Complex Structure of the Eastern Lobe of the Pictor A Radio Galaxy: Spectral Analysis and X-Ray/Radio Correlations

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Abstract

Here we present detailed analysis of the distinct X-ray emission features present within the eastern radio lobe of the Pictor A galaxy, around the jet termination region, utilizing the data obtained from the Chandra X-ray Observatory. Various emission features have been selected for the study based on their enhanced X-ray surface brightness, including five sources that appear pointlike, as well as three extended regions, one characterized by a filamentary morphology. For those, we perform a basic spectral analysis within the 0.5–7 keV range. We also investigate various correlations between the X-ray emission features and the nonthermal radio emission, utilizing the high-resolution radio maps from the Very Large Array at gigahertz frequencies. The main novel findings following from our analysis concern the newly recognized bright X-ray filament located upstream of the jet termination region, extending for at least 30 kpc (projected), and inclined with respect to the jet axis. For this feature, we observe a clear anticorrelation between the X-ray surface brightness and the polarized radio intensity, as well as a decrease in the radio rotation measure with respect to the surroundings. We speculate on the nature of the filament, in particular addressing a possibility that it is related to the presence of a hot X-ray-emitting thermal gas, only partly mixed with the nonthermal radio/X-ray-emitting electrons within the lobe, combined with the reversals in the lobe’s net magnetic field.

Unified Astronomy Thesaurus concepts: Non-thermal radiation sources (1119); Radio galaxies (1343); Relativistic jets (1390); X-ray active galactic nuclei (2035)

1. Introduction

Pictor A, classified as a broad-line radio galaxy (BLRG) with a “classical double” (Fanaroff–Riley type II) large-scale radio morphology (Simkin et al. 1999), and located at the redshift \( z = 0.035 \) (Eracleous & Halpern 2004), is one of the most prominent radio galaxies in the sky, and has become the prime target for detailed multiwavelength investigations in recent decades, from radio to X-ray ranges. More recently, it has also been confirmed as a source of high-energy \( \gamma \)-rays in the Fermi Large Area Telescope (LAT) all-sky survey (Kataoka et al. 2011; Brown & Adams 2012; Ackermann et al. 2015).

The large-scale radio/X-ray jet in Pictor A originates in the galaxy’s nucleus, and extends up to hundreds of kiloparsecs beyond the host galaxy to the west (Perley et al. 1997); the counterjet is not prominent at radio frequencies, but can be spotted in deep X-ray maps by the Chandra X-ray Observatory (Hardcastle & Croston 2005). The hotspots located at both sides of the core at the lobes’ edges mark the termination points of the jet (to the west) and of the counterjet (to the east); the bright western (W) hotspot is clearly detected and even, in some cases, resolved at radio, infrared, optical, and X-ray frequencies (Roeser & Meisenheimer 1987; Thomson et al. 1995; Perley et al. 1997; Wilson et al. 2001; Werner et al. 2012; Isoye et al. 2017; Thimmappa et al. 2020). The radio lobes appear in X-rays as a low-surface brightness cocoon surrounding the large-scale jets (Grandi et al. 2003; Hardcastle & Croston 2005; Migliori et al. 2007; Hardcastle et al. 2016).

Extended lobes in radio galaxies and radio quasars, formed as backflows when the jet plasma passes through the termination shock and is turned away at the contact discontinuity between the shocked outflow and the shocked ambient (intergalactic) medium, are particularly prominent at radio frequencies, due to the synchrotron emission of ultrarelativistic electrons. Detailed radio studies of the lobes with an arcsecond angular resolution often reveal a complex morphology with filamentary structures and tangled polarization patterns (e.g., Carilli & Barthel 1996; Perley et al. 1997; Feain et al. 2011; Anderson et al. 2018). The X-ray observations of the lobes, carried out with high-angular-resolution modern instruments such as Chandra or XMM-Newton, allow for the detection of the nonthermal power-law (PL) continuum; due to the inverse Comptonization of the cosmic microwave background radiation by the lobes’ electrons; this gives the volume-averaged magnetic field intensities of the lobes at the level of the equipartition values, namely \( B \sim 1-10 \, \mu G \) (see Croston et al. 2005; Kataoka & Stawarz 2005, and references therein). During the last decade, some of the most prominent and extended lobes in nearby radio galaxies have been also resolved in high-energy \( \gamma \)-rays by Fermi-LAT (Abdo et al. 2010; Katsuta et al. 2013; Ackermann et al. 2016).

