracted source spectra from the filtered EPIC-pn and MOS
Figure 7. X-ray spectral data, best-fit models and the deviations of the data from the best fit models for SDSS J142452.11+263715.1 (upper panel) and SDSS J142443.78+263616.2 (lower panel) from two observations: Obs.I (left) & Obs.II (right).

Table 3. Best-fit spectral model parameters of the two nearby point sources for Obs.I & Obs.II

| Parameter | SDSS J142452.11+263715.1 | SDSS J142443.78+263616.2 |
|-----------|--------------------------|--------------------------|
| Model     | wabs(ZIBB+ZPL)           | wabs*wabs(BB+PL)         |
|           | Obs.I (21 June 2010)     | Obs.II (2 Aug. 2010)     |
| $N_H^{tot}$ (10^{20} cm^{-2}) | 1.6 (fixed) | 1.6 (fixed) | 1.6 (fixed) | 1.6 (fixed) |
| $kT_{BB}$ (keV) | 0.15^{+0.04}_{-0.07} | 0.14^{+0.02}_{-0.04} | 0.13^{+0.04}_{-0.02} | 0.17^{+0.07}_{-0.04} |
| $f_{BB}^{PL}$ (0.3–10 keV) | 0.25^{+0.17}_{-0.19} | 0.24^{+0.13}_{-0.15} | 2.3^{+1.5}_{-1.7} | 0.6^{+1.6}_{-0.3} |
| $N_H^{intr}$ (10^{22} cm^{-2}) | – | – | 0.36^{+0.22}_{-0.19} | 0.16^{+0.34}_{-0.20} |
| $\Gamma$ | 1.96^{+0.34}_{-0.35} | 2.22^{+0.23}_{-0.22} | 1.20^{+0.21}_{-0.20} | 1.24^{+0.18}_{-0.18} |
| $f_{PL}^{X}$ (2–10 keV) | 0.55^{+0.16}_{-0.19} | 0.43^{+0.09}_{-0.19} | 2.5 ± 0.3 | 2.5 ± 0.2 |
| $\chi^2$/dof | 30/30 | 105/98 | 83/89 | 125/98 |

* In units of 10^{-13} erg cm^{-2}s^{-1}.
event files using circular regions of 40″ radii centered at the source positions. The corresponding background spectra were extracted from the source-free regions. The source SDSS J142452.11+263715.1 falls in the CCD gap in the EPIC-pn data of Obs.I, hence the EPIC-pn spectrum was not useful. The rest of the five spectra from Obs.I and II were grouped to get minimum counts of 20 per energy bin. As before, we performed joint spectral analysis of available spectral data from different instruments for each observation.

We found that the spectra of SDSS J142452.11+263715.1 for each observation are well constrained by a black body plus power-law model modified by the Galactic absorption ($N_{H}^{Gal} = 1.6 \times 10^{20}$ cm$^{-2}$) and the best-fit parameters are listed in Table 3. The X-ray spectrum of SDSS J142452.11+263715.1 consisting of soft X-ray excess, described as a black body with $kT \sim 150$ eV and a powerlaw of $\Gamma \sim 2$, is typical of the spectra of radio-quiet quasars e.g., PG quasars. The total X-ray luminosity of SDSS J142452.11+263715.1 in the 0.3 – 10 keV band is $6.6 \pm 0.3 \times 10^{43}$ erg s$^{-1}$ and $6.8 \pm 0.25 \times 10^{43}$ erg s$^{-1}$ for Obs.I and II, respectively. The best fitted spectra of SDSS J142452.11+263715.1 for both the observations are shown in Figure 7 (upper panels).

The second object SDSS J142443.78+263616.2 has no redshift information. This source shows soft X-ray emission. Initially we used a model $\text{wabs} \times \text{wabs(apec+PL)}$, where thermal plasma component $\text{apec}$ is for the soft excess and powerlaw for the hard continuum. We varied the red shift parameter in $\text{apec}$. The fit resulted in $\chi^2/dof = 132/88$ and the best-fit redshift $z = 1.50 \pm 0.05$, which may not be correct. Next, we fitted the $\text{wabs} \times \text{wabs(BB+PL)}$ model, which resulted in $\chi^2/dof = 83.70/89, 125/98$ for Obs.I and II, respectively. The best-fit parameters are $kT_{BB} \sim 150$ eV and $\Gamma \sim 1.2$ for both the observations. The best fitted spectra of SDSS J142443.78+263616.2 for Obs.I and II are shown in Figure 7 (lower panels) and the spectral fitting parameters are listed in Table 3.

