Extended X-ray emission in PKS 1718–649


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ABSTRACT

PKS 1718–649 is one of the closest and most comprehensively studied candidates of a young active galactic nucleus (AGN) that is still embedded in its optical host galaxy. The compact radio structure, with a maximal extent of a few parsecs, makes it a member of the group of compact symmetric objects (CSO). Its environment imposes a turnover of the radio synchrotron spectrum towards lower frequencies, also classifying PKS 1718–649 as gigahertz-peaked radio spectrum (GPS) source. Its close proximity has allowed the first detection of extended X-ray emission in a GPS/CSO source with Chandra that is for the most part unrelated to nuclear feedback. However, not much is known about the nature of this emission. By co-adding all archival Chandra data and complementing these datasets with the large effective area of XMM-Newton, we are able to study the detailed physics of the environment of PKS 1718–649. Not only can we confirm that the bulk of the ≲ kiloparsec-scale environment emits in the soft X-rays, but we also identify the emitting gas to form a hot, collisionally ionized medium. While the feedback of the central AGN still seems to be constrained to the inner few parsecs, we argue that supernovae are capable of producing the observed large-scale X-ray emission at a rate inferred from its estimated star formation rate.

Key words. galaxies: active – galaxies: nuclei – galaxies: individual: PKS 1718-649 – galaxies: ISM – galaxies: star formation – X-rays: galaxies

1. Introduction

With a turnover at around 4 GHz, PKS 1718–649 is a prominent representative of the class of gigahertz-peaked radio spectrum (GPS) sources (Tingay et al. 1997; Jauncey et al. 1998; Tingay & de Kool 2003). It is one of the closest sources of its kind, with only NGC 1052 and PKS 2254–367 being closer. Spectral variations of the radio continuum led Tingay et al. (2015) to argue for variable free-free absorbing (FFA) and ionized foreground material as opposed to synchrotron-self absorption (SSA) of jet-intrinsic plasma. High-spatial-resolution Very Long Baseline Interferometry (VLBI) observations at 22 GHz (Tingay & de Kool 2003) and 8.4 GHz (Ojha et al. 2004, 2010) consistently confirm a compact double structure of ≲10 mas diameter, that is, ≲3 pc at a luminosity distance of 64.3 Mpc (z = 0.014428 ± 0.000023; Meyer et al. 2004). This compact radio morphology with two distinct hot spots classifies PKS 1718–649 as a compact symmetric object (CSO). Tingay et al. (2002) provide an upper limit on the separation speed of ≲0.08 c. Together with the compact extent of the radio structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young. An extended jet (similar to NGC 1052) beyond the known parsec-scale jet structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young. An extended jet (similar to NGC 1052) beyond the known parsec-scale jet structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young. An extended jet (similar to NGC 1052) beyond the known parsec-scale jet structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young. An extended jet (similar to NGC 1052) beyond the known parsec-scale jet structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young. An extended jet (similar to NGC 1052) beyond the known parsec-scale jet structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young. An extended jet (similar to NGC 1052) beyond the known parsec-scale jet structure, this translates to an approximate age of ≳60 yr. At an age of only hundreds to thousands of years, CSOs, where small advance speeds of terminal hotspots have been constrained (Owsianik & Conway 1998), are therefore considered to be young.
observatories MeerKAT and SKA are able to probe. Moreover, PKS 1718–649 is the first young radio galaxy confirmed to be γ-ray bright (Migliori et al. 2016).

The inverted radio spectrum below a few gigahertz and the morphology of PKS 1718–649 shape the picture of an active galactic nucleus (AGN) embedded in a cocoon of ionized matter. Recently, Maccagni et al. (2014, 2016, 2018) also provided evidence for circumnuclear and clumpy molecular matter that is feeding the new-born AGN. While the line of sight is piercing this obscuring matter, both an inverted radio and photo-absorbed X-ray continuum are expected. Studying the X-ray emission alongside with the radio emission is therefore a valuable tool for a better understanding of the environment of this young AGN (see also Müller et al. 2016, 2015 for a radio and X-ray study of the other γ-ray loud young radio galaxy PMN J1603–4904). While we also provide measures for the X-ray continuum absorption, here we primarily concentrate on the X-ray emission detected from the environment of PKS 1718–649.