Lobes are expected to be extremely low-density but high-pressure envelopes surrounding (and confining) the jets. As “calorimeters” for the jet power deposited over the source lifetime, they are believed to be filled solely by ultrarelativistic electrons and a magnetic field, with the total internal energy equal to that of the jet’s bulk kinetic energy (e.g., Begelman & Cioffi 1989). However, several observational findings have recently been reported of large amounts of a thermal gas within the lobes, providing a prominent contribution to the X-ray radiative output and the pressure balance of the systems (O’Sullivan et al. 2013; Setal et al. 2013; Stawarz et al. 2013; Wykes et al. 2013).

In this paper, we analyze the archival Chandra data for the extended lobes in Pictor A, focusing in particular on the eastern (E) lobe and the complex E hotspot region; the bulk of the analysis is based on the single pointing ObsID 14357, with the 49 ks exposure (see Hardcastle et al. 2016 for a summary of all
Table 1
Chandra Observations Used in Our Analysis of the E lobe in Pictor A

| ObsID | Date (YYYY-MM-DD) | MJD | Exposure (ks) | Detector |
|-------|-------------------|-----|--------------|----------|
| 346   | 2000-01-18        | 55,177 | 14.3 | ACIS-235678 |
| 12039 | 2009-12-07        | 55,174 | 17.3 | ACIS-235678 |
| 12040 | 2009-12-09        | 55,177 | 14.3 | ACIS-235678 |
| 11586 | 2009-12-12        | 56,095 | 49.3 | ACIS-235678 |
| 14357 | 2012-06-17        | 56,674 | 45.4 | ACIS-235678 |
| 14222 | 2014-01-17        | 57,031 | 26.8 | ACIS-235678 |
| 16478 | 2015-01-09        | 57,032 | 18.6 | ACIS-235678 |

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1 The authors thank R. Perley for kindly providing all the radio maps which are presented and analyzed in this paper.

2 The polarization degree
Figure 1. Top: Merged-counts image of the Pictor A radio galaxy for the selected eight Chandra observations listed in Table 1 in the energy range 0.5–7.0 keV with native 0\arcsec.492 pixels. Note a much reduced exposure toward the E lobe when compared to the W lobe. Middle: Exposure-corrected merged Chandra image, smoothed with a 3\sigma Gaussian radius, revealing the bright core, the jet extending to the northwest from the core, the W hotspot, the weak counterjet to the southeast, the E hotspot region, and the surrounding diffuse lobes. Bottom: Same as in the middle panel, but with the point and compact sources (denoted by white contours) detected with the wavdetect tool using the minimum PSF method; different sizes of the point/compact sources across the field reflect the varying PSF and/or sources extension.
for both lobes is relatively high, $\sim 10\%$--$20\%$, increasing up to even $\sim 60\%$--$70\%$ at the lobes’ edges and at the position of the hotspots. The lobes’ spectral index between 0.33 GHz and 1.45 GHz is on average 0.8, with some pronounced variations and generally larger values within the E lobe.

In the upper panel of Figure 2 we show the VLA total intensity $L$-band contours of Pictor A, superimposed on the spectral index map between the $L$ and $C$ bands, with a $10''$ resolution (throughout the paper we use the convention $S_\nu \propto \nu^{-\alpha}$, where $S_\nu$ is the flux density, $\nu$ is the observed frequency, and $\alpha$ is the spectral index). In the lower panel of the figure, we present the polarized intensity $L$-band contours of the source, superimposed on the distribution of the RM taken between $L$- and $C$-band data, with a $10''$ resolution. All of the radio images presented here were made based on the original data analysis by Perley et al. (1997); likewise the
radio flux profiles discussed in Section 3.2 below were calculated based on VLA maps provided directly by R. Perley. As shown, the structure of the E lobe around the jet termination region, and in particular upstream of the E hotspot, appears particularly complex on the polarized intensity and RM maps, and this complexity is not obviously reflected in the total intensity, or the spectral index maps. Below we argue that there indeed is a correspondence between the polarization radio maps and the X-ray Chandra map of this region.