3 DISCUSSION

CTD 86 shows extended X-ray emission with a linear size $\sim 250″$(186 kpc) in the XMM-Newton observations, confirming the previous observation by Canosa et al. (1999) using ROSAT data. Diffuse X-ray emission detected with the XMM-Newton is well described by thermal emission from hot gas with a temperature $kT = 0.79 \pm 0.02$ keV, electron density $n_e \sim 3 \times 10^{-3}$ cm$^{-3}$ and 0.3 – 10 keV X-ray luminosity $L_X = 4.8 \pm 0.2 \times 10^{42}$ erg s$^{-1}$, implying that this system is very likely to be part of a group of galaxies or a poor cluster.
The spectral analysis of the diffuse gas component yielded the metal content of the CTD 86 to be $0.29 \pm 0.05$ and $0.31 \pm 0.04$, respectively, these values are in agreement with those reported earlier by Hodges-Kluck et al. (2010) using 10 ks Chandra data. Such subsolar metallicities are quite common, as reported by Croston et al. (2005) and Helsdon & Ponman (2000), for intragroup medium around several FR-I radio galaxies or gas in groups of galaxies based on measurements with ROSAT PSPC data.

For both the observations, X-ray emission from the low luminosity AGN in CTD 86 is well described by a power-law ($\Gamma \sim 1.55$) modified by intrinsic absorption with $N_H \sim 5.5 \times 10^{22}$ cm$^{-2}$. In a similar analysis, (Markowitz & Suzaku Cen A Team 2007) found high absorption column ($N_H \sim 1.5 \times 10^{23}$ cm$^{-2}$) for the FR-I radio galaxy Centaurus A. Thus, the intrinsic absorption column of CTD 86 is smaller by a factor of $\sim 2.5$ than that in Centaurus A. For a sample of FR-I galaxies (Donato et al. 2004) observed a range of photon indices, $\Gamma = 1.1 - 2.6$, and intrinsic absorption column densities, $N_H = 10^{20} - 10^{21}$ cm$^{-2}$. The power-law photon index derived for CTD 86 is found to lie in the range for FR-I type galaxies. The $2 - 10$ keV luminosity of the nucleus is found to be $L_X = 2 \times 10^{42}$ erg s$^{-1}$, making CTD 86 a low luminosity AGN. Based on the low column densities observed for a sample of FR I galaxies, Donato et al. (2004) concluded that most FR I galaxies lack a standard torus. Since ISM of elliptical galaxies are unlikely to provide absorbing columns more than $10^{21}$ cm$^{-2}$, therefore, CTD 86 provides an intriguing possibility of the presence of a torus around the FR I galaxy.

For the case of CTD 86, we investigated the existence of Fe K$_\alpha$ line in the nuclear spectrum and found that the line is not detected at $3\sigma$ level. Therefore, we calculated the 90% upper limit on the equivalent width of a narrow, neutral Fe K$_\alpha$ line to be 66 eV. This upper limit is a factor of $\sim 1.5$ lower than the equivalent width of $\sim 100$ eV measured for Cen A (Evans et al. 2004). The weaker iron line in CTD 86 could be due to a lower iron abundance or lesser intrinsic absorption column compared to that in Cen A. However, the upper limit on the iron line equivalent width of CTD 86 is comparable to that observed from an intermediate Seyfert galaxy MCG-5-23-16 (EW $\sim 40$ eV) with intrinsic $N_H \sim 1.6 \times 10^{22}$ cm$^{-2}$ (Dewangan et al. 2003) or Seyfert 2/LINER NGC 4258 (EW $\sim 65$ eV) with cold $N_H \sim 10^{23}$ cm$^{-2}$ (Reynolds et al. 2000). Thus, the upper limit on the equivalent width of the Fe K$_\alpha$ line from CTD 86 is similar to that typically found for intermediate type Seyfert galaxies with comparable intrinsic absorption column.

