X-RAY PROPERTIES OF THE GIGAHERTZ PEAKED AND COMPACT STEEP SPECTRUM SOURCES

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ABSTRACT

We present Chandra X-ray Observatory observations of gigahertz peaked-spectrum (GPS) and compact steep spectrum (CSS) radio sources. The Chandra sample contains 13 quasars and 3 galaxies, with measured 2–10 keV X-ray luminosities within 10^{42}–10^{46} erg s^{-1}. We detect all of the sources, five of which are observed in X-rays for the first time. We study the X-ray spectral properties of the sample. The measured absorption columns in the quasars differ from those in the galaxies in that the quasars show no absorption (with limits 0.1–10^{21} cm^{-2}), while the galaxies have large absorption columns (10^{22} cm^{-2}) consistent with previous findings. The median photon index of the sources with a high signal-to-noise ratio is Γ = 1.84 ± 0.24, which is larger than the typical index of radio-loud quasars. The arcsec resolution of the Chandra telescope allows us to investigate extended X-ray emission and to look for diffuse components and X-ray jets. We found X-ray jets in two quasars (PKS 1127–145 and B2 0738+32), and an X-ray cluster surrounding a CSS quasar (3C 186; z = 1.1). We detected a possible binary structure in galaxy 0941–080 and an extended diffuse emission in galaxy PKS B1345+125. We discuss our results in the context of X-ray emission processes and radio source evolution. We conclude that the X-ray emission in these sources is most likely unrelated to a relativistic jet, although the sources’ radio loudness may suggest a high radiative efficiency for the jet power in these sources.

Subject headings: quasars: individual — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Powerful radio sources exemplify the most energetic processes in the universe and demonstrate that an accreting supermassive black hole can influence regions that are megaparsecs away from its immediate sphere of influence. How these sources are triggered and how long they last have been the subject of many scientific investigations. In this paper, we present X-ray observations of a sample of the most powerful but compact radio sources, which may represent an early stage of just-triggered quasar activity. Gigahertz peaked-spectrum (GPS) and compact steep spectrum (CSS) radio sources typically have compact radio morphologies, and their radio emission is contained within their host galaxies (<10 kpc; O’Dea et al. 1991; O’Dea 1998). The compact radio structure on milliarcsecond scales is similar to the morphology of a large radio source, with lobes, hot spots, and jets. Because of this similarity and their observed high radio power, GPS sources are thought to be the precursors of large radio galaxies observed at an early stage of expansion (the evolution model; Fanti et al. 1995; O’Dea & Baum 1997; O’Dea 1998). The compact radio structure on milliarcsecond scales is similar to the morphology of a large radio source, with lobes, hot spots, and jets. Because of this similarity and their observed high radio power, GPS sources are thought to be the precursors of large radio galaxies observed at an early stage of expansion (the evolution model; Fanti et al. 1995; O’Dea & Baum 1997; O’Dea 1998). Note that an alternative model, in which the source is confined by a dense environment (the “frustrated model”) has not been completely ruled out (Snellen et al. 2000; Alexander 2000), although there is no evidence for the existence of a medium with the required column density (Gupta et al. 2006; Morganti 2007).

If the evolutionary hypothesis is correct, study of GPS/CSS sources may impact our understanding of how quasars are triggered. Measured expansion velocities of double radio structures (Polatidis & Conway 2003; Gugliucci et al. 2005) in several nearby GPS galaxies support the idea that they are young (<10^8 yr). In addition, their radio morphology suggests that the sources are observed at high inclination angles, so Doppler beaming is not important. Thus, the young age of GPS galaxies with double or symmetric radio morphologies has not been questioned, and evolution studies often consider only GPS/CSS galaxies, e.g., sources where the central active galactic nucleus (AGN) cannot be directly observed, as it might be buried by a large column of obscuring material (Guainazzi et al. 2004, 2006).

Luminous quasars are thought to be powered by high accretion rates, and radio-loud quasars, in addition to exhibiting strong thermal emission, also exhibit relativistic jets carrying great kinetic power. It is challenging to measure the age of GPS/CSS quasars with core jet radio morphologies, because a truly young GPS/CSS quasar can often be confused with a blazar observed along the jet axes (Lister 2003; Stanghellini et al. 2005). However, there should also be young sources among blazars. Identifying typical blazars and young quasars within the GPS/CSS quasar samples is not trivial and has been basically avoided. In order to distinguish a blazar from a young radio source, one needs to consider the entire broadband spectrum of each source. This is hard and requires simultaneous observations at many frequencies, as blazars typically vary. A correlated rapid variability across many frequencies, including the gamma-ray band, may indicate a blazar nature, as a young GPS/CSS source should not vary on short timescales (less than a few months).

X-ray emission is predicted as a result of the evolution of the radio source and its expansion into the surrounding interstellar and intergalactic medium (ISM/IGM) (Heinz et al. 1998). A detection of such emission could provide information about temperature and density, i.e., the physical conditions of the expanding radio source (see the recent XMM-Newton observations by O’Dea et al. 2006).

