RADIO X-RAY CONNECTIONS IN GPS SOURCES

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Abstract

Giga-Hertz Peaked Spectrum (GPS) radio sources are powerful radio and X-ray emitters. Their radio properties have been extensively studied over the last decade leading to two possible explanations of the compact nature of the GPS sources: (1) a *frustrated source* scenario in which the expansion of the radio source is confined by a dense environment; (2) an *evolution scenario* in which the source is at an early stage of its expansion to a typical large scale radio source. The radio emission has been studied independently of the X-ray emission mostly because of the limitations of the X-ray telescopes and until recently there were only sparse X-ray observations of GPS sources. *Chandra* provides the spatial resolution and effective area adequate for studying the X-ray environment of the GPS sources on sub-arcsecond scales. Although the compact GPS radio source cannot be resolved in X-rays, the X-ray spectra give constraints on the emission processes potentially related to the milliarcsecond radio structures. Here we summarize the recent *Chandra* observations of GPS sources and discuss the X-ray morphology and spectra and their connections to the radio emission.

1 Introduction

Giga-Hertz Peaked Spectrum (GPS) radio sources typically have compact radio morphology with the radio emission contained within their host galaxy (<10 kpc). 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 the GPS sources are thought to be the precursors of large radio galaxies observed at the early stage of their expansion (*evolution model*). However, faint large scale radio structures have been also observed ((Stanghellini, Baum, O'Dea & Morris, 1990; Baum, O'Dea, de Bruyn & Murphy, 1990). This large scale radio emission is interpreted as being a relic of a previous activity phase, so the compact GPS source is rejuvenated and newly expanding. On the other hand the compact size of the source can also be due to confinement by a dense environment preventing the source expansion (*frustrated model*).

Because the classification of GPS sources is based on the shape of the radio spectrum which peaks at ~ 1 GHz, GPS samples are heterogeneous. Testing any physical model requires homogeneity, which can be achieved by for example separating GPS galaxies from quasars (Snellen et al., 2000) or using the Very Long Baseline Interferometry (VLBI) morphology by separating core-jet sources from the double or more complex sources (Stanghellini et al., 2001). The sources with large scale radio emission should also be identified within the samples, however this radio emission is usually faint and difficult to detect in the vicinity of the powerful radio source. The faint extended radio emission can often be not significant and confused with the noise (Siemiginowska et al., 2003). X-rays provide a confirmation of the large scale emission and a new way to differentiate sources and finally to understand the properties of the GPS sample.

While there has been an abundance of GPS radio data collected over the last decade, X-ray observations of GPS sources have been sporadic. Only one GPS galaxy was detected by *ASCA* (O'Dea et al., 2000), while the *ROSAT* PSPC observations of a few GPS quasars showed a relatively high absorbing columns toward the high redshift GPS quasars indicating a possible source of confinement (Elvis et al., 1994). There have been no systematic X-ray studies of GPS samples so far and there is no consistent picture of the X-ray