An exemplary CSO, where extended X-ray emission could be investigated with the unprecedented spatial resolution of Chandra in great detail, is NGC 1052 (Kadler et al. 2004; Boeck et al. 2012). Here, a double-sided radio jet reaches into the kiloparsec (kpc)-scale environment and is observed to align with collisionally ionized X-ray-bright gas. Siemiginowska et al. (2016) were the first to systematically study the X-ray signatures in a large number of CSOs. Within their sample, extended kiloparsec-scale X-ray emission could only be detected for the nearby source PKS 1718–649. To date, the lack of sufficient count statistics, however, has made it impossible to unveil the nature of this X-ray emitting gas. In this Letter, we present novel results from a recent XMM-Newton observation and a stack of three archival Chandra datasets, which combine the large effective area of XMM-Newton with the imaging capabilities of Chandra.

We use the cosmological parameters \( \Omega_m = 0.308 \), \( \Omega_L = 0.692 \), and \( H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Planck Collaboration XIII 2016) and find a correspondence of 1 arcsec \( \sim 312 \text{ pc} \).

### 2. Observations and data reduction

We base our analysis on four archival X-ray observations (three by Chandra and one by XMM-Newton, all listed in Table 1).

For all Chandra observations, the source is observed with the back-illuminated chip S3 of the ACIS-S CCD (Garmire et al. 2003). The VFAINT mode was used to most effectively screen cosmic ray events. We make use of CIAO v. 4.9.1 and CALDB v. 4.7.2 to reprocess event files with the task chandra_reproject and extract spectra using specextract from within regions of 14′′ radius around the source pointing center. We extract the background spectra from annuli of 30–44′′ radius. Pileup can be neglected after fitting an absorbed power-law based on the pileup-kernel in ISIS v. 1.6.2–40. Data are only extracted between 0.5 keV and 8 keV with maximal effective area. We rebin each Chandra spectrum to 4, 6, and 8 channels per bin within 0.5–1 keV, 3–5 keV, and 5–8 keV, respectively. That way the grid oversamples the spectral resolution by no more than a factor of three (Kaastra & Bleeker 2016). We exclude a point source at RA:17:23:42′′, Dec:−65′′00′′ 23′ and extract surface brightness profiles using dmextract with 15 annuli of 1′′ width and 0.5 \( + n \times \text{radius} \) (\( n = 0 \ldots 14 \)), each centered at the source center. The background from an annulus between 30′′ and 60′′ is subtracted from the profile. The Chandra PSF is simulated for the spectrum Ch 2 by combining 25 runs of ChaRT. For each realization, the PSF is projected onto the detector plane using MARX. The resulting angular resolution is limited by the detector pixel size of \( 0.5′′ \sim (\sim 156 \text{ pc}) \) at the given distance of PKS 1718–649.

We observed PKS 1718–649 using XMM-Newton/EPIC-pn (Villa et al. 1996; Meidinger et al. 1996; Strüder et al. 2001) in Large Window mode and extracted the count spectrum using SAS v.16.5.0. After creating calibrated event lists with filtered hot and bad pixels, events in the range 7–15 keV are screened for particle flaring with a threshold of 8 counts ks\(^{-1}\) arcmin\(^{-2}\). We extract source counts from a circular region of 40′′ radius for EPIC-pn and background counts from an off-source region of 49′′ radius. The task epatplot returns no signs for pileup and we consider all counts between 0.3 and 10 keV. Following the same strategy as for Chandra, we apply a geometrical binning with factors of 5, 6, 10 and 20 in the ranges 0.3–1.5 keV, 1.5–2 keV, 2–7 keV, and 7–10 keV, respectively.