3. Analysis Results

In Figure 3 we present a zoomed-in view of the RM distribution within the E hotspot region in Pictor A with the 1.45 GHz polarized intensity contours superimposed (top panel), as well as of the corresponding 0.5–7.0 keV Chandra image with the 1.45 GHz polarized intensity contours superimposed (note that in the bottom panel, radio contours start only from the 3σ confidence level for clarity). The images reveal several interesting features we emphasize below:
1. The double structure of the hotspot—which is in fact often observed in classical doubles (see, e.g., Carilli & Barthel 1996)—is prominent in both the total radio intensity and polarized radio intensity maps. The so-called “secondary” hotspot, i.e., the most prominent and outermost radio feature to the east, coincides with some enhancement in the diffuse X-ray emission, but nonetheless appears dramatically weaker at keV photon energies than the W hotspot on the other side of the nucleus; this secondary hotspot is selected for our Chandra spectral analysis as the extended region “C” (overlapping with the region R2 in Hardcastle et al. 2016). We do not analyze the spectrum of the “primary” hotspot, i.e., of the more compact radio feature located upstream (to the west) from the secondary (see region R1 in Hardcastle et al. 2016). Note the different values of the RM for both features, namely \( \sim 50 \) rad m\(^{-2}\) and \( \sim 80 \) rad m\(^{-2}\) for the secondary and primary, respectively.

2. There are several bright point/compact X-ray sources in close vicinity to the double E hotspot (see the bottom panel in Figure 1), none of which coincides however with the peaks of either the total or polarized radio intensity. For our spectral analysis, we select four such distinct regions, labeled as P2–P5 (three of which overlap with the bright compact X-ray sources X1, X2, and X3 in Hardcastle et al. 2016; see Table 2). On the polarized radio intensity maps, all of these happen to be located almost exactly at the edges of the hotspot’s double structure (corresponding to the 3\( \sigma \) confidence level contours). We emphasize that the bright compact X-ray source region P5 lies well outside the radio intensity on high-resolution total intensity maps.

3. A high-polarized-intensity feature extends to the north from the hotspot, terminating in the moderately prominent spot with some enhanced level of diffuse X-ray emission; this spot is selected for our analysis as the extended region “B”.

4. Upstream of the entire double structure of the E hotspot another prominent and extended feature can easily be seen on the polarized intensity map, which in addition seems to be surrounded by an arc of a sharp RM gradient (\( \Delta \text{RM} \sim 50 \) rad m\(^{-2}\)). A particularly bright point/compact X-ray source is located at the southern edge of the feature; this source is selected for our spectral analysis as region “P1”. Meanwhile, the northeastern edge of the feature is surrounded by a prominent enhancement of the diffuse X-ray emission, appearing as an elongated filament that runs in between high-polarized-radio-intensity domains; this filament is selected for our spectral analysis as region “A”. Note that the filament coincides with the local minimum in the RM distribution (\( \sim 20 \) rad m\(^{-2}\)). The radio continuum at the position of the filament appears marginally steeper when compared with its surroundings (spectral index \( \sim 0.9 \) versus \( \sim 0.8 \)), although such a minor difference seems rather insignificant taking into account the dynamic range artifacts present on the spectral index map (see the top panel in Figure 2).

3.1. Chandra Spectral Analysis

Due to the limited or even very-limited photon statistics, the ObsID 14357-extracted, unbinned spectra of all the selected source regions specified above and listed in Table 2 were fitted simultaneously along with the background within the 0.5–7.0 keV range, using the C-stat fitting statistics and the Nelder–Mead or Levenberg–Marquardt optimization methods, assuming simple PL models for each (with Galactic absorption only). The background was chosen as an extended polygon located just outside of the E lobe and encompassing the E hotspot region, avoiding bright point sources. The results of the fitting are summarized in Table 2.

