First X-ray observations of low-power compact steep spectrum sources

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ABSTRACT

We report on the first X-ray Chandra observations of a sample of seven low-luminosity compact sources, which belong to a class of young compact steep spectrum (CSS) radio sources. Four of these have been detected, while the other three have upper limit estimations for X-ray flux; one CSS galaxy is associated with an X-ray cluster. We have used the new observations, together with the observational data for known strong CSS and gigahertz-peaked spectrum (GPS) objects and large-scale Fanaroff–Riley types I and II objects (FR I and II), to study the relation between morphology, X-ray properties and excitation modes in radio-loud active galactic nuclei (AGNs). We have found the following. (i) The low-power objects fit well with the already established X-ray–radio luminosity correlation for AGNs and occupy the space among FR I objects, which are weaker in X-rays. (ii) The high-excitation and low-excitation galaxies occupy a distinct locus in the radio/X-ray luminosity plane, notwithstanding their evolutionary stage. This is in agreement with the postulated different origins of the X-ray emission in these two groups of objects. (iii) We have tested the AGN evolution models by comparing the radio/X-ray luminosity ratio with the size of the sources and, indirectly, with their age. We conclude that the division for two different X-ray emission modes, which originate in the base of the relativistic jet (FR Is) or in the accretion disc (FR IIs) is already present among the younger compact AGNs. (iv) Finally, we have found that the CSS sources are less obscured than the more compact GPS objects in X-rays. However, the anticorrelation between X-ray column density and radio size does not hold for the whole sample of GPS and CSS objects.

Key words: galaxies: active – galaxies: evolution – X-rays: galaxies.

1 INTRODUCTION

We still know little about how radio galaxies are born and how they subsequently evolve, but it is generally accepted that the gigahertz-peaked spectrum (GPS) and compact steep spectrum (CSS) radio sources are young, smaller versions of the large-scale powerful radio sources (Fanti et al. 1990, 1995; O’Dea, Baum & Stanghellini 1991; Readhead et al. 1996; O’Dea & Baum 1997). Recently, high-frequency peakers have been added to the sequence, as possible progenitors of GPS sources (e.g. Orienti, Dallacasa & Stanghellini 2007, and references therein).

The GPS and CSS sources are powerful but compact radio sources whose spectra are generally simple and convex with peaks near 1 GHz and 100 MHz, respectively. The GPS sources are contained within the extent of the optical narrow emission-line region (≲1 kpc) while the CSS sources are contained within the host galaxy (≲15 kpc; see O’Dea 1998, for a review).

In the general scenario of the evolution of powerful radio-loud active galactic nuclei (AGNs), GPS sources evolve into CSS sources, and these evolve into supergalactic-size Fanaroff–Riley types I and II objects (FR I and II; Fanaroff & Riley 1974). The dynamic evolution of the double-lobed radio sources, characterized by the total extent of the source, the advanced speed of the hotspots and the dependency of the density distribution of the interstellar and intergalactic medium along the way of the propagating jets and lobes, predicts the increase of the radio power with the linear size of the source in the GPS and CSS phases until they reach a size of 1–3 kpc. Then, the luminosity of the larger CSS objects should start to slowly decrease, but the sharp decrease in radio power is visible only in the FR I and FR II phases of evolution (Begelman & Cioffi 1989; De Young 1993, 1997; Carvalho 1994, 1998; Fanti et al. 1995; Begelman 1996; Kaiser & Alexander 1997; Snellen et al. 2000; Kino & Kawakatu 2005; Kawakatu & Kino 2006; Kaiser & Best 2007; Kawakatu, Kino & Nagai 2009a). Finally, after the
cut-off of the material supply to the central engine of the galaxy, the sources begin their fading phase. They can come back on the main evolutionary sequence after the re-ignition of the radio activity (e.g. Konar et al. 2012; Koziel-Wierzbowska et al. 2012).

However, population studies have drawn attention to the existence of far too many compact sources compared to the number of large-scale objects (O’Dea & Baum 1997). Thus, it has been proposed that some of the young radio-loud AGNs (i.e. the GPS and CSS sources) could be short-lived objects (Reynolds & Begelman 1997; Czerny et al. 2009; Kawakatu, Nagai & Kino 2009b; Kunert-Bajraszewska et al. 2010) and that not one but a few evolutionary paths could exist (Marecki, Spencer & Kunert 2003; Kunert-Bajraszewska et al. 2010; An & Baan 2012). The detection of several candidates for dying compact sources (Giroletti, Giovannini & Taylor 2005; Kunert-Bajraszewska, Marecki & Thomasson 2006; Kunert-Bajraszewska et al. 2010; Orienti, Murgia & Dallacasa 2010) supports this view. The determining factors for the further evolution of compact radio objects could occur at subgalactic (or even nuclear) scales, or they could be related to the radio jet–interstellar medium (ISM) interactions and evolution. Our previous studies suggest that the evolutionary track could be related to the interaction, strength of the radio source, and excitation levels of the ionized gas (Kunert-Bajraszewska et al. 2010; Kunert-Bajraszewska & Labiano 2010), instead of the radio morphology of the young radio source.