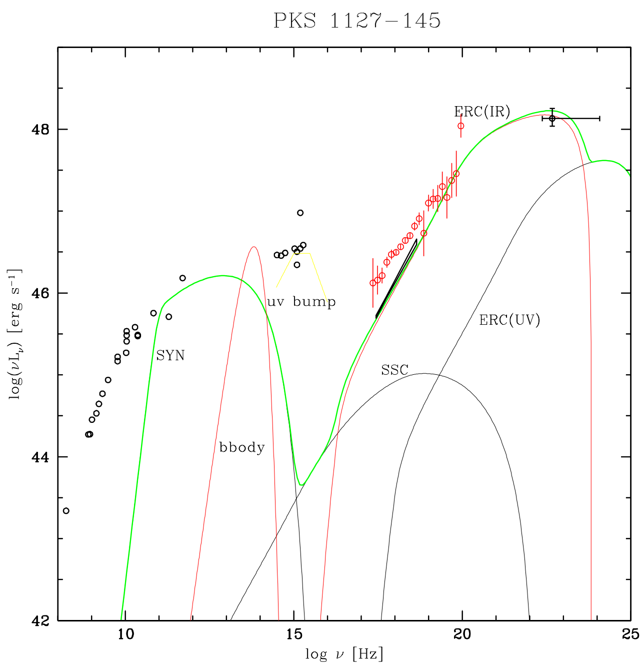

Figure 1: Spectral energy distribution of PKS 1127−145 (quasar at $z = 1.18$) and applied emission model: parsec scale jet electrons scatter infrared dust photons into X-rays. Components are indicated in the figure: SYN - synchrotron jet emission, SSC - synchrotron self-Compton, ERC(UV) - inverse Compton scattering of UV accretion disk photons, ERC(BEL) - inverse Compton scattering of the emission from Broad Emission Line clouds, ERC(IR) - inverse Compton scattering of infrared dust photons (Błażejowski et al., 2004).

properties of GPS sources.

The *Chandra* X-ray Observatory (*Chandra*) is the first X-ray mission with the spatial resolution enable to detect X-ray structures on arcsecond scales with a high dynamic range. We selected 11 sources from the complete sample of Stanghellini et al. (1998) to study their X-ray properties. The *Chandra* archive provides the X-ray data for an additional 7 sources. Our current GPS sample is not complete by any means, but provides a first look at the X-ray properties of these sources. Here we review the observations in the context of the connection between radio and X-ray emission. Is the X-ray emission from GPS sources also compact? Can *Chandra* detect any large scale X-ray emission associated with the GPS environment? Do GPS sources reside in clusters or groups? Do we detect excess absorption in the X-ray spectrum? Does the expanding radio source contribute to the X-ray emission?

2 X-ray observations

Chandra ACIS-S observations were planned in two different categories: (1) long exposures (> 10 ks) to allow detection of diffuse X-ray emission on arcsecond scales; (2) short observations (∼ 5 ks) to detect X-ray emission and obtain an X-ray flux for the sources with no previous X-ray detection. The X-ray analysis was performed in `CIAO 3.0.2` with the calibration files from `CALDB 2.25` data base. Note that the ACIS-S contamination file `acisD1999-08-13contamN0003.fits` was included in our analysis.

3 X-ray/radio connections

3.1 X-rays from an unresolved core

The *Chandra* observations indicate a variety of X-ray morphologies associated with GPS sources (see section below), but on larger scale (> 1″) than a typical compact GPS radio size. GPS sources have a complex radio morphology on milliarcsecond scales (jets, hot spots, core) which is not resolved in the X-ray band. Thus the GPS radio source is entirely embedded in the X-ray core. Does the expanding radio source contribute to the observed X-ray spectrum? The VLBI observations indicate relativistic motions associated with the expanding jet components. The X-rays could therefore be due to the synchrotron emission of the knots and hot spots, or self-Comptonization of the synchrotron emission within the jet. The X-rays can also result from inverse Compton scattering of the lower energy photons on the relativistic jet electrons. Can this emission exceed the emission directly related to accretion and dominate the X-ray spectrum?

The X-ray spectrum of PKS 1127−145 is most likely dominated by inverse Compton process in which the infrared photons are up-scattered to the X-ray band by the jet electrons (Błażejowski et al., 2004). Figure 1 shows a broad-band, radio to X-ray to γ-ray, spectrum of PKS 1127−145. Contributions from different jet emission components are indicated in this figure. The PKS 1127−145 X-ray emission is typical for a blazar, while the optical-UV emission is clearly dominated by a thermal emission from the accretion flow. This source constitutes an example of so-called *masquerading* blazar (Lister, 2003) which are contaminating GPS samples. The PKS 1127−145 has a core-jet VLBI morphology and ∼ 300 kpc (projected) radio and X-