VLBI imaging of CTD 86 has revealed symmetric radio jets on a kpc scale and a possible
one-sided jet on parsec scale (Giovannini et al. 2005). Assuming the parsec scale structure to be real, Giovannini et al. (2005) estimated an inclination angle $i = 45-50^\circ$ and $\beta=0.95$. X-ray absorption column of $N_H \sim 5.9 \times 10^{22} \text{ cm}^{-2}$ in CTD 86 is similar to the absorption columns usually observed for intermediate type Seyfert galaxies (e.g., Seyfert 1.5). Thus, the absorption column and the tentative inclination angle both are consistent with the presence of a torus where the line of sight to the nucleus passes through the outer region of the torus.

It is interesting to investigate the disk-corona geometry in CTD 86 and to check its similarity with that in type 1 radio-quiet AGN like Seyfert 1 galaxies. We measured the stellar velocity dispersion $\sigma = 182 \pm 8 \text{ km s}^{-1}$ of CTD 86 (Pandge et. al 2013 in preparation) using the Penalized Pixel Fitting method (Cappellari & Emsellem 2004) from the SDSS spectrum and calculated the black hole mass, $M_{BH} = (8.8 \pm 2.4) \times 10^7 \text{ M}_\odot$ using the $M_{BH} - \sigma$ relation. We estimated the bolometric luminosity from the $2-10 \text{ keV}$ luminosity assuming a bolometric correction of 20 (e.g., Vasudevan & Fabian 2007). This resulted in $\dot{m} = L_{bol}/L_{Edd} \sim 4 \times 10^{-3}$ quite low compared to that found for typical Seyfert and quasar like objects. One way to find the relative contributions of disk and corona is to compare the ratio of luminosities of $[\text{O III}]\lambda5007$ line and the unabsorbed $2-10 \text{ keV}$ luminosity. The strength of the $[\text{O III}]$ line would depend on the ionizing flux i.e., emission from the accretion disk, while the power-law X-ray emission arises from the hot corona. Donato et al. (2004) found $L_X/L_{[\text{O III}]} \sim 27.8 \pm 9.6$ for Seyfert 1 galaxies and $3.7 \pm 1.1$ for Compton thick Seyfert 2 galaxies, where as the lack of X-ray emission from Seyfert 2 galaxies was attributed to the absorption by Compton-thick torus. We find a very large, $L_X/L_{[\text{O III}]} = 354$, ratio for CTD 86, which either suggests a beamed X-ray emission arising from the jet or a lack of ionizing luminosity from the accretion disk. The first possibility, i.e. the jet origin, is unlikely as the X-ray emission is absorbed by a high column density ($N_H \sim 10^{22} \text{ cm}^{-2}$). The second scenario is possible only if the accretion disk is truncated so that inner disk does not exist and there is no ionizing radiation from the hottest part of the disk. The inner region below the truncation radius may be filled with a hot flow that gives rise to the observed X-ray emission. The inner hot flow may also be responsible for the radio jets.

CTD 86 is a low luminosity radio galaxy with classical double-lobed radio emission. Figure 2 revealed that the lobes extend up to $\sim 65 \text{ kpc}$ from the optical center of the galaxy and the entire radio source is well contained in the hot X-ray emitting gas. The distribution of hot gas in groups and clusters is affected by the presence of radio jets and lobes. Several example of cavities in the distribution of X-ray gas, coinciding with the locations of radio
lobes have been observed with Chandra and XMM-Newton (e.g., McNamara & Nulsen 2007; David et al. 2009; Dong et al. 2010; Pandge et al. 2012, 2013). Though, radio lobes from CTD 86 are found to be embedded in the hot gas, however, there is no clear evidence for the distortions in the radio structures as well as in the hot gas in the form of X-ray cavities. Croston et al. (2005) studied radio source heating in groups and found that the gas around the radio-loud AGN is more likely to be hotter at a given X-ray luminosity compared to the gas in radio-quiet groups. To confirm this, we compared the X-ray luminosity and temperature of extended gas around CTD 86 with that of other radio loud and radio quiet galaxies of similar type. Figure 8 gives a correlation between the log $L_X$ versus log $T_X$ for a sample of galaxies taken from Croston et al. (2005). The filled triangles (black) represent data points for radio loud sample and filled circle (blue) represent sample of radio quiet galaxies. Most of the radio loud systems are found to lie below the best fit for radio quiet groups of galaxies. In the same plot, we have shown CTD 86 with a red hexagon. The temperature and luminosity values of the hot gas in CTD 86 environment are consistent with the $L_X - T$ relation for the radio-quiet groups or galaxies. Thus, the $L_X - T$ relation, the absence of X-ray cavities, symmetric radio structures of CTD 86 all suggest that heating by the radio source in this system is not significant, probably due to the low power of the radio galaxy. Figure 9 shows a correlation between luminosity densities at 5 GHz and 1 keV for a sample of FR I galaxies taken from Evans et al. (2006). In this figure, we also show the position of CTD 86 which is not close to the correlation line for the FR-I galaxies. The X-ray luminosity of CTD 86 is higher by an order of magnitude compared to other sources of comparable radio emission. Thus, based on this correlation, it is unlikely that the X-ray emission from CTD 86 galaxies arise from the jets alone. X-ray emission from CTD 86 is also intrinsically absorbed by a large column within the host galaxy which is not likely if the entire X-ray emission were to arise from the jet. We checked for the presence of an intrinsically unabsorbed X-ray power-law component that could arise from the jet. The contribution of such a power-law is at the most 35% of the total X-ray emission in the 2 – 10 keV band, therefore, most of the X-ray emission above 2 keV might be arising from the hot corona.