The characteristics (size, radio power and young age) of GPS and CSS sources make them excellent probes of the interaction (and therefore evolution) of radio sources. Furthermore, they have not completely broken through the ISM, so these interactions are expected to be more important than in the larger sources. Observations of ultraviolet, Hα, and especially, of the ionized gas in GPS and CSS sources suggest the presence of such interactions (Gelderman & Whittle 1994; de Vries et al. 1997, 1999; Axon et al. 2000; Labiano et al. 2005; Holt, Tadhunter & Morganti 2006; Labiano 2008; Labiano et al. 2008).

Additional clues on the evolution of compact GPS and CSS sources might come from the X-ray band, but little is known still about the nature of the X-ray emission in these young sources. Theoretical models predict strong X-ray emission from young radio sources, because of the recent triggering of nuclear activity and/or the expansion through the ISM (e.g. Siemiginowska 2009, and references therein). The Chandra and XMM–Newton observations of GPS and CSS objects made so far have focused on sources with high radio emission (e.g. Guainazzi et al. 2004, 2006; Vink et al. 2006; Siemiginowska et al. 2008; Tengstrand et al. 2009). These sources, when included in the $L_{2-10}$ keV versus $L_{56}$ diagram, group in the region occupied by powerful FR II sources (Tengstrand et al. 2009). Therefore, the location of GPS and CSS sources in the radio to X-ray luminosity diagram is consistent with these being powered by accretion, and therefore evolving on to a track of constant X-ray, accretion-driven luminosity to FR IIs. It is also consistent with the correlation between radio and X-ray luminosity observed in FR Is, which would point to a common origin for the emission in these two bands.

In this paper, we present the first X-ray observations of low-power radio sources, starting to fill the gap in the $L_{2-10}$ keV versus $L_{56}$ diagram, and shedding some light on the origin of high-energy emission of young radio sources and their evolution.

2 THE SAMPLE

The current sample consists of seven sources (0810+077, 0907+049, 0942+355, 1321+045, 1542−390, 1558+536 and 1624+049) taken from a sample of low-luminosity compact (LLC) sources (LLC; Kunert-Bajraszewska & Thomasson 2009; Kunert-Bajraszewska et al. 2010). The LLC sample consists of 44 nearby ($z < 0.9$) sources, selected from the final release of the Faint Images of the Radio Sky at Twenty cm (FIRST; White et al. 1997), the Green Bank 6-cm Survey (GB6; Gregory et al. 1996) and the Sloan Digital Sky Survey (SDSS), and observed with MERLIN at the $L$-band and $C$-band. The main selection criterion for the LLC sample was the luminosity limit: $L_{56} < 5 \times 10^{23}$ erg s$^{-1}$. The radio and optical properties of the LLC sources have been discussed and analysed by Kunert-Bajraszewska et al. (2010) and Kunert-Bajraszewska & Labiano (2010), respectively.

The seven current sources form the so-called pilot sample and they have been selected to represent different stages of the radio source evolution within the ISM: a weak or undetected radio core and strong lobes or radio lobes that are breaking up with a bright radio core, and linear sizes ranging from 2 to 17 kpc.

3 X-RAY OBSERVATIONS AND DATA REDUCTION

The sample was observed using Chandra ACIS-S3 with 1/8 sub-array and standard pointings, with exposure times of $\sim$9500 s (see Table 1). The Chandra data were reduced using CIAO 4.5 (Fruscione et al. 2006) with the calibration files from CALDB 4.4.5. All our sources are contained within the FWHM of the point spread function. We used a circular extraction region for each source, with a radius of 2 arcsec, which also contains all the radio emission. The background regions consist of four circular regions of radius 10 arcsec around the source. The CIAO default tools were used to extract the spectra and associated rmf and arf files. The total counts detected for each source are listed in Table 1.

We used SHERPA (Freyman, Doe & Siemiginowska 2001) to fit the spectra, using an absorbed power law in the 0.5–7 keV energy range:

$$N(E) = \exp \left( -N_H^{\text{Gal}} \sigma(E) \right) \times \exp \left( -N_H^{\text{CMB}} \sigma(E(1+z_{\text{obs}})) \right) \times AE^{-\Gamma}.$$ (1)

Here, $N(E)$ is in photons cm$^{-2}$ s$^{-1}$, $A$ is the normalization at 1 keV, $\Gamma$ is the photon index of the power law, $\sigma(E)$ and $\sigma(E(1+z_{\text{obs}}))$ are the absorption cross-sections (Morrison & McCammon 1983; Wilms, Allen & McCray 2000) and $N_H^{\text{Gal}}$ and $N_H^{\text{CMB}}$ are the column densities of the Milky Way (Kalberla et al. 2005; Dickey & Lockman 1990) and the source, respectively. The Galactic absorption was kept constant during the fitting. The second absorption component is assumed to be intrinsic to the quasar and located at the redshift of the source. The model was applied to all sources. However, 0907+049, 1558+536 and 1624+049 do not have enough counts to produce a reasonable fit. The results are summarized in Table 1.