### Table 2

| Region | Size\[^a\] [px] | Photon index \( \Gamma \) | Energy Flux \( F_{0.5-7.0 \text{keV}} \) [10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\)] | Counts\[^b\] |
|--------|-----------------|----------------|-----------------------------|--------|
| src A  | 40/24           | 1.70\(^{+0.23}_{-0.21}\) | 21.19\(^{+1.35}_{-1.53}\) | 219    |
| src B  | 22              | 1.89\(^{+0.46}_{-0.44}\) | 4.86\(^{+1.74}_{-1.34}\) | 68     |
| src C (R2)\[^c\] | 28/13         | 2.17\(^{+0.02}_{-0.03}\) | 5.59\(^{+1.52}_{-1.22}\) | 66     |
| src P1 (X1)\[^c\] | 6              | 2.21\(^{+0.34}_{-0.37}\) | 5.07\(^{+1.94}_{-1.15}\) | 41     |
| src P2 (X2)\[^c\] | 6              | 2.15\(^{+0.42}_{-0.39}\) | 3.56\(^{+0.19}_{-0.10}\) | 27     |
| src P3  | 6              | 0.47\(^{+0.07}_{-0.04}\) | 4.55\(^{+0.08}_{-0.07}\) | 12     |
| src P4 (X3)\[^c\] | 6              | 1.13\(^{+0.30}_{-0.31}\) | 7.85\(^{+1.41}_{-1.11}\) | 38     |
| src P5  | 6              | 1.02\(^{+0.58}_{-0.57}\) | 3.11\(^{+1.51}_{-0.53}\) | 12     |
| Background | … | 0.27\(^{+0.03}_{-0.03}\) | … | …     |

#### Notes.
\[^a\] Radius in the case of a circle, and major/minor semi-axes in the case of an ellipse; note the conversion scale 0.492\(^{a}\)/px.
\[^b\] Total number of counts within the 0.5–7.0 keV range.
\[^c\] The corresponding/overlapping regions in Hardcastle et al. (2016).

### Table 3

| Model\[^a\] | Parameter | Value with 1\( \sigma \) Errors | C-stat./DOF |
|------------|-----------|----------------------------------|------------|
| Power law  | Photon index \( \Gamma \) | 1.71\(^{+0.24}_{-0.22}\) | 1077.31/888 |
| PL normalization | 4.37\(^{-0.56}_{+0.52}\) \times 10\(^{-6}\) | 0.25\(^{-0.08}_{+0.08}\) |
| Background photon index \( \Gamma_{\text{bck}} \) | 6.44\(^{-0.56}_{+0.57}\) \times 10\(^{-6}\) | 1079.54/888 |

APEC   | Temperature \( kT \) | 8.22\(^{+12.18}_{-3.20}\) | 1074.3/886 |
| APEC normalization | 1.78\(^{-0.25}_{+0.26}\) \times 10\(^{-5}\) | 0.26\(^{-0.08}_{+0.08}\) |
| Background photon index \( \Gamma_{\text{bck}} \) | 6.52\(^{-0.56}_{+0.57}\) \times 10\(^{-6}\) | 1074.3/886 |

#### Note.
\[^a\] All the models include the Galactic hydrogen column density \( N_{\text{H,Gal}} = 4.12 \times 10^{20} \) cm\(^{-2}\); the thermal model assumes one-third solar abundance.
As follows, the region A appears harder within the Chandra range when compared with the other extended regions selected for the analysis, in particular with the secondary hotspot C, but the difference in the best-fit photon index ($\Gamma \approx 1.7 \pm 0.2$ versus $\approx 2.2^{+0.6}_{-0.5}$) is not statistically significant. The point/compact sources P1 and P2 are characterized by relatively steep X-ray continua ($\Gamma > 1.8$ within the errors), while the remaining sources P3–P5 appear very hard ($\Gamma < 1.5$ within the errors), especially P3, although here the photon statistics are particularly poor. We note that Hardcastle et al. (2016) obtained the spectral index $1.76 \pm 0.10$ for the “whole E hotspot region”, and $1.80 \pm 0.12$ when excluding X1 (=P1) and X3 (=P4) point/pointlike sources.

