ON THE ENVIRONMENT OF POWERFUL RADIO GALAXIES AT \( z > 0.5 \)

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Active galaxies are the most powerful engines in the Universe for converting gravitational energy into radiation, and radio galaxies and radio-loud quasars are highly luminous and can be detected across the Universe. The jets that characterise them need a medium to propagate into, and thus radio galaxies at high redshift point to gaseous atmospheres on scales of at least the radio source diameter, which in many cases can reach hundreds of kpc. The variation with redshift of X-ray properties of radio-selected clusters provides an important test of structure formation theories as, unlike X-ray selection, this selection is not biased towards the most luminous clusters in the Universe. We present new results from a sample of 19 luminous radio galaxies at redshifts between 0.5 and 1. The properties of the gaseous atmosphere around these sources as mapped by Chandra and XMM-Newton observations are discussed. By combining these with observations at radio frequency, we will be able to draw conclusions on cluster size, density, and pressure balance between the radio source and the environment in which it lies.

1 Introduction

Most powerful radio galaxies lie at high redshift (\( z > 0.3 \)), but a few of them are also found in the nearby universe, the best example of which is Cygnus A. Sources classified as Fanaroff-Riley type II (FRII) have double-sided jets which can terminate at distances as far as 1 Mpc from the centre of the host galaxy. Radio lobes that result from jet disruption require a gaseous environment in order to exist and to be confined\(^1\). This has suggested that powerful radio galaxies can be used as a means to discover high-redshift clusters of galaxies (e.g.\(^{16,18}\)), which can be traced by their X-ray emission. Studies based on ROSAT data of radio galaxies and quasars in the 3CRR catalogue\(^{15}\) supported this hypothesis, and several detection of hot-massive clusters were claimed\(^{5,15,22,6,7,17,18}\). No spectral confirmation was possible with ROSAT data due to limited energy sensitivity and count rates. Moreover, the point-like, X-ray emission from the central radio source together with lobe inverse Compton (IC) emission, was difficult
to separate from any cluster emission. Hence, detections more often represented upper limits to cluster emission. XMM-Newton and Chandra have opened a new era of X-ray astrophysics, and in particular make it possible to carry out studies aimed at searches for clusters around active galaxies. These studies are fundamental to obtain a complete, unbiased picture of the number density of clusters and structure formation and evolution.

Chandra observations of radio galaxies and quasars at redshift \( z > 0.5 \) have found relatively few sources in the rich gaseous environments associated with massive clusters. Given the low number of counts, for most of them a full spectral analysis was not possible (e.g.\cite{2009}), although the detected extended counts were properly separated from the Point Spread Function (PSF) of the central point source. For a few objects a spectral detection did confirm that extended X-ray emission was associated with thermal radiation from an intra-cluster medium (3C 220.1, \( kT = 5 \) keV\cite{2009}; 3C 294, \( kT = 3.5 \) keV\cite{14}, although a large non-thermal contribution to the emission was found to be possible). The detected atmospheres of other sources are more typical of a group or poor cluster (e.g.\cite{9}). Although the very presence of edge-brightened radio lobes points to the existence of some gas in order that the lobes should be confined, a particularly rich environment is not required, and the Chandra observations seem to point in this direction. A few more cluster atmospheres were detected spectrally using the higher sensitivity of XMM-Newton\cite{2}.

In this paper we present the results of a study based on an unbiased (although not complete) sample of radio galaxies and quasars in the redshift range \( 0.5 < z < 1 \) and extracted from the 3CRR catalogue. The sample comprises 19 sources selected as described in Belsole et al. (2006). Here we discuss preliminary results on the environment of the sources.

Throughout the paper we use a cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \). If not otherwise stated, errors are quoted at 1\( \sigma \) confidence level.

2 The sample and data

This study is based on the sample described in\cite{3} (hereafter paper I). Sources are drawn from the 3CRR catalogue\cite{15}, and are in the redshift range \( 0.5 < z < 1.0 \), with the exception of 3C200 (\( z = 0.458 \)). The sample is composed of a similar number of broad-line and narrow-line radio sources. The 3CRR is selected on the basis of low-frequency (178 MHz) radio emission, which has the advantage of not being biased towards beamed radio emission and therefore contains radio galaxies as well as quasars.