### 3. X-ray image and spectral analysis

In order to quantify the extended and non-variable X-ray emission that has been detected by Siemiginowska et al. (2016) based on the Chandra observation Ch 1, we study a stacked image consisting of Ch 1 and the more recent observations Ch 2 and Ch 3. The stacking was performed using the standard CIAO task merge_obs. Figure 1 (left and right panels) shows that the bulk of the photons and in particular hard X-rays above \( \sim 1.5 \text{ keV} \) are emitted from the unresolved core region with an excess of \( \sim 60\% \) above the soft X-rays within a radius of 3′′. The PSF is encircling 99% of the point-source flux within \( \sim 3′′ \). In contrast, soft \( (\sim 0.3–1.5 \text{ keV}) \) X-ray emission exceeds that in the hard band by \( \sim 54\% \) in the extended region between \( 3′′ \) and \( 8′′ \).

Despite the unprecedented spatial resolution of Chandra, the soft-X-ray effective area of XMM-Newton makes up twice and ten-times the area of Chandra/ACIS at around 1 keV and 0.5 keV, respectively. We therefore fit the Chandra spectra combined with recently acquired XMM-Newton data to unveil the origin of the extended emission (see Fig. 2). The hard-X-ray data follow a common power-law of constant photon index \( (\Gamma = 1.78) \) that is absorbed towards lower energies. Given the limited number of counts, we are not sensitive to the continuum signatures of a possible ionized absorber and instead apply a model for neutral absorbing gas (tbabs). Above this continuum, XMM-Newton allows us to confirm an emission feature consistent with O vii around 0.56–0.57 keV and a broad emission complex around 0.7–0.9 keV, likely due to Ne and Fe (\( \sim 0.5–0.6 \text{ keV} \) and \( \sim 0.6–1.2 \text{ keV} \)). The former is described with the photoionized plasma component xstar (Bautista & Kallman 2000; Porquet & Dubau 2000; Bautista & Kallman 2001) for a nuclear irradiating power-law as measured, and an ambient gas density of \( 10^4 \text{ cm}^{-3} \) (Tingay et al. 2015). We find the ionization parameter to be log \( \xi = 0.04^{+0.13}_{-0.05} \). The latter broad feature is best described with emission of a collisionally ionized plasma \( (kT = 0.75^{+0.07}_{-0.08} \text{ keV}) \) using apec (Smith et al. 2001). This component dominates the soft X-rays and must therefore account for

### Table 1. List of the X-ray observations used in this Letter.

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Date</th>
<th>obsid</th>
<th>det</th>
<th>exp [ks]</th>
<th>cnts [( \times 10^2 )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch 1</td>
<td>2010-11-09</td>
<td>12849</td>
<td>ACIS-S</td>
<td>4.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Ch 2</td>
<td>2014-06-20</td>
<td>16070</td>
<td>ACIS-S</td>
<td>15.9</td>
<td>14.2</td>
</tr>
<tr>
<td>Ch 3</td>
<td>2014-06-23</td>
<td>16623</td>
<td>ACIS-S</td>
<td>33.0</td>
<td>35.3</td>
</tr>
<tr>
<td>XMM</td>
<td>2017-03-05</td>
<td>0784530201</td>
<td>EPIC-pn</td>
<td>20.3</td>
<td>50.7</td>
</tr>
</tbody>
</table>
Fig. 1. Left: difference map between the hard (1.5–10 keV) and soft (0.3–1.5 keV) band including counts of Ch 1, Ch 2, and Ch 3. Positive pixels (blue) depict a hard excess, negative pixels (red) a soft excess. Overlaid contours in black show \( \text{H}_2 \) 1–0 S(1) emission (Maccagni et al. 2016). Right: surface brightness profiles for the stacked map for the energy intervals 0.5–10 keV (black/circles), 0.3–1.5 keV (red/squares) and 1.5–10 keV (blue/triangles). The blue and red dashed lines show the \textit{Chandra} PSF normalized to the hard (1.5–10 keV) and soft (0.3–1.5 keV) X-ray profile. The yellow shaded section marks the extent of the map on the left.