The total number of 219 counts detected from the A region allows us to attempt a more detailed spectral modeling, and in particular to confront the most basic thermal and nonthermal emission models. With this goal in mind, we exclusively fit the ObsID 14357 spectrum for region A together with the background (same as before), assuming either the power-law emission model, the Astrophysical Plasma Emission Code (APEC) model, or a combination of the two; in the APEC model, we freeze the abundance at 0.3 of the solar value. The resulting best-fit parameters are summarized in Table 3, and the background-subtracted modeled spectrum corresponding to the power-law + APEC fit is shown in Figure 4.

As follows, the goodness of all the three fits is comparable in terms of the reduced statistics, but the gas temperature in the single APEC model is basically unconstrained, $kT > 5.0$ keV; for this reason, we do not consider a pure thermal model as plausible. A combination of the power-law and APEC components, on the other hand, returns a rather reasonable gas temperature $kT \approx 0.3 \pm 0.1$ keV, though it implies at the same time a rather flat nonthermal continuum, with $\Gamma \approx 1.3^{+0.3}_{-0.4}$. The corresponding confidence contours for the model parameters $\Gamma$ and $kT$, as well as $\Gamma$ and the APEC normalization, are presented in Figure 5 (upper and lower panels, respectively). All in all, we conclude that while the presence of a thermal-X-ray-emitting gas within the analyzed filamentary region A—in addition to the nonthermal population of electrons emitting inverse Compton X-rays—is allowed by the data, it is not, strictly speaking, required or even favored by the spectral modeling.

3.2. The Surface Brightness Profile

In Figure 6, we present again the exposure-corrected 0.5–7.0 keV merged Chandra image of the entire structure of Pictor A, with the 1.45 GHz VLA polarized intensity (3$\sigma$) contours superimposed. The two elongated red rectangles denote the areas across the high-polarization regions of the E lobe, for which we extracted the surface brightness profiles at X-ray and radio frequencies. The “Profile 2” region includes the double structure of the E hotspot, while the “Profile 1” region includes the X-ray filament A.

The Profile 1 region, rotated by $\theta = 335^\circ$ using dmregrid, is divided into 16 vertical boxes, as indicated in the upper panel of Figure 7. X-ray counts were extracted from the merged Chandra map within the energy range 0.5–7.0 keV (binsize = 1), summed for each box, and then converted to the surface brightness units as recommended by the CIAO 4.13 Science Threads. The total and polarized radio flux densities for the corresponding segments of the lobe were calculated based on the 1.45 GHz VLA maps; polarization degree was calculated as a ratio of the polarized and total intensities. The resulting profiles are presented in the three lower panels of Figure 7. In an analogous way, we calculated the X-ray and

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Figure 4. The background-subtracted Chandra 0.5–7.0 keV spectrum for the selected source region A, binned with signal-to-noise ratio = 3 and fitted with a two-component power-law+APEC model. See Table 3 for the corresponding best-fit model parameters.
radio profiles also for the Profile 2 rectangular region, divided into eight vertical boxes, and rotated by $\theta = 360^\circ$; see Figure 8.

Figure 7 reinforces our main observational finding stated above that the prominent X-ray filament A runs in between high-polarization radio domains: while the total radio intensity peak ($\lesssim 0.2$ Jy) coincides roughly with the integrated X-ray surface brightness maximum, the polarized radio flux peak ($\sim 0.08$ Jy) is located upstream of the X-ray maximum. As a result, the degree of radio linear polarization increases from about 25% at the position of the X-ray filament, up to about 45% at the filament’s edges.

The surface brightness profiles shown in Figure 8 should be taken with caution, due to the fact that the integrated X-ray fluxes here are affected by the presence of the point/compact X-ray sources P2, P3, and P5. Still, we note a much better match between the total and polarized radio fluxes in this case (as compared with Profile 1), with both peak maxima shifted downstream (i.e., to the east) with respect to the X-ray surface brightness maxima; also, we note that the primary and secondary hotspots in general display a very high degree of radio polarization, at the level of $\sim 40\%-50\%$.