We use $H_0 = 71$, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$ (Spergel et al. 2003) throughout the paper.

4 DISCUSSION

4.1 X-ray and radio morphology

We have observed a pilot sample of LLC sources (seven out of 44 objects) with Chandra. Four of these have been detected, and the other three have upper limit estimations for X-ray flux (see Table 1). One of the objects, 1321+045, appeared to be associated with an X-ray cluster and has been discussed in a separate paper.
Basic properties of the sample and X-ray models. Redshifts followed by a ’p’ are photometric. Fluxes are in $10^{-15}$ erg s$^{-1}$ cm$^{-2}$. Limits are 3σ. The numbers in parentheses indicate the errors calculated as $\sqrt{\text{counts}}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>ID</th>
<th>$z$</th>
<th>Counts 0.5–7 keV</th>
<th>$F_{0.5 - 2 \text{keV}}$</th>
<th>$F_{2 - 10 \text{keV}}$</th>
<th>$N_{\text{H} \text{gal}}$ (10$^{20}$ cm$^{-2}$)</th>
<th>$N_{\text{H}}$ (10$^{20}$ cm$^{-2}$)</th>
<th>$\Gamma$</th>
<th>Chandra Obs ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>0810+077</td>
<td>08:13:23.76</td>
<td>07:34:05.80</td>
<td>Q</td>
<td>0.112</td>
<td>119 (11)</td>
<td>32$^{+11}_{-10}$</td>
<td>190$^{+140}_{-90}$</td>
<td>2.14</td>
<td>13$^{+1.3}_{-1.3}$</td>
<td>0.64$^{+0.15}_{-0.15}$</td>
<td>12716</td>
</tr>
<tr>
<td>0907+049</td>
<td>09:09:51.13</td>
<td>04:44:22.13</td>
<td>G</td>
<td>0.64p</td>
<td>3$^a$</td>
<td>&lt;2.5</td>
<td>&lt;4.6</td>
<td>1.41</td>
<td>–</td>
<td>1.7$^b$</td>
<td>12717</td>
</tr>
<tr>
<td>0942+355</td>
<td>09:45:25.89</td>
<td>35:21:03.50</td>
<td>G</td>
<td>0.208</td>
<td>103 (10)</td>
<td>32$^{+5.0}_{-3.0}$</td>
<td>66$^{+33}_{-24}$</td>
<td>3.55</td>
<td>&lt;23</td>
<td>1.6$^{+0.24}_{-0.16}$</td>
<td>12714</td>
</tr>
<tr>
<td>1321+045</td>
<td>13:24:19.70</td>
<td>04:19:07.20</td>
<td>G</td>
<td>0.263</td>
<td>53 (7)</td>
<td>14$^{+3.0}_{-3.0}$</td>
<td>9.4$^{+16.6}_{-5.4}$</td>
<td>2.04</td>
<td>–</td>
<td>2.35$^{+0.39}_{-0.36}$</td>
<td>12715</td>
</tr>
<tr>
<td>1542+390</td>
<td>15:43:49.49</td>
<td>38:56:01.40</td>
<td>G</td>
<td>0.553</td>
<td>0$^b$</td>
<td>&lt;2.5</td>
<td>&lt;4.6</td>
<td>1.55</td>
<td>–</td>
<td>1.7$^b$</td>
<td>12718</td>
</tr>
<tr>
<td>1558+536</td>
<td>15:59:27.66</td>
<td>53:30:54.70</td>
<td>G</td>
<td>0.179</td>
<td>9 (3)</td>
<td>2.8$^{+1.5}_{-1.5}$</td>
<td>5.2$^{+1.6}_{-1.6}$</td>
<td>1.26</td>
<td>–</td>
<td>1.7$^b$</td>
<td>12719</td>
</tr>
<tr>
<td>1624+049</td>
<td>16:26:50.30</td>
<td>04:48:50.50</td>
<td>G</td>
<td>0.04p</td>
<td>4$^a$</td>
<td>&lt;1.2</td>
<td>&lt;2.6</td>
<td>5.01</td>
<td>–</td>
<td>1.7$^b$</td>
<td>12720</td>
</tr>
</tbody>
</table>

$^a$No detection, only upper limit for flux.

$^b$We assume $\Gamma = 1.7$ for the flux calculation.

(Kunert-Bajraszewska, Siemiginowska & Labiano 2013). Fig. 1 shows the Chandra ACIS-S images of two of the sources discussed here, which have the largest number of X-ray photons. We have also overlaid the radio MERLIN 1.6-GHz contours on the X-ray emission with the indications of radio components.

The source 0810+077 is a quasar, classified as a low-excitation galaxy (LEG). Its radio morphology consist of three components: the weak central component (C) and two lobes (E and W). The optical counterpart is coincident with the component C and we have suggested that this could be a radio core (Kunert-Bajraszewska et al. 2010). However, this suggestion is based on observations at only one radio frequency, so it should be treated as tentative. The brightest part of the X-ray emission lies between the components C and W. The potential offset between the centroid of the X-ray emission and component C or W can be consistent with the astrometric uncertainty of Chandra.