Although there has been an abundance of radio data collected over the last decade, X-ray observations of GPS/CSS sources have been sporadic. O’Dea (1998) lists 31 GPS sources that show quite high X-ray luminosities (L_X(Y) = 10^{45}–10^{46} erg s^{-1}) (only quasars were detected in X-ray, while the seven galaxies were undetected, so only upper limits were used). An intrinsic
X-ray absorption was reported by Elvis et al. (1994) in two out of three high-redshift GPS quasars, suggesting that their environment might be different from that of other quasars. *ROSAT* upper limits for a few GPS/CSS galaxies with $L_X < 3 \times 10^{42}$ erg s$^{-1}$ are consistent with the X-ray emission expected from poor clusters or early-type galaxies. The first X-ray detection of a GPS galaxy at $L_X \sim 2 \times 10^{42}$ erg s$^{-1}$ by *ASCA* was reported by O'Dea et al. (2000). Recent *XMM-Newton* observations of a few GPS galaxies (Guainazzi et al. 2004, 2006; Vink et al. 2006) indicate an intrinsic absorption with an average column of $\sim 10^{22}$ cm$^{-2}$ and radio–to–X-ray luminosity ratios comparable to those of normal radio galaxies. There is also no compelling evidence for a hot gas in the X-ray spectra of GPS galaxies. These observations support the evolution model, in which GPS galaxies are “young” counterparts for large-scale FR II type galaxies (Guainazzi et al. 2006).

The highest spatial resolution X-ray observations before the launch of *Chandra* were made with the High-Resolution Imager on *ROSAT*, in which 2 out of 4 GPS quasars showed traces of an extended emission (Antonelli & Fiore 1997; Siemiginowska et al. 2003b; see also Schoenmakers et al. 1999 for an X-ray detection in a double-double galaxy with a GPS core). The spatial resolution of *Chandra* enables us to detect X-ray structures on arcsecond scales with a high dynamic range (Weisskopf et al. 2003). During the first years of the mission, we made a surprising discovery: two of the GPS quasars showed hundred-kiloparsec-scale X-ray jets in the *Chandra* X-ray images (Siemiginowska et al. 2002, 2003b). These two quasars have been classified as GPS quasars in radio band, with no indication of a large-scale emission. However, a careful reanalysis of archival radio data shows that there was indeed a large-scale radio structure present, but that due to a strong quasar core emission it was only detectable in the high-dynamic-range radio data.

For this exploratory X-ray study, we selected 16 GPS/CSS sources from the sample presented in O’Dea (1998). Our X-ray sample is not complete by any means, but so far it is the largest sample of GPS/CSS sources with the highest quality X-ray data. The main goals of this study are to obtain the X-ray flux and spectra, investigate an extended X-ray emission, disentangle diffuse and nuclear components, look for X-ray jets, and study absorption properties. We found X-ray jets in two quasars, discovered an X-ray cluster surrounding a $z = 1$ CSS quasar, and detected a possible binary structure in one galaxy and an extended diffuse emission in the other. Overall, the absorption properties of GPS quasars are different from those of GPS galaxies in that the quasars show no absorption (with limits $\sim 10^{21}$ cm$^{-2}$), while the galaxies have large absorption columns consistent with the previous findings.

The paper is structured as follows. We present the X-ray sample in § 2. In § 3, we show the X-ray *Chandra* data and describe the data analysis process. In § 4, we present the results, and § 5 contains the discussion of the results. We summarize the results in § 6. Throughout this paper, we use cosmological parameters based on the *WMAP* measurements (Spergel et al. 2003): $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$.

2. X-RAY SAMPLE

Our original *Chandra* sample of GPS/CSS sources was chosen from the complete sample compiled by O’Dea (1998), which consists of two samples studied by Fanti et al. (1990) and Stanghellini et al. (1998). The Fanti et al. (1990) sample was derived from the 3C catalog with the following criteria: (1) a flux density > 10 Jy at 178 MHz; (2) a projected linear size > 20 kpc; (3) $|b| > 10^\circ$ and $|l| > 10^\circ$; and (4) log power at 178 MHz > 26.75 W Hz$^{-1}$. The Stanghellini et al. (1998) sample was selected from the complete catalog of radio sources stronger than 1 Jy at 5 GHz compiled by Kühr et al. (1981) with the following criteria: (1) a source flux density measured at 5 GHz of above 1 Jy; (2) a radio spectrum with a turnover between 0.4 and 6 GHz; (3) a steep spectral index $\alpha > 0.5$ at the high frequency end, after the turnover; and (4) a source declination $> -25^\circ$ and galactic latitude $> 10^\circ$. The radio spectra for this sample were derived from simultaneous observations to prevent ambiguity from variability. Also, no regard was given to the optical counterpart, i.e., quasars and galaxies are both included. This means that the sample can be used to investigate the GPS phenomenon in a range of galaxy environments.

The 11 GPS/CSS sources were selected based on existing X-ray detections, the size of the radio emission, and a low Galactic equivalent hydrogen column. Four other sources from the O’Dea (1998) sample had already been observed by *Chandra*, and we obtained the data from the archive. We also added one more GPS source available in the archive, although it was not on the O’Dea (1998) list. The main purpose of this study is to investigate the X-ray properties of the GPS/CSS sources, and we decided to expand the samples using archival data.

The final *Chandra* sample presented here contains 3 GPS galaxies and 13 GPS/CSS quasars. The sample is listed in Table 1, with the date of each observation, observation IDs, and exposure times. Eleven sources have previously been observed in X-rays. The *Chandra* exposure time was estimated assuming a detection of the extended emission 10 times fainter than the core emission. Short $\sim 5$ ks exposures were obtained for the five sources that have never been observed in X-rays to determine their count rates and X-ray luminosity. The sample spans moderate redshifts (from $z = 0.228$ to $z = 1.95$; see Fig. 1) and radio luminosities in the range $L(5 \text{GHz}) \sim 10^{43}$–$10^{45}$ erg s$^{-1}$, with one GPS galaxy below $L(5 \text{GHz}) \sim 10^{42}$ erg s$^{-1}$.