Table 1 lists the main properties of the sources.

Preparation of the Chandra data are described in paper I. However for this paper we reprocessed the data with a later version of CIAO(3.3.0.1). The XMM-Newton data preparation is described elsewhere\cite{2}.

3 Results

Thermal X-ray emission from a cluster-like atmosphere is best detected at energies between 0.5 and 2.5 keV, corresponding to the energy range where X-ray telescopes are most sensitive and where contamination by the central point source is lower (as many cores are absorbed).

We generated images in the 0.5-2.0 keV energy band and in a harder band (2.5-7.0 keV), and we applied a wavelet reconstruction algorithm (ZHTOOLS, Vikhlinin private communication) as an efficient way to search for extended emission not associated with the PSF. In Figure\cite{11} we show 3C 220.1 as an example of this analysis. Comparison between the images in the soft and hard energy band give an immediate indication of the presence of extended emission.

Extended emission from the 19 sources in the sample was characterised more quantitatively by extracting a radial profile in the 0.5-2.5 keV energy band. Point sources in the field were removed. Each radial profile was modelled with a PSF (generated using MARX) appropriate
Table 1: The sample and X-ray observations

| Source   | RA(J2000) | Dec(J2000) | redshift | scale | type    | \(N_H\) |
|----------|-----------|------------|----------|-------|---------|---------|
|          | h m s     | °′ ″       |          | kpc/arcsec |       | \(10^{20}\) cm \(^{-2}\) |
| 3C 6.1   | 00 16 30.99 | +79 16 50.88 | 0.840   | 7.63 | NLRG    | 14.80   |
| 3C 184   | 07 39 24.31 | +70 23 10.74 | 0.994   | 8.00 | NLRG    | 3.45    |
| 3C 200   | 08 27 25.44 | +29 18 46.51 | 0.458   | 5.82 | LERG    | 3.74    |
| 3C 207   | 08 40 47.58 | +13 12 23.37 | 0.684   | 7.08 | QSO     | 4.12    |
| 3C 220.1 | 09 32 39.65 | +79 06 31.53 | 0.610   | 6.73 | NLRG    | 1.87    |
| 3C 228   | 09 50 10.70 | +14 20 00.07 | 0.552   | 6.42 | NLRG    | 3.18    |
| 3C 254   | 11 14 38.71 | +40 37 20.29 | 0.734   | 7.28 | QSO     | 1.90    |
| 3C 263   | 11 39 57.03 | +65 47 49.47 | 0.646   | 6.90 | QSO     | 1.18    |
| 3C 265   | 11 45 28.99 | +31 34 49.43 | 0.811   | 7.54 | NLRG    | 1.90    |
| 3C 275.1 | 12 43 57.67 | +16 22 53.22 | 0.557   | 6.40 | QSO     | 1.99    |
| 3C 280   | 12 56 57.85 | +47 20 20.30 | 0.996   | 8.00 | NLRG    | 1.13    |
| 3C 292   | 13 50 41.95 | +64 29 35.40 | 0.713   | 6.90 | NLRG    | 2.17    |
| 3C 309.1 | 14 59 07.60 | +71 40 19.89 | 0.904   | 7.80 | GPS-QSO | 2.30    |
| 3C 330   | 16 09 34.71 | +65 56 37.40 | 0.549   | 6.41 | NLRG    | 2.81    |
| 3C 334   | 16 20 21.85 | +17 36 23.12 | 0.555   | 6.38 | QSO     | 4.24    |
| 3C 345   | 16 42 58.80 | +39 48 36.85 | 0.594   | 6.66 | core-dom QSO | 1.13 |
| 3C 380   | 18 29 31.78 | +48 44 46.45 | 0.691   | 7.11 | core-dom QSO | 5.67 |
| 3C 427.1 | 21 04 06.38 | +76 33 11.59 | 0.572   | 6.49 | LERG    | 10.90   |
| 3C 454.3 | 22 53 57.76 | +16 08 53.72 | 0.859   | 7.68 | core-dom QSO | 6.50 |

Galactic column density is from\(^{11}\). NRLG means Narrow Line Radio Galaxy; LERG means low-excitation radio galaxy. Redshifts and positions are taken from\(^{15}\).