The source 0942+355 is a galaxy classified as a high-excitation galaxy (HEG). It is larger than 0810+077 and has a more complex radio structure. Its 1.6-GHz asymmetric radio morphology consist of three components: a weak radio core (C) and two lobes (E and W). There are also 5-GHz observations of this source (Kunert-Bajraszewska et al. 2010) showing only emission from the southeastern radio lobe. In the case of 0942+355, the brightest part of the X-ray source is right in the centre of the source, between the two jets.

The source 1558+536 is a galaxy classified as a LEG with a diffuse, double-like morphology (Kunert-Bajraszewska et al. 2010). Only nine counts were detected in the X-ray source is right in the centre of the source, between the two jets.

The source 1558+536 is a galaxy classified as a LEG with a diffuse, double-like morphology (Kunert-Bajraszewska et al. 2010). Only nine counts were detected in the X-ray source is right in the centre of the source, between the two jets.
and they could be progenitors of large-scale LEGs (Kunert-Bajraszewska & Labiano 2010).

4.2 Optical-line emission

Labiano (2008) found that compact AGNs show a strong correlation between the [O iii] λ5007 line luminosity and the size of the radio source, suggesting a possible deceleration in the jet as it crosses the host ISM. However, this correlation breaks down when including LLC sources, more specifically the compact LEGs (Kunert-Bajraszewska & Labiano 2010). As we have already shown in the optical analysis of the whole sample of LLC sources, the LLC HEGs show a ~10 times higher [O iii] λ5007 luminosity than LLC LEGs. This could be caused by a stronger jet contribution to the ionization of the ISM in HEGs and/or this could indicate differences in the environments of HEG and LEG objects.

In the pilot sample of LLC sources observed with Chandra, we have found that two sources, 0810+077 and 0942+355, have the same radio and X-ray luminosities (Table 2). However, 0942+355 (HEG) has higher [O iii] emission than 0810+077 (LEG). If we compare the \( \text{[O ii]} \) and \( \text{[O iii]} \) relative column densities (Guainazzi et al. 2008), 0810+077 is consistent with 100 per cent photoinionization and 0942+355 is consistent with 80 per cent photoinionization and 20 per cent shocks (Kunert-Bajraszewska & Labiano 2010).

4.3 Can the central AGN power the emission-line luminosity in the extended nebulae?

We have compared the number of ionizing photons produced by the nucleus of the source, with the number of photons needed to produce the observed emission-line luminosity (e.g. Wilson, Ward & Haniff 1988; Baum & Heckman 1989; Axon et al. 2000; O’Dea et al. 2000). Assuming radiative recombination under case B conditions, the number of ionizing photons \( s^{-1} \), \( N_{\text{HII}} \), needed to produce the observed \( H\beta \) luminosity \( L_{H\beta} \) is

\[
N_{\text{HII}} = 2.1 \times 10^{52} \left( L_{H\beta} / 10^{40} \text{ erg s}^{-1} \right). \tag{2}
\]

We use the integrated [O iii] λ5007 fluxes from Kunert-Bajraszewska & Labiano (2010) and scale using the typical ratio for the narrow-line components in CSS sources (e.g. Gelderman & Whittle 1994): \( H\beta / [\text{O iii}] \lambda 5007 = 0.18 \pm 0.02 \).

The number of photons \( s^{-1} \) in the continuum, between frequencies \( v_1 \) and \( v_2 \), is given by

\[
N_{\text{Nuc}} = 4\pi D^2 S_0 \left( a H \right)^{-1} \left( v_1^{-\alpha} - v_2^{-\alpha} \right), \tag{3}
\]

where \( D \) is the luminosity distance, the flux density spectrum is given by \( F_\nu = S_0 \nu^{-\alpha} \) (we adopt \( \alpha = 1 \); e.g. O’Dea et al. 2000) and \( h \) is the Planck constant. We are only interested in photons with \( \lambda \geq 2006 \) Å and \( \lambda \leq 2006 \) Å.