3. X-RAY OBSERVATIONS AND DATA ANALYSIS

The *Chandra* ACIS-S data were collected in two different ways: (1) long exposures (>10 ks) to allow detection of a diffuse X-ray emission on arcsecond scales, and (2) short observations (<5 ks) to detect X-ray emission and obtain an X-ray flux for sources with no previous X-ray detections. All observations were performed with the source located $30^\circ$ from the default aim-point position on the ACIS-S backside illuminated chip S3 (Proposers’ Observatory Guide [POG]).$^4$ Most data were collected with the 1/8 subarray readout mode of only one CCD to mitigate pileup; however, some of the archived data were taken in the full readout mode and are affected by up to $\sim20\%$ pileup. All 16 sources were detected by *Chandra*, with a number of counts between 9 and 14,800.

The X-ray data analysis was performed in CIAO, version 3.4 with calibration files from the CALDB, version 3.3 database. Note that these calibration files are in fact for ACIS-S contamination. Although the pileup fractions are relatively low, we include in our analysis the pileup model specified by Davis (2000) and implemented in Sherpa (Freeman et al. 2001) to recover the intrinsic source continuum for a few sources that are the most affected by pileup (see details below).

3.1. Imaging Analysis

The ACIS-S images were inspected for the presence of an extended X-ray emission. The data show extended components in the vicinity of the X-ray core for two sources: the quasar Q0740+380 and the galaxy PKS B1345+125. We used the CHART simulator to obtain the point-spread function (PSF) for these sources and confirmed the presence of an extended

$^4$ See http://cxc.harvard.edu/proposer/POG/index.html.
| Name               | Other Name | Type | Redshift | $N_H$ | Radio Size | Radio Morphology | Exposure | Chandra Obs. Date | ObsID  | Total Counts | Net Counts |
|--------------------|------------|------|----------|-------|------------|------------------|----------|------------------|--------|--------------|------------|
| Q0134+329          | 3C 48      | Q/CSS| 0.367    | 4.54  | 0.5        | CJ (1)           | 9.2      | 2002 Mar 6       | 3097   | 6726         | 5318.8     |
| Q0615+820          | ...        | Q/GPS| 0.71     | 5.3   | 0.5        | IR (2)           | 47.3     | 2001 Oct 18      | 1602   | 2395         | 2178.0     |
| B2 0738+31         | ...        | Q/GPS| 0.63     | 4.18  | 0.01       | CJ (3)           | 27.6     | 2000 Oct 10      | 377    | 3675         | 3431.2     |
| Q0740+380          | 3C 186     | Q/CSS| 1.063    | 5.64  | 2.2        | DLJ (4)          | 34.4     | 2002 May 16      | 3098   | 1830         | 1702.2     |
| PKS 0941−080       | ...        | G/GPS| 0.228    | 3.67  | 0.05       | CSO (3)          | 5.35     | 2002 Mar 26      | 3099   | 9            | 8.8        |
| PKS 1127−145       | ...        | Q/GPS| 1.18     | 3.12  | 0.003      | CJ (3)           | 27.3     | 2000 May 28      | 866    | 14972.6      | 14972.6    |
| Q1143−245          | ...        | Q/GPS| 1.95     | 5.22  | 0.006      | CJ (5)           | 4.95     | 2002 Mar 08      | 3100   | 222          | 219.7      |
| Q1245−197          | ...        | Q/GPS| 1.28     | 4.72  | 0.5        | CSO (6)          | 5.1      | 2001 Dec 23      | 3101   | 44           | 43.8       |
| Q1250+568          | 3C 277.1   | Q/CSS| 0.32     | 1.22  | 1.67       | DLJ (1)          | 14.0     | 2002 Oct 27      | 3102   | 2337         | 2277.1     |
| Q1328+254          | 3C 287     | Q/CSS| 1.055    | 1.08  | 0.048      | CJ (2)           | 36.2     | 2002 Jan 06      | 3103   | 3509         | 3415.6     |
| PKS B1345+125      | 4C 12.50   | G/GPS| 0.122    | 1.9   | 0.08       | CSO (3)          | 25.3     | 2000 Feb 24      | 836    | 1347         | 1335.2     |
| Q1416+067          | 3C 298     | Q/CSS| 1.439    | 2.5   | 1.49       | DLJ (1)          | 17.9     | 2002 Mar 01      | 3104   | 10183        | 9522.1     |
| Q1458+718          | 3C 309.1   | Q/CSS| 0.905    | 2.33  | 2.11       | CSO (7)          | 16.95    | 2002 Jan 28      | 3105   | 5434         | 5104.6     |
| Q1815+614          | ...        | Q/GPS| 0.601    | 3.9   | ...        | CSO (8)          | 4.9      | 2002 Sep 25      | 3056   | 164          | 142.0      |
| Q1829+290          | 4C 29.56   | Q/CSS| 0.842    | 11.16 | 3.1        | CSO (9)          | 5.3      | 2002 Oct 08      | 3106   | 19           | 18.9       |
| B2128+048          | G/GPS      | 0.99  | 5.23     | 0.03  | CSO (3)    | 5.7      | 2002 Oct 11      | 3107   | 92           | 90.7       |

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**Notes:**

a. G=Galaxy; Q=Quasar. GPS or CSS radio classification based on O’Dea (1998).

b. Equivalent hydrogen column in the Milky Way from COLDEN (Stark et al. 1992).

c. Values from O’Dea (1998).

d. CJ=core jet; DLJ=double-lobed jet; CSO=compact symmetric object; IR=irregular.

