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CSS galaxy embedded within the core of a bright X-ray cluster

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We discovered an X-ray cluster in a recent pointed *Chandra* observation of the radio-loud compact-steep-spectrum source 1321+045 at the redshift of 0.263. 1321+045 is part of larger survey which aims to study the X-rays properties of weak compact radio sources. Compact radio sources are young objects at the beginning of their evolution and if embedded in an X-ray cluster offer unique opportunities to study the cluster heating process.

11th European VLBI Network Symposium & Users Meeting
9-12 October 2012
Bordeaux (France)

*Speaker.

PoS(11th EVN Symposium)009

1. Introduction

Clusters of galaxies are the largest gravitationally bound objects in the Universe. The space between the galaxies is filled with a hot plasma that emits X rays. High-resolution images of nearby cluster cores taken by the *Chandra* X-ray Observatory show that large amounts of energy are injected into the surrounding medium by powerful outbursts of active galactic nuclei (AGN) lying at the hearts of galaxy clusters. The combination of high-resolution X-ray and radio imaging provides a direct measure of this energy, which is in most cases sufficient to prevent cooling of the intra-cluster medium and the substantial growth at late times of giant elliptical (gE) and cD galaxies [6].

Most X-ray clusters are found around radio-loud active galaxies with large-scale radio structures and the majority of them is classified as FR Is [1]. The FR I radio sources are old (> 10^7 years) and their long-term interaction with the cluster environment imprinted a rich variety of structures into the X-ray morphology, such as bubbles, shock fronts and ripples [6, 9]. Gigahertz Peaked Spectrum (GPS) and Compact Steep Spectrum (CSS) radio sources are young (< 10^5 years) and have not developed large-scale radio structures (typical size <20 kpc[1] [8]); and they are believed to be in the beginning of their evolution [10]. These objects, if found in clusters, can potentially test the cluster heating process and the significance of the AGN in the evolution of the cluster. The first X-ray cluster known to host a compact steep spectrum radio source was 3C 186 discovered by Siemiginowska et al. [11, 13]. The X-ray morphology indicates that the cluster is well formed and has a cool core with a short central cooling time. The radio source can potentially supply the energy required to stabilize the cluster core against catastrophic cooling, as it expands into the cluster medium.

The 1321+045 radio source presented here is the second compact steep spectrum radio source known to be associated with a large X-ray cluster. It has a radio morphology different from that of 3C 186 (FR I vs FR II-like) and it is much less luminous at radio waves. These two cases indicate that the radio source properties may be different even though they are located in a similar cluster environment. They provide a great opportunity to investigate the radio source evolution and interaction with the cluster environment.

2. Sample and observations

1321+045 is one of the seven radio sources observed with *Chandra* ACIS-S3 using 1/8 subarray and standard pointings. The observations of the whole sample were performed in February 2011 and June 2012, with exposure times of ∼9.5 ks for each source (see Table 1). The target sources belong to the sample of Low Luminosity Compact (LLC) objects and their radio and optical properties were analyzed in [4] and [5], respectively. The main criterion for selecting LLC objects is the radio luminosity threshold. All sources fall below $L_{1.4GHz} < 10^{26}$W Hz^{-1} and occupy a poorly-studied locus in the radio power versus linear size diagram (Fig. 1) [4]. We believe that it means that the majority of the LLC objects are short-lived objects, at least in the current phase of evolution. They can go up and down on the main evolutionary scheme, restarting their activity many times. Most probably one of the crucial stages for AGN is when they leave their host galaxy.

[1]We use the following cosmology: H_0=71 km s^{-1} Mpc^{-1}, Ω_M=0.27, Ω_Λ=0.73.