### Table 2

<table>
<thead>
<tr>
<th>Source</th>
<th>( \log L_{2-10\text{keV}} )</th>
<th>( \log L_{5\text{GHz}} )</th>
<th>( \log L_{[\text{O III}]} )</th>
<th>Spectral type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0810+077</td>
<td>42.8</td>
<td>41.4</td>
<td>40.8</td>
<td>LEG</td>
</tr>
<tr>
<td>0907+049</td>
<td>&lt;42.9</td>
<td>42.6</td>
<td>&lt;42.2</td>
<td>–</td>
</tr>
<tr>
<td>0942+355</td>
<td>42.9</td>
<td>41.4</td>
<td>42.0</td>
<td>HEG</td>
</tr>
<tr>
<td>1321+045</td>
<td>42.3</td>
<td>41.6</td>
<td>40.3</td>
<td>LEG</td>
</tr>
<tr>
<td>1542+390</td>
<td>&lt;42.7</td>
<td>42.4</td>
<td>41.9</td>
<td>HEG</td>
</tr>
<tr>
<td>1558+536</td>
<td>&lt;41.7</td>
<td>41.4</td>
<td>40.8</td>
<td>LEG</td>
</tr>
<tr>
<td>1624+049</td>
<td>&lt;40.0</td>
<td>40.0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance</th>
<th>( \log N_{\text{HII}} )</th>
<th>( \log N_{\text{Nuc}} )</th>
<th>( N_{\text{Nuc}} / N_{\text{HII}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0810+077</td>
<td>513.6</td>
<td>52.7</td>
<td>54.7</td>
<td>100.0</td>
</tr>
<tr>
<td>0942+355</td>
<td>1014.3</td>
<td>53.5</td>
<td>55.3</td>
<td>63.0</td>
</tr>
<tr>
<td>1321+045</td>
<td>1323.9</td>
<td>53.0</td>
<td>55.1</td>
<td>126.0</td>
</tr>
</tbody>
</table>

The number of photons \( s^{-1} \), \( N_{\text{Nuc}} \), needed to produce the \( H\beta \) luminosity is

\[
N_{\text{Nuc}} = 2.1 \times 10^{52} \left( L_{H\beta} / 10^{40} \text{ erg s}^{-1} \right). \tag{2}
\]

The Chandra and XMM–Newton studies of GPS and CSS sources performed so far show that they are strong X-ray emitters (Guainazzi et al. 2004, 2006; Vink et al. 2006; Siemiginowska et al. 2008; Tengstrand et al. 2009). The X-ray emission of CSS and GPS objects is probably a result of a recent triggering of the nuclear activity and can be characterized by an absorbed power-law model with high (>10^{22} cm^{-2}) column densities (Guainazzi et al. 2006; Vink et al. 2006; Siemiginowska et al. 2008; Tengstrand et al. 2009). However, there are also several detections of X-ray morphology in these compact objects. Extended hot 0.5–1 keV ISM has been detected in the case of two CSS sources, 3C303.1 (O’Dea et al. 2006) and 3C305 (Massaro et al. 2009), which is interpreted as shock-heated environment gas. Siemiginowska et al. (2008) have reported X-ray jets in GPS sources and large-scale X-ray emission associated with some of them. These objects are classified as GPS sources with extended emission and are discussed in the framework of the theory of intermittent radio activity (Stanghellini et al. 2005). However, the radio structures of GPS and CSS sources are much smaller than the spatial resolution of the current X-ray instruments in most cases, which prevents us from identifying the origin of their X-ray emission. There are several theoretical predictions concerning X-ray emission from evolving radio sources: (i) it is thermal emission emitted by the ISM of the hot galaxy, shock heated by the expanding radio structure (Heinz, Reynolds & Begelman 1998; O’Dea et al. 2006); (ii) it is produced in the accretion disc’s host corona (Guainazzi et al. 2004, 2006; Vink et al. 2006; Siemiginowska et al. 2008); (iii) it is non-thermal radiation produced through IC scattering of the local thermal radiation fields off the lobe electron population (Stawarz et al. 2008; Ostorero et al. 2010) or by mini-shells (Kino...
et al. 2013). Tengstrand et al. (2009) have shown that the radio versus X-ray luminosity plane can be a useful tool to derive constraints on the evolution of compact radio sources. Studies of compact radio AGNs so far have been biased towards high-luminosity objects ($L_{5\,\text{GHz}} > 10^{42}\,\text{erg}\,\text{s}^{-1}$). In this section, we extend these studies to the low-luminosity regime that our pilot $Chandra$ study has probed for the first time.

Our goal is to compare the X-ray properties of different groups of radio objects, GPS, CSS and large-scale FR I and FR II sources, as well as the X-ray properties of low- and high-power compact AGNs. For this purpose, we have built the control sample of GPS and CSS sources (Siemiginowska et al. 2008; Tengstrand et al. 2009; Massaro et al. 2010, 2012) and FR I and FR II objects (Sambruna, Eracleous & Mushotzky 1999; Donato, Sambruna & Gliozzi 2004; Grandi, Malaguti & Fiocchi 2006; Evans et al. 2006; Balmaverde, Capetti & Grandi 2006; Belsole, Worrall & Hardcastle 2006; Hardcastle, Evans & Croston 2006; Massaro et al. 2010, 2012) from results recently published in the literature. Our pilot sample of low-luminosity CSS sources consists of only seven objects, which is why we have also included the low-luminosity source, 3C 305, described by Massaro et al. (2009). The total number of GPS/CSS sources is 40 objects, and there are 34 FR I and 85 FR II sources. However, the samples are biased in terms of their redshift distribution. The GPS/CSS and FR II samples are well matched in their redshift, but the FR Is are generally at lower redshift. There are six GPS/CSS objects with redshift in the range $1 > z < 2$. All other sources from different groups have redshift $z < 1$.

