Extended X-ray emission in PKS 1718–649


1 Anton Pannekoek Institute for Astronomy, Universiteit van Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
e-mail: tobias.beuchert@sternwarte.uni-erlangen.de
2 Dr. Remise-Observatory & Erlangen Centre for Astroparticle Physics, Universität Erlangen-Nürnberg, Sternwartstrasse 7, 96049 Bamberg, Germany
3 Lehrstuhl für Astronomie, Universität Würzburg, Emil-Fischer-Straße 31, 97074 Würzburg, Germany
4 Laboratório Nacional de Astrofísica/MCTIC, Rua dos Estados Unidos, 154, Bairro da Nações, Itajubá, MG, Brazil
5 Instituto de Astrofísica de Canarias, C/Vía Láctea, s/n, 38206 La Laguna, Tenerife, Spain
6 Netherlands Institute for Radio Astronomy (ASTRON), PO Bus 2, 7990AA Dwingeloo, The Netherlands
7 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
8 GRAPPA & Anton Pannekoek Institute for Astronomy, Universiteit van Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
9 INAF-Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047 Selargius (CA), Italy
10 IMAPP/Department of Astrophysics, Radboud University, PO box 9010, 6500 GL Nijmegen, The Netherlands
11 NASA/GSFC, Mail Code: 661, Greenbelt, MD 20771, USA
12 Observatori Astronòmic, Universitat de València, Parc Científic, C. Catedrático José Beltrán 2, 46980 Paterna, València, Spain
13 Departament d’Astronomia i Astrofísica, Universitat de València, C. Dr. Moliner 50, 46100 Burjassot, València, Spain
14 International Centre for Radio Astronomy Research (ICRAR), Curtin University, Bentley, WA 6102, Australia

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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-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 VLBI structure of PKS 1718–649 seems unlikely. The ATCA data presented by Maccagni et al. (2014) are also consistent with a point source. Given the uv-coverage of the Murchison Widefield Array (MWA), we can spectrally exclude extended radio emission at hundreds of megahertz down to arcsecond scales. In the image plane, however, we are not sensitive to faint remnant radio structures on these scales – a regime that the future
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 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 $\Omega_m = 0.308$, $\Omega_{\Lambda} = 0.692$, and $H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration XIII 2016) and find a correspondence of 1 arcsec $\sim 312$ 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. 4.8.1 and CALDB v. 4.7.2 to reprocess event files with the task *chandra_repro* 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 rebinned 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:17h23m42s, Dec:−65°00′23′′ and extract surface brightness profiles using *dmextract* with 15 annuli of 1″ width and 0.5 $+ n^2$ 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 $0.5″ \sim 156$ 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. 8. 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 ects-keV1 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 *eptaplot* 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 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 keV) X-ray emission exceeds that in the hard band by $\sim$54% in the extended region between $\sim$3 and $\sim$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 ($Γ = 1.78$) 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 broadband emission complex around 0.7–0.9 keV, likely due to Ne and Fe xvi (Corcione & Kallman 2000; Porquet & Dubau 2000; Bautista & Kallman 2001) for a photoionized plasma component ($\xi = 0.04_{-0.05}^{+0.13}$). The latter broad feature is best described with emission of a collisionally ionized plasma ($kT = 0.75_{-0.08}^{+0.07}$ keV) using *apex* (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. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Abbv. | Date | obsid | det | exp [ks] | cnts $[\times 10^2]$ |
| Ch 1 | 2010-11-09 | 12849 | ACIS-S | 4.8 | 3.1 |
| Ch 2 | 2014-06-20 | 16070 | ACIS-S | 15.9 | 14.2 |
| Ch 3 | 2014-06-23 | 16623 | ACIS-S | 33.0 | 35.3 |
| XMM | 2017-03-05 | 0784530201 | EPIC-pn | 20.3 | 50.7 |

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

Besides the non-variable emission components 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 (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 Chandra data available for this object, and analyzed the combined spectra of Chandra and 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...
 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 (Kennicutt 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 × 10−2 galaxy−1 yr−1 for a galactic stellar mass of M∗ ≈ 4.9 × 1011 M⊙ for PKS 1718−649 (Maccagni et al. 2014). When considering a SFR of ∼0.8–1.9 M⊙ yr−1 (Willett et al. 2010, using PAH signatures), Sullivan et al. (2006) infer a SN rate of ∼0.7–1.3 × 10−3 galaxy−1 yr−1. Very similar SN rates, namely (4 × 10−3–4 × 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 H2 in the ISM is generally too cold to emit, Maccagni et al. (2016) observe a disk-like distribution in the inner few arcseconds (∼skpc) of PKS 1718−649. Roughly perpendicular to it, an outer disk of H2 at distances larger than 650 pc aligns with neutral H I (Maccagni et al. 2014) and Hα (Keel & Windhorst 1991). Among the several H2 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, H2 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 ε = 0.04−0.05) gas phase on sub-parsec scales, the bulk of the soft X-rays is emitted by diffuse, hot (T = (7.8–9.5) × 106 K), and collisionally ionized gas that dominates the nuclear emission in the range ∼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 driven 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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