4 CONCLUSIONS

We have presented X-ray images and spectra of the CTD 86 and its environment using the publicly available XMM-Newton observations. The main results of the study are:
Figure 8. $L_X$ plotted against the temperature of the hot gas for a sample of galaxies from Croston et al. (2005). The filled triangles represent radio-loud galaxies and the filled circles represent radio-quiet galaxies. CTD 86 is shown as the filled hexagon.

Figure 9. Relationship between the flux densities at 1 keV and 5 GHz for FR I galaxies taken from Evans et al. (2006). CTD 86 is shown by the triangle.

(i) An extended ($\sim 186$ kpc) X-ray emission from CTD 86 with spectral properties $kT \sim 0.79$ keV, $n_e \sim 10^{-3}$ cm$^{-3}$, $M_{\text{gas}} = 1.83 \times 10^{11}$ M$_\odot$ and $Z=0.29 \pm 0.05$ Z$_\odot$, is seen, and is similar to that found in other group galaxies.

(ii) No signs of interaction between the radio lobes and the hot gaseous environment of CTD 86 are evident in the form of X-ray cavities.
(iii) Mild nuclear activity with $2 - 10$ keV X-ray luminosity of $\sim 2.0 \times 10^{42}$ erg s$^{-1}$ is evident in CTD 86.

(iv) The Nuclear X-ray spectrum of CTD 86 absorbed by a larger column ($N_H = 5.9 \times 10^{22}$ cm$^{-2}$) and may be due to the presence of a torus around CTD 86, similar to that seen in other type 2 AGN.

(v) The large $L_X/L_{[O III]}$ ratio and very small relative accretion rate of CTD 86 suggest that the accretion disk of this low luminosity AGN is likely truncated at some large inner radius, where the inner regions are filled with a hot flow.

(vi) Two bright X-ray sources, SDSS J142452.11+263715.1 and SDSS J142443.78+263616.2, near CTD 86 are reported here. SDSS J142452.11+263715.1 has been identified as a star like object, probably harbors a type 1 AGN with $z = 0.3761$ and has unabsorbed $0.3 - 10$ keV X-ray luminosity $L_X \sim 8 \times 10^{43}$ erg s$^{-1}$, while SDSS J142443.78+263616.2 is probably a galaxy hosting an AGN.

ACKNOWLEDGMENTS

MBP gratefully acknowledge support by the DST, New Delhi under the INSPIRE fellowship program (sanction No. IF10179). MBP and MKP acknowledge the usage of high performance computing facilities procured under the DST-FIST scheme (SR/FST/PSI-145). This work is based on observations obtained with XMM-Newton, ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. This work has made use of data from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center.