For all plots presented in this paper we have used the total radio and X-ray luminosity for all groups of sources. The reason for this is a lack of information about the radio core fluxes of most of our compact GPS and CSS sources. Among the seven low-power CSS objects, only two have 5-GHz observations but without core detection (Kunert-Bajraszewska et al. 2010). A significant part of our sample of GPS/CSS sources is also unresolved in X-rays. The exceptions from the above-stated rule are a few GPS sources with extended structures (Stanghellini et al. 2005). For these, the radio and X-ray values used in this paper refer to their milliarcsec Very Long Baseline Array (VLBA) structures, as reported by Tengstrand et al. (2009) and Siemiginowska et al. (2008).

4.4.1 Radio/X-ray luminosity plane

We have compared the X-ray luminosity of the sources from the pilot sample with their radio properties at 5 GHz and 365 MHz (Fig. 2). We have also included the control sample of GPS/CSS and FR I and FR II objects as described above.

The low-power objects fit well to the already established X-ray–radio luminosity correlation for AGNs and occupy the space among FR I objects, which are weaker in X-rays. This trend is visible on both plots, X-ray versus 356 MHz and 5 GHz (Fig. 2), and is independent of radio frequency. However, the 356-MHz radio luminosity versus X-ray luminosity plot shows larger scatter among observable data than in the case of 5-GHz luminosity. This is caused by the fact that the X-ray emission is mostly associated with the compact central regions of AGNs, while the low-frequency flux density is dominated by the extended radio structures. As has also been shown by Hardcastle & Worrall (1999), much of the dispersion in the 5-GHz luminosity originates in beaming. Future X-ray observations of the whole sample of LLC sources would give us definitive information about their place on the radio/X-ray luminosity plane.

We have plotted all groups of AGNs on the 5-GHz/X-ray luminosity plane (Fig. 3) with a division for HEGs and LEGs. We have taken the optical identification from Buttiglione et al. (2010) in the case of FR I and FR II objects, and we have indicated them as LEGs and HEGs/broad-line objects (BLOs). According to Buttiglione et al. (2010), the BLOs can be considered as members of the HEG class. Identifications of GPS/CSS objects have been taken from Kunert-Bajraszewska & Labiano (2010) – see also Table 2 – and from Table A1. We have only four LEGs among the GPS/CSS class and, actually, all of these have been classified as CSS sources. HEGs are found among strong GPS and CSS objects. The HEG/LEG plot confirms what we have previously found (Kunert-Bajraszewska & Labiano 2010). The HEG and LEG AGNs group in two different parts of the plot.

A Pearson correlation analysis applied to both subsamples revealed a significant X-ray/radio correlation (Table 4). In the radio versus X-ray luminosity plane (Fig. 2), objects with a different morphology are aligned along the same correlation, with an increasing fraction of large-scale FR II morphologies at higher luminosities. Compact sources are well aligned along this correlation, with weak
Figure 3. Luminosity diagram for AGNs classified as HEGs and LEGs: 2–10 keV–5 GHz. The FR II HEG/BLO sources and GPS/CSS HEG objects are indicated as open red circles and red circles, respectively. The FR II LEGs are indicated with black crosses and FR I LEGs and GPS/CSS LEGs are denoted by open and black squares, respectively.

Table 4. Correlation and regression analysis for Fig. 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>N</th>
<th>r-Pearson coefficient</th>
<th>Linear regression coefficient</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEG</td>
<td>82</td>
<td>0.68</td>
<td>0.76 ± 0.09</td>
<td>11.49 ± 3.90</td>
</tr>
<tr>
<td>LEG</td>
<td>38</td>
<td>0.78</td>
<td>0.87 ± 0.12</td>
<td>5.45 ± 4.81</td>
</tr>
</tbody>
</table>

CSS (strong CSS/GPS) closer to the parameter space occupied by FR I (FR II) objects. However, the ionization mechanism seems to discriminate more neatly the radio sources in this plane. Low versus high ionization sources occupy a distinct locus in this plane, notwithstanding their evolutionary stage. This evidence agrees with a scenario whereby the X-ray emission in large-scale HEG sources is dominated by spectral components because of (obscured) accretion, as opposed to LEG objects where the X-ray emission should be dominated by non-thermal synchrotron jets (Hardcastle, Evans & Croston 2009; Antonucci 2012; Son et al. 2012). As seen on the radio/X-ray luminosity diagram (Fig. 3), there are two branches, each being driven by different excitation mode and each containing compact sources. The FR morphology, as well as the GPS and CSS division, seems to be independent of the excitation modes (Buttiglione et al. 2010; Kunert-Bajraszewska & Labiano 2010; Gendre et al. 2013).