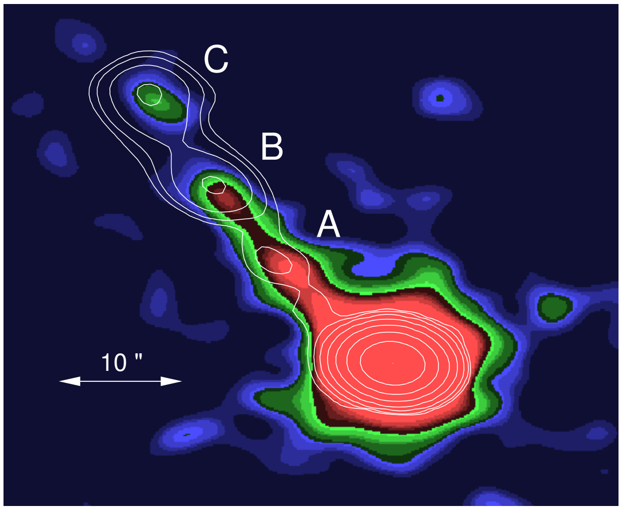

Figure 2: PKS 1127−145 X-ray color map overlaid with the low resolution 1.4 GHz radio contours. X-ray data have been smoothed to match the radio beam size. The X-ray peak intensities precede the radio for each knot (Siemiginowska et al., 2002).

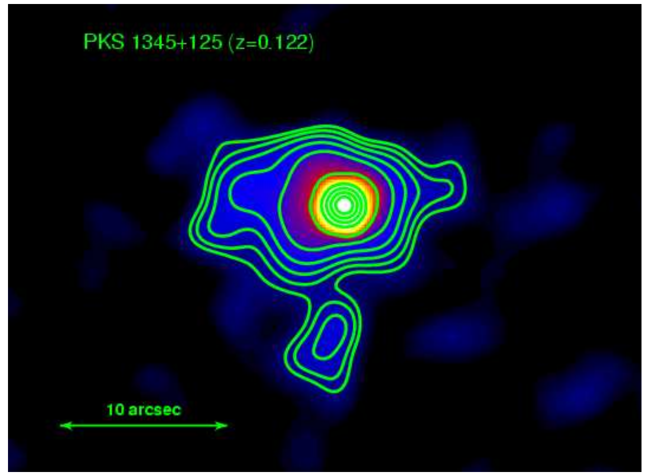

Figure 3: PKS B1345+125 *Chandra* X-ray color map overlaid with the X-ray contours for clarity. The X-ray data were smoothed with Gaussian function FWHM = 0.75″. The GPS radio source is embedded within the central core. The direction of the X-ray extension agrees with the VLBI jet propagating toward south-west (Stanghellini et al., 2001).

ray jet (Fig. 2 (Siemiginowska et al., 2002)). There must be a good fraction of sources with similar properties within GPS samples. They should be taken into account in studies of blazar evolution (Fossati et al., 1998). X-rays are critical to identifying these sources.

Disentangling the X-ray emission components requires good quality X-ray data. Emission associated with the reflection off cold/warm matter can be present in some sources, although separating different emission components is difficult. If intrinsic absorption is high the reflection can only be detected at higher energies ($\sim$ 4–10 keV), where the *Chandra* effective area decreases. GPS galaxies are likely to be highly absorbed and we find an equivalent Hydrogen column density of $N_H > 10^{22}$cm^{-2} in two galaxies (Siemiginowska et al. 2004, see also Guainazzi, Siemiginowska, Rodriguez-Pascual & Stanghellini (2004)). In contrast there is no significant absorption present in the observed GPS quasars. A larger X-ray sample is needed to confirm the difference in columns between GPS quasars and galaxies.

3.2 Large scale X-ray emission

We observe three types of large scale X-ray morphology associated with the GPS source: (1) an X-ray jet (Fig. 2); (2) a diffuse X-ray emission surrounding the source (Fig. 3) and (3) a secondary source within 10–20″(Fig. 4).

3.2.1 Jets

Many detections of large scale radio emission were not claimed significant before the corresponding X-ray detections. Do the radio and X-ray emission have the same morphology? How are these features related? A careful analysis of the radio data confirmed the presence of radio jets in PKS 1127−145 (Fig. 2 and B2 0738+380; Siemiginowska et al. (2003)). Both jets are similar in X-ray and radio, however there is no detailed correspondence between the radio and X-ray morphologies. The peak of the X-ray brightness precedes the peak of the radio brightness, as in other large scale jets observed in radio loud quasars (Sambruna et al. (2004); Siemiginowska et al. (2003). In addition in some jets the X-ray emission decreases along the jet while the radio emission increases with the distance from the core. The X-ray emission is modeled as the synchrotron emission from several populations of relativistic electrons or as a result of the inverse Compton scattering of the cosmic microwave background photons on relativistic electrons within the jet (see Stawarz, Sikora, Ostrowski & Begelman (2004) for the most recent review of the models). There is no confirming evidence favoring either of the two models. Detailed mapping between the X-ray and radio emission from the jets is the key to constraining models in the future.