Fig. 2. Panel a: unfolded spectra for the observations Ch 1, 2, and 3 and XMM in color with the individual model evaluations in black on top. The residuals are shown below. Panel b: model evaluations of the variable absorbed power law in color and the non-variable emission plasmas in gray (\texttt{xstar}) and black (\texttt{apec}).

Table 2. Best-fit parameters for the simultaneous fit of the data from Table 1.

<table>
<thead>
<tr>
<th>Abbrv.</th>
<th>pow norm</th>
<th>( \Gamma )</th>
<th>thabs ( N_H ) [(10^{22} \text{cm}^{-2})]</th>
<th>Flux (0.5–10 keV) [(10^{-13} \text{erg cm}^{-2} \text{s}^{-1})]</th>
</tr>
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<tr>
<td>Ch 1 ({1.1^{+0.3}<em>{-0.5}} \times 10^{-4}) &amp; (1.78^{+0.10}</em>{-0.09}) &amp; (0.53^{+0.11}_{-0.07}) &amp; 5.4</td>
<td></td>
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<tr>
<td>Ch 2 (2.2\pm 0.3 \times 10^{-4}) &amp; - &amp; (0.69^{+0.10}_{-0.06}) &amp; 9.9</td>
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<tr>
<td>Ch 3 (2.5\pm 0.3 \times 10^{-4}) &amp; - &amp; (0.55^{+0.11}_{-0.08}) &amp; 11.6</td>
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<tr>
<td>XMM (1.99^{+0.15}<em>{-0.10}) &amp; (1.04^{+0.14}</em>{-0.09}) &amp; (0.31^{+0.10}_{-0.06}) &amp; 5.8</td>
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</table>

Notes. All spectra are fitted with apec (norm 2.0\(^{+0.6}_{-0.5}\) \(\times 10^{-5}\); \(kT = 0.75^{+0.07}_{-0.05}\) keV) and \texttt{xstar} \(N_H = 1 \times 10^{22} \text{cm}^{-2}\) based on an ambient gas density of \(10^4 \text{cm}^{-3}\) and an assumed path length of 10 pc; see Tingay et al. (2015); \(\log \xi = 0.04^{+0.11}_{-0.05}\). The unit of the apec normalization is \(10^{-14}/\text{erg} \,(D_A(1+z))^2 \int n_e n_H dV\) (see the apec manual for details). Overall, we apply a redshift of \(z = 0.0144\) (Doyle et al. 2005) and a Galactic column density of \(5.7 \times 10^{20} \text{cm}^{-2}\) (Kalberla et al. 2005).

Besides the non-variable emission components \texttt{xstar} and apec, the only parameters that turn out to be variable (on time scales of years) are the source-intrinsic column density \(N_H = 0.3–0.7 \times 10^{22} \text{cm}^{-2}\) and flux of the incident hard X-ray power law \((5.4–11.6 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1})\). We use Cash statistics due to the low number of counts in Ch 1 and Ch 2. The simultaneous fit describes all four data sets well with \(C \, (\text{dof}) = 444 \,(439)\). The resulting parameters and uncertainties are listed in Table 2.

4. Discussion

We are able to report, for the first time in the literature, on variable X-ray absorption and on the physics of the extended X-ray emission in the CSO PKS 1718–649 that is for the most part unrelated to nuclear feedback. We stacked all archival \textit{Chandra} data available for this object, and analyzed the combined spectra of \textit{Chandra} and \textit{XMM-Newton}. Our results form a two-fold picture. The bulk of the unresolved core emission comprises Comptonized hard X-rays. The X-ray source may be a corona close to the accretion disc (e.g., Dove et al. 1997, and references therein), the parsec-scale radio jet, or its jet base

a significant portion of the extended emission in Fig. 1. The low source flux prevents a detailed line-diagnostic study with \textit{XMM-Newton/RGS}.