4.4.2 Radio/X-ray luminosity ratio

Another test for the AGN evolution models is a comparison of the radio to X-ray luminosity ratio with the size of the sources and, indirectly, with their age (Fig. 4). The long-term evolution of extragalactic radio sources has been investigated by a number of authors in different ways: (i) as a variation of the radio power versus the total linear size (O’Dea & Baum 1997; Kunert-Bajraszewska et al. 2010; An & Baan 2012); (ii) dynamic evolution of FR II-like double radio sources characterized by the advance speed of the hotspots, the total extent of the source and depending on the density distribution in the host galaxy along the path of the jets and lobes (Begelman & Cioffi 1989; Fanti et al. 1995; Begelman 1996; Kaiser & Alexander 1997; Kino & Kawakatu 2005; Kawakatu & Kino 2006; Kaiser & Best 2007; Kawakatu et al. 2009a). The radio luminosity of the sources evolves through phases governed by the dominant energy-loss mechanism of the radiating, relativistic electrons. From the onset of the radio activity, the GPS/CSO (compact symmetric objects) stage, the radio power of the sources increases with time and source size. The increased rate of radio power diminishes in the transition region (1–3 kpc from the centre of the host galaxy) where a balance between adiabatic losses and synchrotron losses has been achieved. After this short period, the radio power of CSS sources starts to slowly decrease with the source size. The sharp decrease in the radio power versus the total extent of the source occurs only in large FR I and FR II objects, with FR I objects being below the luminosity threshold, \( L_{178\text{MHz}} \approx 10^{25.5} \text{ W Hz}^{-1} \text{ sr}^{-1} \), on the radio power/linear size plane. If the X-ray emission in radio-loud AGNs is due to accretion only, the evolution of the radio and X-ray wavebands could be totally decoupled and the radio/X-ray luminosity ratio should reproduce the radio power evolution with the linear size of the source. Fig. 4 shows that the above assumption is not true, not only in the case of large FR I and FR II objects, but also probably in the case of young GPS and CCS sources. The less radio powerful FR I objects have a radio/X-ray

![Figure 4](https://example.com/figure4.png)

Figure 4. The 5-GHz luminosity/2–10 keV luminosity ratio versus linear size diagram for AGNs classified as follows. Left: GPS (black squares), CSS (blue circles), FR I (open black squares) and FR II (open red circles). Right: GPS (black squares), CSS (blue circles), LERG (red crosses), NLRG (green triangles), Q (open black circles) and BLRG (violet diamonds).
luminosity ratio higher than many FR II objects, which might imply a greater decrease in X-ray luminosity with radio power in FR I objects than in FR II objects. This can be explained by the idea that the X-ray emission in FR I objects originates from the base of a relativistic jet (Evans et al. 2006) and is thought to be synchrotron emission (Sambruna et al. 2004; Worrall 2009). However, the X-ray emission of FR II objects comes mostly from the obscured X-ray component, probably associated with the accretion, and, to a lesser degree, from the relativistic jet produced in an inverse Compton process (Balmaverde et al. 2006; Belsole et al. 2006; Evans et al. 2006). When incorporating a different division among large-scale objects, we notice that, on average, the low-excitation radio galaxies (LERGs) and narrow-line radio galaxies (NLRGs) have higher radio to X-ray luminosity ratios than quasars (Q) and broad-line radio galaxies (BLRGs). According to Hardcastle et al. (2009), the common correlation of FR II NLRGs LERGs and FR I objects indicates that the X-ray and radio emission comes from the same jet-related component. The interpretation of the place of GPS and CSS sources on the radio/X-ray luminosity ratio versus linear size plane is even more difficult because of the large scatter of the observable values. As we have already mentioned, the beaming can disrupt the radio/X-ray correlations. However, at least in the case of CSS objects, this effect should be small (Wu et al. 2013). Thus, we suggest what we observe in the group of young GPS and CSS sources is a mix of two different types of X-ray/radio relation. We conclude that at some radio power level, the compact AGNs start to resemble the FR I objects, where the X-ray emission is a synchrotron type associated with the jet. It has been already proposed, using the spectral energy distribution (SED) modelling of two strong CSS objects, that their X-ray emission can be a sum of X-ray emission from the accretion disc and non-thermal X-ray emission from the parsec-scale radio jet (Kunert-Bajraszewska et al. 2009; Migliori, Siemiginowska & Celotti 2012).

Recently, Stawarz et al. (2008) and Ostorero et al. (2010) have discussed an alternative evolutionary model for GPS sources, which predicts the dependency of the broad-band SED on the linear size of the source. In their model, high-energy emission is produced by upscattering of various photon fields by the electrons of the lobes of the radio source with a size \( < 1 \) kpc. This process can cause a decrease of the X-ray to radio luminosity ratio by one to two orders of magnitude when the GPS source size increases. However, with the data set gathered in this paper, we cannot conclude that there is any correlation between the radio/X-ray luminosity ratio and the linear size of the sources.