**Radio Morphology References:** (1) Akujor & Garrington 1995; (2) Kellermann et al. 1998; (3) Stanghellini et al. 2005; (4) Cawthorne et al. 1986; (5) Edwards & Tingay 2004; (6) Taylor & Peck 2003; not definite classification for this source; (7) Pearson & Readhead 1988; (8) Taylor et al. 1994; (9) Dallacasa et al. 1995.
component. A detailed analysis and a discussion of the properties of the X-ray cluster emission with a total of 740 counts detected out to $\sim$120 kpc from Q0740+380 ($z = 1.063$) were presented in Siemiginowska et al. (2005).

Figure 2 shows a smoothed ACIS-S image of the galaxy PKS B1345+125 ($z = 0.122$), with extended emission on the $\sim$10$''$ scale ($\sim$20 kpc). A detailed analysis of this structure will be given in M. Guainazzi et al. (2008, in preparation).

3.2. Spectral Analysis

We used CIAO, version 3.4 and CALDB, version 3.3 to analyze all data sets, using the CIAO default tools to extract the spectrum and the associated calibration files (rmf and arf). We used Yaxx$^5$ to uniformly analyze and fit the data. The spectra were extracted from circular regions centered on each source. Annuli surrounding the source regions were assumed for the background regions. The total counts detected for each source are listed in Table 1.

We fit an absorbed power-law model to the spectral data: $N(E) = AE^{-\Gamma} \exp\{-N_H^{gal}\sigma(E) - N_H^{abs}\sigma(E(1+z_{abs}))\}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$, where $A$ is the normalization at 1 keV, $\Gamma$ is the photon index of the power law, and $N_H^{gal}$ and $N_H^{abs}$ are the two components for the absorption. The first absorption component is the effective Galactic absorption characterized by the equivalent neutral hydrogen column $N_H^{gal}$, which we list for each source in Table 1 (COLDEN$^6$). This absorption was constant during fitting. We assume that the second absorption component is intrinsic to the quasar and located at redshift $z_{abs}$, with $N_H^{abs}$ as the equivalent hydrogen column. The values $\sigma(E)$ and $\sigma(E(1+z_{abs}))$ are the corresponding absorption cross sections (Morrison & McCammon 1983; Wilms et al. 2000). We used Powell optimization and $\chi^2$ (data variance) statistics (binning the data to contain a minimum of 16 counts in a bin) to determine the best-fit parameter values. The modeling results are presented in Table 2.

The above model was applied to each source to obtain a uniform description of the sample. For sources with a high count rate and a high number of counts, we also included the effects of pileup in our modeling.

3.2.1. Pileup Analysis

The pileup fractions for the observations were estimated in a plot of pileup fraction versus photons per frame in § 6.14 of the POG. The photons per frame parameter was calculated by dividing the number of counts by the exposure time, and multiplying this ratio by the frame time for each observation. These estimates indicated that pileup was significant in Q0134+329 (see also Worrall et al. 2004) and Q1416+067.

In order to correctly model pileup, we removed the ACIS afterglow correction applied in standard data processing (SDP). This correction, intended to discard cosmic-ray events, can also remove as much as 20% of valid source photons.

In Sherpa, absorption (xsphabs) and power-law (pow) models were fit to the data within the 0.3–7.0 keV energy range; Q1416+067 also included a redshifted absorption (xszabs) component, since the absorption column $N_H$ was detected in the previous fit for this source. A pileup model (jdpileup) was included in these fits using the Monte-Powell fitting method. The results of these fits are shown in Table 1, which displays the spectral index $\Gamma$ obtained from adding in the pileup component, as well as the estimated pileup fraction and the pileup fraction found from running the fit. For each target, the index $\Gamma$ increased after including the pileup component in the fit as expected. For Q0134+329, the pileup fraction calculated through Sherpa was significantly higher than that estimated from the POG. For the quasars in the sample, the average photon index increased from 1.77 $\pm$ 0.06 to 1.84 $\pm$ 0.06 when the pileup model was included (see Fig. 4). Due to the strong pileup (which modifies the PSF), it is hard to determine whether any extended X-ray emission component is present in these sources.

4. RESULTS

In general, GPS/CSS sources are strong X-ray point sources; however, an extended X-ray emission is detected in several cases in the form of large-scale jets or a diffuse component. We discuss this aspect of our studies in more detail in the next section.

Figure 3 plots the absorbed power-law model fits to the X-ray spectra for each source with the residuals. Table 2 shows best-fit values for the absorption column and photon index, with 90% errors for one significant parameter. All sources are relatively well described by the power-law model. However, the $\chi^2$ values reflect the scatter observed in the residuals in Figure 3 and indicate the need for a spectrum more complex than a simple power-law model for a few sources. For example, PKS B1345+125 has a large absorption column ($N_H = 2.54^{+0.68}_{-0.54} \times 10^{22}$ cm$^{-2}$) and a soft X-ray excess, Q0134+329 is better described by a two-component model.
power-law model, and Q0740+380 shows a possible absorption line (although in this case, the signal-to-noise ratio [S/N] is low in this part of the spectrum, and calibration uncertainties are large enough that we cannot claim this line detection).

We applied a two-component model, specifically an absorbed power law and a bremsstrahlung emission, to the PKS B1345+125 X-ray spectrum to determine the luminosity of the soft X-ray thermal emission. The parameters of this model are as follows: the column density of the intrinsic absorber \( N_{\text{HI}} \), the photon index of the absorbed power law \( \Gamma \), the normalization of the absorbed power law, and the normalization of the bremsstrahlung emission. We found that two of these quasars (PKS 1127−145 and B2 0738+313) are known to have damped Ly\( \alpha \) (DLA) absorption systems (Bechtold et al. 2001; Siemiginowska et al. 2003b), and that the third (Q1416+067) has a broad absorption line system (BAL; Bechtold et al. 2002). In general, the upper limits for intrinsic absorption less than a few \( 10^{21} \) cm\(^{-2} \) indicate low columns in the majority of quasars.