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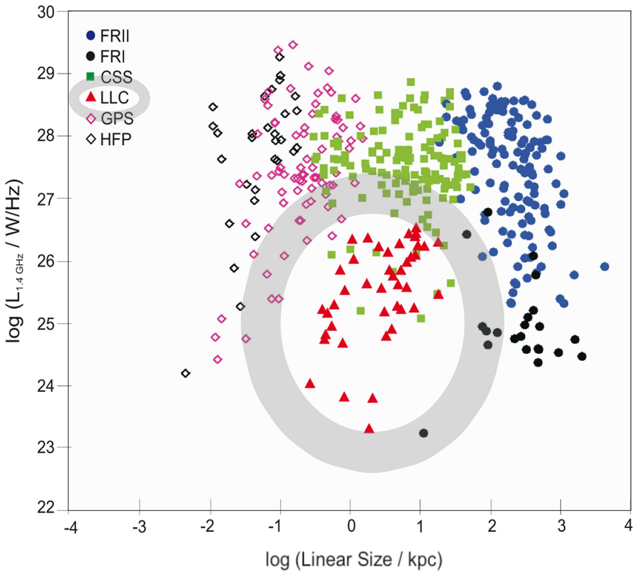

Figure 1: Evolutionary diagram of AGN taken from [4]. LLC objects occupy a poorly sampled locus (grey circle) in the diagram.

At this stage, the interaction of the radio jets with the interstellar medium (ISM) can disrupt the jet and change the morphology and luminosity of the source, which is likely to affect its evolution.

Our *Chandra* targets were selected based on their radio morphology to represent a different evolutionary state of the source growth, so they have either a weak or undetected radio core and strong lobes, or breaking up radio lobes with a bright radio core. All sources have been resolved by MERLIN at 1.6 GHz and have a CSO (compact symmetric object)-type or complex radio morphology. Their linear radio sizes are in the range 2–16 kpc [4].

There is a limited number of known bright compact AGNs with X-ray data available [2, 15, 12, 7, 14], however no X-ray data have been obtained for low power CSS sources so far. It is thus expected that our recent *Chandra* observations will establish the X-ray properties of these sources for the first time. Our project aims at answering several important questions: (1) determine the locus of the low radio power CSS sources in the radio to X-ray luminosity parameter space; (2) study the effect of the environment on the deceleration of the jet [2]; (3) analyze the correlation between the absorption column and the size of the radio source using the new data together with archival X-ray observations [14]; (4) determine if there is any diffuse X-ray emission exceeding nuclear scales in these sources.

3. Preliminary results

We have detected all but one target source (1542+390) in the X-rays. We used the software package Sherpa to fit the spectra, assuming an absorbed power-law in the 0.5–7 keV energy range. The Galactic absorption was kept frozen during the fitting. The second absorption component was assumed to be intrinsic to the quasar and located at the redshift of the source. The model was applied to six detected sources. However, since 0907+049, 1558+536 and 1624+049 did not have

Table 1: Basic parameters of the 7 LLC objects observed with Chandra.

Source name (1)	z (2)	Obs ID (3)	$\mathrm{Counts}_{0.5-7\,\mathrm{keV}}$ (4)	$\log(\mathrm{L}_{5\,\mathrm{GHz}})$ (5)	Γ (6)	$\log(\mathrm{L}_{2-10\,\mathrm{keV}})$ (7)
0810+077	0.112	12716	119 (11)	41.4	$0.64^{+0.15}_{-0.15}$	42.9
0907+049	0.640^{phot}	12717	3^{a}	42.6	1.7^{b}	42.9^{c}
0942+355	0.208	12714	103 (10)	41.4	$1.6^{+0.24}_{-0.16}$	42.9
1321+045	0.263	12715	53 (7)	41.6	$2.35^{+0.39}_{-0.36}$	42.3
1542-390	0.553	12718	0^{a}	42.4	1.7^{b}	42.7^{c}
1558+536	0.179	12719	9 (3)	41.4	1.7^{b}	41.7
1624+049	0.040^{phot}	12720	4^{a}	40.0	1.7^{b}	40.0^{c}

(1) Source name; (2) Redshift, 'phot' indicates a photometric redshift; (3) Observation ID; (4) Counts number, only upper limits are given for sources with a ^{a} symbol, numbers in parentheses indicate the errors calculated as $\sqrt{\mathrm{counts}}$; (5) Luminosity at 5 GHz taken from [4] in erg s^{-1}; (6) Photon index, ^{b} means Γ=1.7 was assumed for the flux calculation; (7) Luminosity at 2–10 keV in erg s^{-1}, ^{c} means only an upper limit is available.

enough counts to produce a reasonable fit, we assumed a photon index value $\Gamma = 1.7$ (see Table 1) to derive the flux of these three sources. We have placed our low-power compact sources on the X-ray vs radio luminosity plot, together with known strong CSS and GPS objects and large scale FR Is and FR IIs. Their locus (within the FR Is that are weaker in the X-rays) is consistent with the established X-ray - radio luminosity correlation for AGN. A detailed study of the whole sample will be presented in a forthcoming paper.