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Supernovae in the host galaxy are supported by the observation of active star formation in PKS 1718−649 via Hα and PAH (PolyCYclic Aromatic Hydrocarbon) emission (Kenneclit 1983; Maccagni et al. 2014; Willett et al. 2010). Sullivan et al. (2006) study star-forming host galaxies of 100 confirmed SNe Ia. Their results imply a SN rate of \(3.2 \times 10^{-2}\) galaxy\(^{-1}\) yr\(^{-1}\) for a galactic stellar mass of \(M_\odot \approx 4.9 \times 10^{11}\) \(M_\odot\) for PKS 1718−649 (Maccagni et al. 2014). When considering a SFR of \(0.8-1.9\) \(M_\odot\) yr\(^{-1}\) (Willett et al. 2010, using PAH signatures\(^1\)), Sullivan et al. (2006) infer a SN rate of \(0.7-1.3 \times 10^{-3}\) galaxy\(^{-1}\) yr\(^{-1}\). Very similar SN rates, namely \((4 \times 10^{-3}-4 \times 10^{-2})\) galaxy\(^{-1}\) yr\(^{-1}\), can explain the diffuse X-ray emission of M 81 (Shelton 1998; Page et al. 2003), which is classified as LINER as well (Heckman 1980). Moreover, the gas temperature that Page et al. (2003) determine for M 81 corresponds well to that measured in our work.

An independent indicator for the presence of SNe is given by the emission of different forms of hydrogen. While H\(_2\) in the ISM is generally too cold to emit, Maccagni et al. (2016) observe a disk-like distribution in the inner few arcseconds \((\lesssim 0.1\) kpc\) of PKS 1718−649. Roughly perpendicular to it, an outer disk of H\(_2\) at distances larger than 650 pc aligns with neutral H I (Maccagni et al. 2014) and H\(_\alpha\) (Keel & Windhorst 1991).

Among the several H\(_2\) excitation mechanisms at play (e.g., Maloney et al. 1996; Rodríguez-Ardila et al. 2004; Dors et al. 2012, and references therein), Maccagni et al. (2018) favor nuclear, non-thermal X-rays for the inner few parsecs. Besides that, shock excitation by the parsec-scale jet or nuclear UV radiation may also play a role in this compact environment. At larger distances of hundreds to thousands of parsecs, H\(_2\) appears co-spatial with and most likely excited by the warm and diffuse soft X-ray-emitting gas (Fig. 1), which we suggest to be due to the direct influence of SNe. The excitation can, however, to some smaller degree also arise due to nuclear UV/X-ray emission or UV photons of dense molecular star-forming regions (Puxley et al. 1990; Davies et al. 1998).

5. Conclusions

In this Letter, we investigated the nature of the extended X-ray emitting gas in PKS 1718−649. By stacking all archival Chandra data, we find this gas to primarily emit in soft X-rays. Our recent observation by XMM-Newton and its large effective area allow us to perform a detailed spectral analysis of this emission. Besides a photoionized (log \(\xi\) = \(0.4-0.6\)) gas phase on sub-parsec scales, the bulk of the soft X-rays is emitted by diffuse, hot \((T = (7.8-9.5) \times 10^6\) K\), and collisionally ionized gas that dominates the nuclear emission in the range \(\sim 1-2.8\) kpc. We argue that supernovae are plausible candidates to power this region as opposed to the overly compact parsec-scale jets of the young AGN. This conclusion is drawn from observations of active star formation in PKS 1718−649, estimates on the expected SN rate, as well as the theoretically predicted X-ray flux of SN remnants.

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\(^1\) PAH features at \(6.2\mu m\) \((EW = 0.04\mu m)\) and \(11.3\mu m\) \((EW = 0.13\mu m)\) are measured with Spitzer/IRS and a slit of \(11''\times168''\).
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