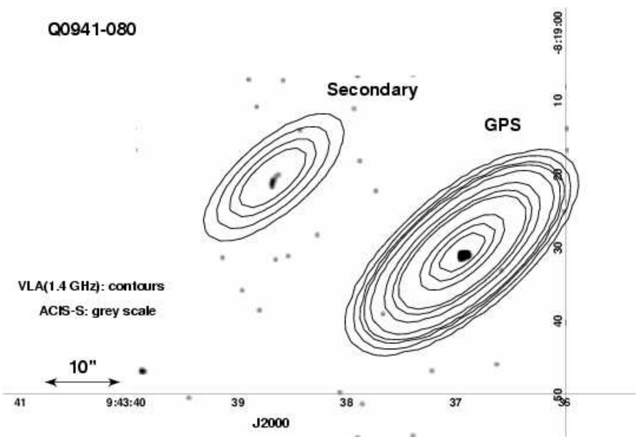

Figure 4: PKS 0941−080 Very Large Array 21 cm contours overlaid on the *Chandra* ACIS-S image smoothed with Gaussian function (FWHM = 0.75″).

A large scale jet associated with the GPS source may indicate that the source is similar to the other quasars, that it is a blazar, or that it had outbursts of radio activity in the past (Siemiginowska et al., 2002; Stawarz, 2004). Detailed studies of the X-ray and radio morphologies can discriminate between these possibilities.

3.2.2 Diffuse emission

The diffuse X-ray emission seen in PKS B1345+125 (Fig. 3) does not have corresponding radio emission present in the currently available radio data. This diffuse X-ray emission may originate as thermal emission associated with the cluster. The size of the extended X-rays is of order $\sim$ 100 kpc and it is located outside the host galaxy. The X-ray emission is usually elongated into the direction of the propagation of the milliarcsecond radio jet. In PKS B1345+125 (Fig. 3) the emission extends toward the South-West and agrees with the VLBI jet axis (Stanghellini et al., 2001), suggesting that it is somehow related to the expanding GPS source.

3.2.3 Binary

The secondary source in the vicinity of PKS 0941−080 (Fig. 4, z = 0.228) is identified by de Vries, O'Dea, Barthel & Thompson (2000) to be interacting with the GPS source. Some GPS sources show signatures of mergers, although at the same level as other active and non-active galaxies (de Vries et al., 2000). The *Chandra* observation of PKS 0941−080 was only $\sim$ 5 ks, i.e., good enough to detect both components, but not deep enough to study X-ray environment of this interacting system. This is the only interacting binary in the sample.

4 Summary and open questions

The present X-ray observations indicate that the GPS sources have several types of X-ray morphologies and that the X-ray observations are more efficient than radio in detecting large scale emission associated with the GPS sources. The large scale X-ray emission is common and can be related to the cluster, the jet or the secondary component possibly interacting with the GPS source. The X-ray detections provide a new way to diversify the GPS samples. However, we need to collect X-ray information for complete samples in order to attempt any statistical analysis. There are also several questions which we only begin to approach with these data:

- Is the observed nuclear X-ray emission related to the GPS radio source or directly related to the active galactic nucleus? We need good quality X-ray spectra to disentangle different emission component, especially assess the amount of reflection.
- Are large scale jets an indication of misclassified blazars? Or indication of the intermittency of the nucleus (Stawarz, 2004)? or both?
- Is the large scale diffuse X-ray emission a signature of the confining medium?
- We do not detect large absorption in the X-ray spectra of GPS quasars, however large columns are present in GPS galaxies (Guainazzi, Siemiginowska, Rodriguez-Pascual & Stanghellini, 2004). The absorption may indicate a dense environment affecting the jet expansion. This confuses calculations of expansion timescales and age estimates of the GPS radio sources.

We describe the connection between X-rays and radio emission in GPS sources. By studying the sources in both wave bands we may be able to understand the connection between large scale radio sources and the GPS sources. Future X-ray data can bring some answers to the above questions and provide an evidence to one of the models describing the nature of the GPS sources.

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