REFERENCES

Arnaud, K. A., 1996, in Astronomical Society of the Pacific Conference Series, Vol. 101, Astronomical Data Analysis Software and Systems V, G. H. Jacoby & J. Barnes, eds., p. 17

Becker, R. H., White, R. L., & Helfand, D. J., 1994, in Astronomical Society of the Pacific Conference Series, Vol. 61, Astronomical Data Analysis Software and Systems III, Crabtree, D. R., Hanisch, R. J., & Barnes, J., eds., p. 165

Beers, T. C., Geller, M. J., Huchra, J. P., Latham, D. W., & Davis, R. J., 1984, ApJ, 283, 33

Canosa, C. M., Worrall, D. M., Hardcastle, M. J., & Birkinshaw, M., 1999, MNRAS, 310, 30

Cappellari, M. & Emsellem, E., 2004, PASP, 116, 138

Colla, G., Fant, C., Fant, R., Gioia, I., Lari, C., Lequeux, J., Lucas, R., & Ulrich, M. H., 1975, A&AS, 20, 1

Croston, J. H., Hardcastle, M. J., & Birkinshaw, M., 2005, MNRAS, 357, 279

David, L. P., Jones, C., Forman, W., Nulsen, P., Vrtilek, J., O’Sullivan, E., Giacintucci, S., & Raychaudhury, S., 2009, ApJ, 705, 624

Dewangan, G. C., Griffiths, R. E., & Schuch, N. J., 2003, ApJ, 592, 52

Donato, D., Sambruna, R. M., & Gliozzi, M., 2004, ApJ, 617, 915
Dong, R., Rasmussen, J., & Mulchaey, J. S., 2010, ApJ, 712, 883
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
Fanaroff, B. L. & Riley, J. M., 1974, MNRAS, 167, 31P
Fanti, R., Gioia, I., Lari, C., & Ulrich, M. H., 1978, A&A, 34, 341
Giovannini, G., Feretti, L., & Stanghellini, C., 1991, A&A, 252, 528
Giovannini, G., Taylor, G. B., Feretti, L., Cotton, W. D., Lara, L., & Venturi, T., 2005, ApJ, 618, 635
Hardcastle, M. J., 2005, Royal Society of London Philosophical Transactions Series A, 363, 2711
Helsdon, S. F. & Ponman, T. J., 2000, MNRAS, 315, 356
Hodges-Kluck, E. J., Reynolds, C. S., Cheung, C. C., & Miller, M. C., 2010, ApJ, 710, 1205
Jansen, F., Lumb, D., Altieri, B., et al., 2001, A&A, 365, L1
King, I., 1962, AJ, 67, 471
Lakhchaura, K., Singh, K. P., Saikia, D. J., & Hunstead, R. W., 2011, ApJ, 743, 78
Mack, K.-H., Gregorini, L., Parma, P., & Klein, U., 1994, A&AS, 103, 157
Markowitz, A. & Suzaku Cen A Team, 2007, Progress of Theoretical Physics Supplement, 169, 278
Mathews, W. G. & Brighenti, F., 2003, ARA&A, 41, 191
McNamara, B. R. & Nulsen, P. E. J., 2007, ARA&A, 45, 117
Merkelijn, J. K., 1968, Australian Journal of Physics, 21, 903
Miller, N. A., Ledlow, M. J., Owen, F. N., & Hill, J. M., 2002, AJ, 123, 3018
Mulchaey, J. S., 2000, ARA&A, 38, 289
Pandge, M. B., Vagshette, N. D., David, L. P., & Patil, M. K., 2012, MNRAS, 421, 808
Pandge, M. B., Vagshette, N. D., Sonkamble, S. S., & Patil, M. K., 2013, Ap&SS, 345, 183
Parma, P., Fanti, C., Fanti, R., Morganti, R., & de Ruiter, H. R., 1987, A&A, 181, 244
Reynolds, C. S., Nowak, M. A., & Maloney, P. R., 2000, ApJ, 540, 143
Sarazin, C. L., 1986, Reviews of Modern Physics, 58, 1
Snowden, S. L., Mushotzky, R. F., Kuntz, K. D., & Davis, D. S., 2008, A&A, 478, 615
Spinrad, H., Marr, J., Aguilar, L., & Djorgovski, S., 1985, PASP, 97, 932
Strüder, L., Briel, U., Dennerl, K., et al., 2001, A&A, 365, L18
Turner, M. J. L., Abbey, A., Arnaud, M., et al., 2001, A&A, 365, L27
Vasudevan, R. V. & Fabian, A. C., 2007, MNRAS, 381, 1235