Figure 1: Wavelet reconstructed images in the soft (0.5-2.0 keV, left) and hard (2.5-7.0 keV, right) energy band for the radio galaxy 3C 220.1. The figure shows that extended emission is visible in the soft band. Contours show the emission at 1.4 GHz and are drawn on a logarithmic scale.
Figure 2: X-ray luminosities of the clusters found around 16 of the objects in the sample. The shaded histogram indicates radio galaxies, the unfilled quasars.

for the position and spectrum of each of the sources. As extended emission may also come from the radio lobes (e.g. [10]), we excluded the spatial region coincident with them before extracting the radial profile. When a PSF-only model was not a good representation of the data, a $\beta$-model convolved with the PSF was added to account for the excess emission above the PSF.

90 per cent of the sources in the sample required the inclusion of a $\beta$-model to represent the radial profile at soft energies, although a search in the $\beta - r_c$ parameter space (where $r_c$ is the core radius) was not possible for all of them. In these cases, the value of $\beta$ was fixed to 0.6.

We derived the number of counts associated with the $\beta$-model representing the extended emission out to the radius used for the background region. This is in the range 35 arcsec to 80 arcsec (which corresponds roughly to 200-500 kpc by taking an average redshift for the sources in the sample). We then calculated the X-ray luminosity of the cluster-like environment. When possible, we carried out spectral analysis and used the best-fit temperature to calculate the luminosity. In other cases we adopted a temperature of 3 keV.

In Figure 2 we show the distribution of number of objects as a function of the X-ray luminosity. The shaded area corresponds to radio galaxies, the unfilled area to quasars. We find that 50% of the radio sources in the sample lie in clusters with luminosity above $10^{44} \text{ erg s}^{-1}$, and 7 more objects appear to lie in more moderate luminosity clusters, or groups. Only 1 object shows no sign of extended emission and is a pure point source at the sensitivity of this observation. For 2 more objects only upper limits can be obtained from the radial profile analysis; these are omitted from the histogram above.

We find no obvious correlation between X-ray luminosity and redshift. However, the redshift range in this sample is relatively limited, and a larger sample including sources at lower and higher redshift should be used to be more conclusive.
4 Discussion and conclusions

This preliminary study, based on a sample of 19 radio galaxies in the redshift range $0.5 < z < 1$, that were selected by their low frequency radio emission, indicates that a significant fraction of them (90 per cent) are located at the centre of thermal X-ray emitting environments. The detected extended emission is unlikely to be associated with inverse Compton emission from the radio lobes since we have masked the lobe region from our analysis. 50 per cent of the sources in our sample lie in relatively massive clusters, with X-ray luminosities greater than $10^{44}$ erg s$^{-1}$. Although preliminary, these results suggest that powerful radio galaxies may indeed be an efficient method to search for luminous (massive) galaxy clusters, and as a by-product they allow an investigation of a wider population of X-ray structures.

This is particularly important in view of the new generation of X-ray cluster surveys for cosmology: current X-ray cluster catalogues exclude these sources since they are dominated by the emission of the point source, with the result that many objects are only found in Active Galactic Nuclei catalogues and not in cluster catalogues. They are also likely to be excluded from current and future Sunyaev-Zeldovich (SZ) surveys as the radio emission associated with them is difficult to account for and remove from SZ maps.

This may introduce an important bias in the real number of clusters in the Universe, yielding significant errors (of order 10-20 per cent) on parameters derived from the number density of clusters. Their number can also increase with redshift as shown by Celotti & Fabian (2004).

To fully understand this issue, XMM-Newton and Chandra observations able to complete statistical samples of radio galaxies (and the 3CRR sample looks the most obvious), especially at redshift above 0.1, need to be carried out now, as future X-ray missions may not have the necessary instrumental characteristics to perform these studies.

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