We do not detect any trends in absorption with photon index or source luminosity. A comparison with GPS galaxies (Guainazzi et al. 2006) indicates that galaxies have larger absorption columns than GPS quasars. This may be due to a difference in the viewing angle between quasars and galaxies in that the galaxies are observed along the direction of an obscurer, e.g., a torus.

5. DISCUSSION

5.1. X-Rays from an Unresolved Core

The typical radio size of a GPS/CSS source is relatively small in comparison to the resolution of Chandra X-ray images. This means that the X-ray emission measured in a standard source extraction region (radius = 1.75\( \alpha \)) contains the entire complex radio structure of the GPS radio source (i.e. jets, hot spots, and core), and we cannot resolve the individual radio components in X-rays. This observational fact complicates any theoretical interpretation of the origin of the X-ray emission. A contribution to the observed X-ray spectrum can come not only from the central quasar power engine, but also from unresolved jets, hot spots, or thermal gas heated by an expanding radio source.

The X-ray emission could originate in an accretion flow onto a supermassive black hole and be associated with a hot ionized medium, e.g., a corona, a hot wind, a jet, or a hot innermost flow (Sobolewska et al. 2004a, 2004b). It can also be a result of reflection of the primary emission off the cold (10\(^5 \) K) disk flow (e.g., Ross & Fabian 1993). However, in radio-loud sources the
jet emission often dominates over these accretion components. In fact, the radio–to–gamma-ray emission is entirely dominated by the jet emission in blazars, which are observed along the jet axes (Sikora et al. 1997). Some of the GPS sources might indeed be observed along the jet axis and have a significant X-ray emission due to relativistic jet particles.

If, for example, a relativistic jet is propagating within a strong IR photon field, the IR photons upscattered by the jet electrons can contribute to the X-ray and gamma-ray emission (see Sikora et al. 2002; Blażejowski et al. 2004). The expected spectrum is flat in comparison to the photon index found in our sample except for PKS 1127–145, which has \( \Gamma = 1.20 \pm 0.03 \), the smallest in the sample. The distribution of a power-law photon index for the sample is plotted in Figure 4. A majority of the sources have \( 1.8 < \Gamma < 2 \), with a median value of \( \Gamma = 1.84 \pm 0.24 \) for the quasars in the sample. This \( \Gamma \) is higher than the values of 1.57 \( \pm \) 0.08 (Bechtold et al. 1994a, 1994b) or 1.55 \( \pm \) 0.17 (Belsole et al. 2006) observed for the other radio-loud quasars, and similar to the value of 2.03 \( \pm \) 0.31 observed in radio-quiet quasars (Kelly et al. 2007), where the X-ray emission is not associated with a jet. We conclude that there is no evidence for jet emission often dominates over these accretion components.

![Figure 3](https://example.com/fig3.png)

**Figure 3.**—*Chandra* ACIS-S spectra of GPS/CSS sources fit with the absorbed power-law model. The lower panel shows the residuals in terms of sigma. From top left: Q0134+329, Q0740+380, Q1143–245, Q1250+568, Q1328+254, PKS B1345+125, Q1416+067, and Q1458+718. [See the electronic edition of the Journal for a color version of this figure.]

![Figure 4](https://example.com/fig4.png)

**Figure 4.**—Histogram of number of sources vs. photon index \( \Gamma \). The top plot represents all sources in the sample, with the three galaxies denoted by the filled regions. The bottom plot contains only quasars; the jdp13.eup model was applied to the three sources with significant pileup (see Table 2).
a strong contribution of a parsec-scale jet to the X-ray spectrum in 13 out of 14 objects in our sample of GPS/CSS quasars. This needs to be confirmed with observations of a larger X-ray sample of GPS/CSS sources.

5.1.1. Expanding Radio Source

Can a powerful expanding radio source (unresolved by Chandra) contribute to the X-ray spectrum? Very long baseline interferometry (VLBI) observations indicate relativistic motions associated with expanding jet components. Outside a parsec-scale region, the GPS radio jets show knots and hot-spot emission. Such features indicate the sites of shocks, interactions, and particle acceleration, and in principle lead to X-ray emission through the synchrotron, inverse Compton processes, or thermal emission of the hot, shocked interstellar medium. Heinz et al. (1998) considered the evolution of radio source expansion within host galaxies. They simulated interactions between a growing radio source and the ISM and IGM. In the highly supersonic expansion of a young source, a shock forms around the expanding source and heats up the medium to X-ray temperatures. As a result, a “cocoon” of hot medium surrounds the radio source. Depending on the density of the medium and the strength of the shock, a source of 16 kpc can emit $\sim 10^{43}$ erg s$^{-1}$ in the Chandra band. Such an X-ray luminosity is on the order of the luminosity observed for the sources in our sample (Table 3). Recently, Stawarz et al. (2007) (see also Perucho & Martí 2002) modeled the spectra of GPS galaxies with the emission from expanding radio lobes and applied the model to a sample of GPS galaxies. Such emission will be featureless. Spectral lines would be present if the emission originated from a hot thermal plasma, and depending on metallicity we would expect to detect the emission lines due to metals, in particular oxygen and iron.