4. Discussion and Conclusions

The relationship of pointlike/compact X-ray features with no optical counterparts to the radio lobes and especially to hotspot regions of radio galaxies and radio quasars is often unclear and subject to speculation (see the discussion in, e.g., Hardcastle et al. 2007). Such features may simply be unrelated background active galactic nuclei, but may also result from various energy dissipation processes taking place within the lobes with a complex magnetic field structure. For example, Stawarz et al. (2013) speculated that if the lobes’ radio filaments do indeed represent tangled magnetic field tubes (O’Neill & Jones 2010), then at the places of the filaments’ interactions with density or magnetic enhancements in the
surrounding plasma localized multiple compact sites of violent reconnection may form, loading turbulence and in this way enabling efficient particle acceleration and plasma heating.

Among the point/compact X-ray sources P1–P5 analyzed here, none possess any obvious optical counterpart. However, the steep-spectrum P1 spot coincides exactly with the midinfrared (MIR) source listed in the CatWISE2020 Catalog (Marocco et al. 2021), which includes objects selected from the Wide-field Infrared Survey Explorer (Wright et al. 2010) and NEOWISE (Mainzer et al. 2014) all-sky survey at 3.4 and 4.6 μm (W1 and W2), conducted between 2010 and 2018. In fact, in the same catalog, possible MIR counterparts to P4 and P5 may also be noted (each with a separation below 6″). However, no MIR features have so far been detected at and around the positions of P2 and P3, and so we believe that at least those two spots may be plausible candidates for lobe-related compact X-ray structures. We note in this context that the two spots are located just upstream of the primary and secondary hotspots, respectively. In addition, P3 seems extremely hard in X-rays, as revealed by our spectral modeling despite very low photon statistics (photon index $\Gamma < 1.2$ within the errors; see Table 2), while P2 seems partly resolved by Chandra (see Hardcastle et al. 2016).

The main findings following from the analysis presented in this paper concern, however, the elongated X-ray filament A, located upstream of the jet termination region, extending for at least 30 kpc (projected), and inclined with respect to the jet axis. Its 0.5–7.0 keV radiative output is consistent with a pure power-law emission with a photon index $\Gamma \approx 1.7 \pm 0.2$, or alternatively a combination of a flat power-law component with $\Gamma \approx 1.3 \pm 0.3$ and a thermal $kT \approx 0.3 \pm 0.1$ keV plasma. In the former case, the X-ray slope would be consistent (within the errors) with the slope of the radio continuum at the position of the filament. The latter case would, on the other hand, be in accordance with recent findings of a larger amount of a thermal gas within the radio lobes of radio galaxies (Stawarz et al. 2013; O’Sullivan et al. 2013).

It is interesting to note in this context a scenario proposed by Anderson et al. (2018), in which the low-polarization regions associated with the magnetic field’s line-of-sight reversals, as observed within the radio lobes of the Fornax A galaxy, are due to thermal matter with mass $\mathcal{O}(10^9 M_\odot)$ distributed within thin shells or filaments. It is possible that the observed characteristics of the X-ray filament A in the E lobe of Pictor A, as presented in this paper, conform to this particular model. The degree of the radio linear polarization does increase from about 25% at the filament’s axis up to about 45% at the filament’s edges, and this could indeed be due to the depolarization related to the thermal (X-ray-emitting) gas present within the filament. But at the same time the filament also coincides with the local minimum in the RM distribution, and this would then imply that the magnetic field increases its net out-of-line-of-sight component, at the expense of the net line-of-sight component $B_{\parallel}$, since $\text{RM} \propto \int B_{\parallel} \cdot d\vec{r} \sim 0.8 (n_e/10^{-3} \text{ cm}^{-3}) (B_{\perp} / \mu G) (L / \text{pc}) \text{ rad m}^{-2}$, where $n_e$ stands for the gas electron number density, $B_{\perp}$ is the magnetic field intensity vector, and the integration $d\vec{r}$ is over the path length through the plasma.