Diffuse X-ray emission from a cluster of galaxies was only found around one of the sources in our sample, 1321+045 (see Fig. 2, left panel). The position of the central bright component visible in the 1.6 GHz MERLIN image of this source is well correlated with the position of the optical counterpart suggesting this component is the radio core, on opposite sides of which there is diffuse emission from two radio lobes (Fig. 2, right panel). This rather symmetric structure has a total length of 17 kpc. The *Chandra* observations provided an X-ray luminosity of $10^{42.3}$ erg/s (Table 1), a cluster temperature kT = $4.4^{+0.5}_{-0.3}$ keV and an X-ray morphology typical of other massive, relaxed clusters. We have obtained the cluster temperature and density profiles which suggest that the cluster has a cooling core. There is no evidence for the presence of any ripples or discontinuities in the X-ray image of the cluster. Instead, there is a rather uniform emission without indications of interaction with the radio jets. The detailed analysis of this cluster is presented in a separate paper [3].

Chandra observations of GPS/CSS sources brought surprising results so far. One of which was the detection of X-ray emission in the jets of such sources [12]. Additionally, an X-ray cluster at z=1 associated with the radio-loud CSS source 3C186 was unveiled [11, 13]. Another extraordinary example is the discovery of thermal diffuse X-ray emission associated with an emission line region in 3C305 [7]. Finally, the most recent intriguing outcome from Chandra observations is the discovery of the first low-power CSS object (1321+045) associated with an X-ray cluster.

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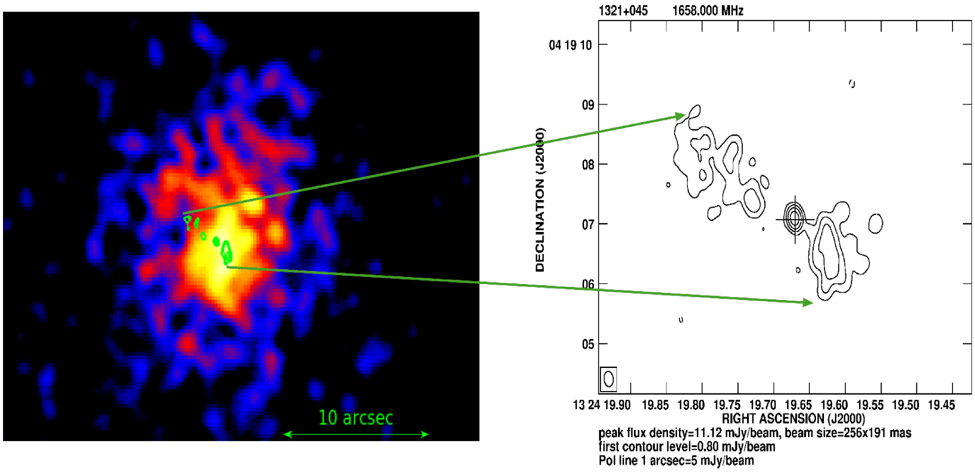

Figure 2: (Left) *Chandra* ACIS-S X-ray image of 1321+045 in the 0.5–7 keV energy range. The original image was smoothed with a Gaussian function of width 2 arcsecond. A 10 arcsec scale is marked in the image. The X-ray color image is overlayed with the green radio contours from the MERLIN 1.6 GHz image. (Right) MERLIN radio image of 1321+045 at 1.6 GHz [4]. Contour levels increase by the factor 2 and the first contour level corresponds to 0.80 mJy/beam (3σ). The position of the optical counterpart is marked with a cross and is taken from the Sloan Digital Sky Survey (SDSS).

Acknowledgements
MERLIN is a UK National Facility operated by the University of Manchester on behalf of STFC. This research has made use of data obtained by the *Chandra* X-ray Observatory and of the *Chandra* X-ray Center (CXC) software packages CIAO, ChIPS, and Sherpa. This research is funded in part by NASA contract NAS8-39073. Partial support for this work was provided by the *Chandra* grants GO1-12124X.

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