Thermal X-ray emission due to the shock-heated plasma can be easily confused with the emission from the accretion flow. Reflection off cold/warm matter in the accretion disks can be present in some sources. A characteristic Fe Kα fluorescent emission line is usually associated with the reflection component and indicates that the X-ray emission originates in the accretion flow. Of the eight sources in our sample with a good S/N, we detected Fe-line emission in two quasars, Q0740+380 and Q1328+254. In both sources, the equivalent width of the emission line is relatively small, $<0.4$ keV (90%). The energy of the detected line, $E_{\text{rest}} = 6.40 \pm 0.06$ keV in both cases, indicates that it is not coming from ionized, thermal material; however, it may indicate a reflection component becoming important in these sources.

If the intrinsic absorption is high, the reflection component can be detected at higher energies ($E_{\text{rest}} = \sim 4$–10 keV) and can provide information on the intrinsic source luminosity. GPS galaxies are likely to be highly absorbed (Guainazzi et al. 2006; Vink et al. 2006). We find an equivalent hydrogen column density of $N_{\text{HI}} > 10^{22}$ cm$^{-2}$ in two galaxies (Siemiginowska et al. 2003a). In contrast, there is no significant absorption present in the GPS quasars observed by Chandra. This result is in agreement with other X-ray studies of radio sources, in which higher absorption was detected in galaxies than in quasars (Belsole et al. 2006); however, absorption columns in GPS galaxies are not higher than columns observed in other galaxies (Guainazzi et al. 2006; Vink et al. 2006).

We note that we detected absorption columns in three quasars (see Table 2) and that two are known to have intervening damped Lyα absorbers on the line of sight, while the third is a metal-line-associated absorber system detectable in the optical spectrum. The current data do not allow us to constrain the redshifts of X-ray absorbers, so there is no confirmation as to whether the detected absorption is due to intervening DLA systems or intrinsic to the quasar. A full description of the detectability of the X-ray absorption due to DLA will be given in Bechtold et al. (2008, in preparation).

5.1.2. Spectral Energy Distributions

The optical–UV emission of the GPS/CSS sources is typical of broad-line quasars. Both broad emission lines and a big blue bump are present in all cases, and there is no signature of a jet synchrotron emission in the optical–UV band. However, GPS sources are strong radio emitters. We compiled the spectral energy distribution (SED) for our sample using the existing broadband data available in NED (Table 3). Figure 7 shows the radio loudness [$\log (F_{5\,\text{GHz}}/F_{\beta})$] of the GPS/CSS sources in our sample in comparison to the other radio-loud quasars in Elvis et al. (1994). The GPS/CSS quasars are at the higher end of the radio loudness distribution, with most of the sources at $R_{\beta} > 4$. Note that this

![Figure 5](https://example.com/figure5.png)

**Fig. 5.** Photon index $\Gamma$ vs. X-ray–to–radio luminosity ratio for the sample. PKS 0941–080 is not included in the figure.

![Figure 6](https://example.com/figure6.png)

**Fig. 6.** X-ray luminosity in 2–10 keV energy range vs. redshift for the GPS/CSS sample. The galaxies are marked with triangles. [See the electronic edition of the Journal for a color version of this figure.]
Q0615+820 and Q1231+481 came from Ve´ ron-Cetty & Ve´ ron (2001; Vizier Online Data Catalog 7224). All luminosity values are unabsorbed and in rest frame.

**Table 3**

Flux and Luminosity for GPS/CSS Chandra Sample

| Name                   | Flux (0.5–2 keV) (10^{-13} erg cm^{-2} s^{-1}) | L_{X} (0.5–2 keV) (10^{44} erg s^{-1}) | Flux (2–10 keV) (10^{-13} erg cm^{-2} s^{-1}) | L_{X} (2–10 keV) (10^{44} erg s^{-1}) | L_{B} (5 GHz) (10^{44} erg s^{-1}) | R_{L}^a | R_{B}^b | \alpha_{os}^c | \alpha_{io}^d |
|------------------------|-----------------------------------------------|----------------------------------------|-----------------------------------------------|----------------------------------------|----------------------------------|--------|--------|---------|---------|
| Q0134+329.............. | 15.22                                         | 2.89                                   | 15.58                                         | 5.17                                   | 11.66                           | 0.94   | 7.36   | 4.28    | 1.54    |
| Q0615+820°............. | 1.07                                          | 0.70                                   | 2.24                                          | 3.46                                   | 2.98                            | 0.87   | 7.64   | 5.05    | 1.35    |
| B2 0738+313............ | 3.12                                          | 1.46                                   | 7.37                                          | 7.53                                   | 1.65                            | 2.05   | 7.76   | 5.61    | 1.72    |
| Q0740+380.............. | 1.28                                          | 1.39                                   | 1.55                                          | 4.57                                   | 13.37                           | 0.52   | 7.14   | 4.29    | 1.74    |
| PKS 0941−080°........... | 0.05                                          | 0.006                                  | 0.03                                          | 0.005                                  | 0.004                           | 0.07   | 9.31   | 6.53    | 2.11    |
| PKS 1127−145°........... | 12.22                                         | 15.74                                  | 49.38                                         | 179.41                                  | 80.82                           | 8.15   | 7.10   | 4.74    | 1.29    |
| Q1413−245°.............. | 1.03                                          | 2.91                                   | 2.17                                          | 20.33                                  | 7.13                            | 8.20   | 7.81   | 6.04    | 1.56    |
| Q1245−197°................ | 0.22                                          | 0.33                                   | 0.32                                          | 1.29                                   | 0.80                            | 5.91   | 8.77   | 6.65    | 1.57    |
| Q1250−568°................ | 4.12                                          | 0.62                                   | 6.27                                          | 1.56                                   | 2.18                            | 0.13   | 7.15   | 4.13    | 1.44    |
| Q1328+254°................ | 2.39                                          | 2.57                                   | 3.51                                          | 10.22                                  | 15.70                           | 5.41   | 7.90   | 5.23    | 1.59    |
| PKS B1345+125°........... | 4.04                                          | 0.11                                   | 12.18                                         | 0.41                                   | 10.08                           | 0.05   | 7.53   | 3.67    | 1.52    |
| Q1416+067°.............. | 15.33                                         | 26.96                                  | 23.69                                         | 126.23                                  | 98.68                           | 4.81   | 6.76   | 4.32    | 1.42    |
| Q1458+718°.............. | 7.04                                          | 5.93                                   | 17.05                                         | 36.55                                  | 173.46                          | 4.29   | 7.37   | 4.03    | 1.47    |
| Q1815+614°................ | 0.73                                          | 0.32                                   | 0.12                                          | 1.13                                   | 0.02                            | 0.24   | 7.50   | 5.50    |        |
| Q1829+290°................ | 0.09                                          | 0.07                                   | 0.18                                          | 0.32                                   | 1.16                            | 1.16   | 8.73   | 6.17    | 1.73    |
| PKS B2128+048°........... | 0.32                                          | 0.31                                   | 1.25                                          | 3.21                                   | 1.23                            | 2.99   | 8.37   | 6.06    | 1.91    |