4.4.3 Relation between \( N_H \) and linear size

Finally, we have drawn a relation between the measured column density and the total extent of the radio source for GPS and CSS sources (Fig. 5). It has been already reported (Pihilstrom, Conway & Vermeulen 2003; Vermeulen et al. 2003) that small sources \( ( < 0.5 \) kpc) tend to have larger \( H_\text{I} \) column density than larger sources \( ( > 0.5 \) kpc), which indicates that GPS/CSO objects evolve in a disc distribution of gas with a power-law radial density dependence. The same explanation could lie behind the (tentative) anticorrelation between X-ray column density and radio size in GPS galaxies (Tengstrand et al. 2009). Ostorero et al. (2010) have reported a positive correlation between the radio and X-ray hydrogen column densities, which can point towards the co-spatiality of the radio and X-ray emission regions. We have extended the discussion about the relation of \( N_H \) versus linear size to CSS sources. We have noticed that the \( N_H \) value of the CSS sources is, on average, lower than that of GPS objects. However, the correlation of X-ray column density and radio size does not hold when including larger CSS objects in the sample of small and young AGNs.

5 SUMMARY

In this paper, we have presented the X-ray Chandra observations of a pilot sample of low-luminosity CSS sources. Four of these have been detected, and the other three have upper limit estimations for the X-ray flux. Only for two CSS objects we were able to estimate the X-ray column density, which is of the order of \( 10^{21} \) cm\(^{-2} \). We have expanded the sample of compact AGNs with other GPS/CSO sources with X-ray detections found in the literature and we have used this, together with a sample of large FR I and FR II sources, to determine the nature of the relation between morphology, X-ray properties and excitation modes in radio-loud AGNs. We have found the following results.

(i) We have compared the X-ray luminosity of the radio sources from all the above-mentioned groups with their radio properties. The large-scale FR II sources and strong GPS and CSS objects settle at higher X-ray and radio luminosities, while the low-power CSS objects occupy the space among FR I objects, which are weaker in X-rays. This trend is visible independent of radio frequency.

(ii) The HEG and LEG sources occupy a distinct locus in the radio/X-ray luminosity plane, notwithstanding their evolutionary stage. This is in agreement with the postulated different origin of the X-ray emission in low- and high-ionization objects. Compact sources can be found in the branches driven by both excitation modes.

(iii) The less radio powerful FR I objects have higher radio/X-ray luminosity ratio than many FR II objects, which might imply a greater decrease in X-ray luminosity with radio power in FR I objects than in FR II objects. This is in agreement with the previous finding that the X-ray emission in FR I objects originates from the base of a relativistic jet while the X-ray emission of FR II objects has an accretion origin. The same can be true for smaller radio AGNs, namely GPS and CSS sources. The result of this study hints at the fact that below some radio power level, the compact GPS and CSS sources start to resemble FR I objects or, to be more specific, LERG and NLRG objects.

(iv) The X-ray hydrogen column density of the CSS sources is, on average, lower than that of GPS objects. However, the correlation...
between the X-ray column density and radio size does not hold for the whole sample of GPS and CSS objects.

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APPENDIX A: SPECTROSCOPIC CLASSIFICATION OF THE OTHER CSS/GPS SOURCES WITH X-RAY DATA

The spectroscopic data are available for six CSS sources from the samples of CSS/GPS sources of Tengstrand et al. (2009) and Siemiginowska et al. (2008) (Table A1). The HEG/LEG classification was based on the line ratios observed in the SDSS spectra, according to the description by Kunert-Bajraszewska & Labiano (2010).

<table>
<thead>
<tr>
<th>Source name</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>z</th>
<th>[O,\text{II}](\lambda\lambda 3727,3729/\text{O},\text{III}](\lambda 5007)</th>
<th>H(_\beta)</th>
<th>log (L_{2-10\text{keV}})</th>
<th>log (L_5,\text{GHz})</th>
<th>log (\text{L}_{\text{[O},\text{III}]})</th>
<th>Spectral type</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 0738+31</td>
<td>07:41:10.7</td>
<td>31:12:00</td>
<td>0.63</td>
<td>445.7</td>
<td>1490.6</td>
<td>3675.6</td>
<td>44.9</td>
<td>44.3</td>
<td>43.4</td>
</tr>
<tr>
<td>Q1250+568</td>
<td>12:52:26.3</td>
<td>56:34:20</td>
<td>0.32</td>
<td>1066.0</td>
<td>3564.8</td>
<td>1653.3</td>
<td>44.2</td>
<td>43.2</td>
<td>43.1</td>
</tr>
<tr>
<td>1345+125</td>
<td>13:47:33.3</td>
<td>12:17:24</td>
<td>0.12</td>
<td>1038.9</td>
<td>4682.3</td>
<td>623.9</td>
<td>43.8</td>
<td>42.7</td>
<td>42.2</td>
</tr>
<tr>
<td>4C+00.02</td>
<td>14:07:00.4</td>
<td>28:27:15</td>
<td>0.07</td>
<td>37.8</td>
<td>1068.0</td>
<td>18749.0</td>
<td>&gt;43.9</td>
<td>42.2</td>
<td>41.2</td>
</tr>
<tr>
<td>PKS1607+26</td>
<td>16:09:13.3</td>
<td>26:41:29</td>
<td>0.47</td>
<td>63.6</td>
<td>200.0</td>
<td>44.6</td>
<td>44.5</td>
<td>43.8</td>
<td>42.2</td>
</tr>
</tbody>
</table>

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