**Note.**—The flux was calculated at 2500 Å by using the ν magnitude from O’Dea (1998) and from the relation f_ν ~ ν^{−0.5}, where α = 0.5. The ν magnitudes for Q0615+820 and Q1231+481 came from Véron-Cetty & Véron (2001; Vizier Online Data Catalog 7224). All luminosity values are unabsorbed and in rest frame.

- a log (Flux_{5 GHz}/Flux_{2 keV}).
- b log (Flux_{5 GHz}/Flux_{high}).
- c log [Flux(2500 Å)/Flux(2 keV)]/2.605 in rest frame.
- d −log (Flux(2500 Å)/Flux(5 GHz))/5.38 in rest frame.
- e Radio flux values at 5 GHz were calculated from NED data for these sources; we used published values for radio flux from O’Dea (1998) for the other sources.

The trend is also true when we compare GPS/CSS sources to the sample of radio-loud sources presented by Sikora et al. (2007), for which the calculated radio luminosity included the entire radio source, i.e., the core, lobes, and jets. Figures 5 and 8 show the X-ray luminosity in comparison to the radio luminosity at 5 GHz. There is no correlation between radio and X-ray properties visible in these two figures.

The plots in Figure 9 show the four quasars for which we were able to build a broadband SED. The big blue bump is prominent in all sources. For comparison, we plot the radio-loud SED compiled by Elvis et al. (1994) normalized at 1 μm. A strong radio emission exceeding an average radio-loud quasar’s SED is clearly visible, indicating a much stronger radio/optical power in GPS sources (by a factor of ~30) than in normal radio-loud quasars. Interestingly, the X-ray luminosity shown in the SEDs is similar to or even lower than that of the radio-loud quasars. This might indicate that the contribution from the GPS radio components to the X-ray spectrum is small. We calculated the optical–to–X-ray luminosity (α_{os}) parameter for all the sources in the sample (see Table 3). The median for the sample is 1.53 ± 0.24. This is in agreement with α_{os} = 1.49 ± 0.19 for radio-quiet quasars (Kelly et al. 2007, 2008; Sobolewska et al. 2008) and suggests that the X-ray emission for the sources in our sample is most likely related to the accretion process, as it is in radio-quiet quasars. We note that PKS 1127−145 may be an exception, because it has both a hard X-ray spectrum (Γ = 1.2 ± 0.03) and a small α_{os} of 1.29. Therefore, X-ray spectral analyses of the photon index and

**Figure 7.**—Histogram of radio loudness. The shaded region indicates a parameter space for the GPS/CSS sources in our sample. For comparison, the quasars from Elvis et al. (1994) are shown (thick solid line) with a smaller radio loudness parameter than the GPS/CSS sample. The upper limits for the sources in Elvis et al. (1994) are indicated by arrows.

**Figure 8.**—X-ray luminosity in 2–10 keV energy range vs. radio luminosity at 5 GHz. The galaxies are marked by triangles. [See the electronic edition of the Journal for a color version of this figure.]
other spectral features for a larger sample are needed to firmly establish such conclusions.

5.2. Large-Scale X-Ray Emission

In the following sections, we will address three types of large-scale X-ray morphology associated with a GPS source: (1) an X-ray jet, (2) a diffuse X-ray emission surrounding the source, and (3) a secondary source within 10"–20".

5.2.1. Jets

In general, many detections of large-scale radio emission were not deemed significant before the corresponding X-ray detections were found by *Chandra*. High-dynamic-range observations are required for detecting faint structures in the vicinity of a bright point source, and the experiments need to be designed for the specific purpose of detecting such emission.

Large-scale X-ray jets were discovered in two sources in our sample: PKS 1127–145 (Siemiginowska et al. 2002, 2007) and B2 0738+313 (Siemiginowska et al. 2003b). A reanalysis of the radio data confirmed the presence of radio jets. Both jets have similar morphologies in X-rays and radio. As in the other large-scale X-ray jets (Harris & Krawczynski 2006), the question of the primary mechanism responsible for the X-ray emission has not been resolved. The X-ray emission is modeled either as the synchrotron emission from several populations of relativistic electrons or as a result of the inverse Compton scattering of the cosmic microwave background (CMB) photons off relativistic electrons within the jet (see Harris & Krawczynski 2006 for the most recent review of the X-ray jets). There is no confirming evidence favoring either of the two models.

A large-scale jet emission gives possible evidence for the non-GPS status of the source (see Stanghellini et al. 2005 for a discussion on the classification of the GPS sources). The blazar-like emission could be responsible for the overall emission, and the analysis of a "young" GPS class is confusing. On the other hand, there should be some young sources within the blazar class, and the question is how to find them.

5.2.2. Diffuse X-Ray Emission

Why do we expect any diffuse X-ray emission to be associated with a GPS/CSS source? Several possibilities have been considered, including (1) a relic of past activity, (2) a confining medium, (3) signatures of the interactions between the jet and the ISM, (4) a remnant of a past merger, and (5) an X-ray cluster.

The typical size of a GPS/CSS source is comparable to the size of its host galaxy. However, a small fraction of GPS/CSS sources exhibit large-scale radio emission, which has been associated with past source activity (Baum et al. 1990; Kunert-Bajraszewska et al.)
In a few cases, a young GPS source is growing within a large-scale double radio source (Marecki et al. 2006). Do we expect any extended X-ray emission to be present in those sources? An old relic can produce X-rays by upscattering CMB photons onto an old population of electrons in its old radio structures, or if there is still remaining jet activity supplying energy to its outer structures. The large-scale jet in B2 0738+313 could represent such an old structure (Siemiginowska et al. 2003b). A faint radio lobe emission has been detected on both sides of the core, while the X-ray jet is propagating toward one of the two lobes. However, we do not detect any X-rays associated with the radio lobes in this source.

Powerful radio-loud quasars are often found in rich clusters of galaxies (Yee & Green 1987). However, there have been no systematic studies of the X-ray environment of GPS/CSS sources. In our sample, we detect an extended diffuse X-ray emission associated with the X-ray cluster of the quasar 3C 186 ($z = 1.063$) and an extended emission in the GPS galaxy PKS B1345+125. The properties of the 3C 186 cluster were discussed in Siemiginowska et al. (2005). One important conclusion from the studies of 3C 186 is that the hot cluster gas is not able to confine the expanding radio source and that the jet moves out of the host galaxy with no significant energy loss.

The diffuse X-ray emission in PKS B1345+125 may originate as a thermal emission associated with the galaxy halo. The size of the extended X-rays is of order ~20 kpc, which agrees with the size of the extended emission line region of ~200 kpc studied in optical (Holt et al. 2003; Axon et al. 2000). Holt et al. (2003) identified three kinetically distinct emission-line regions in this source. They associated the most extended narrow line component with the quiescent ISM in the galaxy halo. The X-ray emission is elongated toward the southwest, as is the optical emission, and it also agrees with the VLBI jet axis (Stanghellini et al. 2001), suggesting that it is somehow related to the expanding GPS source. More detailed discussion of this interesting source and the signatures of the radio source interactions with the ISM will be presented in M. Guainazzi et al. (2008, in preparation).

In the models for GPS/CSS source confinement, the density required to slow down the jet significantly is relatively high (De Young 1993). Such a dense medium could be detected in X-rays through intrinsic absorption (or emission). Although A central supermassive black hole requires a large amount of fuel to power a quasar. Recent simulations of hierarchical structure formation suggest that quasar activity is a direct consequence of galaxy interactions resulting in a rapid fuel supply to the central black hole. On the other hand, some "feedback" or other intermittency mechanism (see, e.g., Janiuk et al. 2004; Siemiginowska et al. 1996) for accretion flow instabilities is required to induce the intermittent source activity observed in nearby clusters of galaxies (McNamara & Nulsen 2007).

If GPS/CSS sources are representative of an initial activity stage, then one would expect to detect some signatures of the increased fuel supply into the central regions of their host galaxies. The age of the smallest GPS galaxies as estimated from the expansion velocity of their radio components is below $10^7$ yr (Polatidis & Conway 2003; Gugliucci et al. 2005), while the synchrotron ages for larger samples are usually $<10^5$ yr (Murgia et al. 1999).

Sikora et al. (2007) studied the relationship between the source radio power and the accretion power (defined as Eddington luminosity) for a large sample of AGNs. They compare the total radio power of the source (the nucleus plus the large-scale radio emission) to the accretion power of the nucleus, and show that the radio luminosity is relatively constant for large optical luminosities, but decreases for low optical luminosities. The sources in our sample are extremely radio-luminous and radio-bright. Figure 7 shows that the radio loudness for the sources in our sample exceeds the radio loudness of the radio-loud quasars in Elvis et al. (1994). Their optical to X-ray luminosities, expressed as $\alpha_{opt} = 1.53 \pm 0.24$, are instead within the range values of radio-quiet quasars, 1.49 $\pm$ 0.19 (Kelly et al. 2007), suggesting that X-ray emission processes are most likely related to the accretion process. Their high radio loudness may be related to a higher radiative efficiency for the jet power in compact radio sources.

6. SUMMARY

We have discussed Chandra X-ray observations of a sample of GPS/CSS sources. We detected all sources and have studied their X-ray spectral and spatial properties. GPS quasars are not absorbed, in contrast to GPS galaxies, which show high X-ray column densities. The median X-ray photon index $1.84 \pm 0.24$ is steeper than that observed in radio-loud quasars, while the optical–to–X-ray luminosity ratios $\alpha_{opt} = 1.53 \pm 0.24$ are typical of radio-quiet quasars. We may conclude that the X-ray emission in these sources is mostly likely related to the accretion power, as in radio-quiet quasars, and not to the relativistic jet, with the exception of PKS 1127–145.

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