For a rough estimate in this context, let us approximate the X-ray filament A by an elongated ellipsoid with the major axis $a \approx 80$ px $\sim 27.5$ kpc, and the minor axis $b \approx 48$ px $\sim 16.5$ kpc. The volume then reads as $V = \frac{4}{3} \pi (a/2)(b/2)^2 \sim 10^{68}$ cm$^3$, and—given the APEC normalization provided in Table 3—the thermal gas electron density $n_e \sim [5 \times 10^{-6}] 4\pi d_l^2 / 10^{-14} (1 + z)^2 \mu V_{1/2} \sim 3.8 \times 10^{-3}$ cm$^{-3}$, assuming uniform ionized plasma with the ratio of proton-to-electron number

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**Figure 6.** The exposure-corrected 0.5–7.0 keV merged Chandra image of the entire structure of Pictor A, smoothed with a 3σ Gaussian radius, with the 1.45 GHz VLA polarized intensity (3σ) contours superimposed. The two elongated red rectangles denote the areas across the high-polarization regions of the E lobe, for which we extracted the surface brightness profiles at X-ray and radio frequencies.
Figure 7. Top: the Profile 1 rectangular region, rotated by $\theta = 335^\circ$, and divided into 16 vertical boxes. Middle top: the X-ray photon fluxes per unit area (filled circles), and the polarized radio flux densities (empty circles), integrated over each box. Middle bottom: the X-ray photon fluxes per unit area (filled circles), and the total radio flux densities (empty circles), integrated over each box. Bottom: the X-ray photon fluxes per unit area (filled circles), and the degree of radio polarization (empty circles), integrated over each box.
Figure 8. Top: the Profile 2 rectangular region, rotated by $\theta = 360^\circ$, and divided into eight vertical boxes. Middle top: the X-ray photon fluxes per unit area (filled circles), and the polarized radio flux densities (empty circles), integrated over each box. Middle bottom: the X-ray photon fluxes per unit area (filled circles), and the total radio flux densities (empty circles), integrated over each box. Bottom: the X-ray photon fluxes per unit area (filled circles), and the degree of radio polarization (empty circles), integrated over each box.
densities $\mu \equiv n_{HI}/n_e \simeq 0.82$. This corresponds to the total mass in the filament $M \simeq m_p \mu n_e V \sim 3 \times 10^4 M_\odot$, which is in a very good agreement with the model by Anderson et al. (2018). Moreover, the total pressure of the thermal gas, $p_e = n_e k T \simeq 1.6 \times 10^{-12}$ dyn cm$^{-2}$, would be then comparable to that of the lobes’ magnetic field for the magnetic field intensity $B \simeq 6 \mu G$, which is, in fact, very close to the equipartition value, i.e., the value obtained by assuming pressure balance between ultra-relativistic radio-emitting electrons and the lobes’ magnetic field. We note in this context that, based on the inverse Compton modeling of the observed X-ray emission, Hardcastle et al. (2016) have estimated the mean magnetic field strength in the extended lobes of Pictor A as $(B) \approx 4 \mu G$, which is a factor of 1.5 below the equipartition level.

With the above estimates, one can show that the depolarization effect due to the RM dispersion in the beam, related to the tangled magnetic field (Burn 1966; Laing 1984). The $\sigma_{RM}$ parameter can be estimated by assuming that the Faraday screen consists of cells of coherent magnetic field with the size scale $d$, and that all the dispersion comes from the line-of-sight field reversals, so that the product of the gas density and $B_l$ is roughly equal to $n_e \times (B)$ (see van Breugel et al. 1984; Knuettel et al. 2019). This gives us

$$\sigma_{RM} \approx 0.081 \left( \frac{n_e}{\text{cm}^{-3}} \right) \left( \frac{(B)}{\mu G} \right) \times \left( \frac{d}{\text{kpc}} \right)^{1/2} \left( \frac{R}{\text{kpc}} \right)^{1/2} \text{rad cm}^{-2},$$

where $R$ is the depth of the screen. Hence, taking $n_e \simeq 3.8 \times 10^{-3}$ cm$^{-3}$, $(B) \approx 4 \mu G$, as well as—for illustrative purposes—$R \sim 16.5$ kpc (i.e., the maximum size of the screen) and $d = 0.7$ kpc (i.e., 10% of the resolution), we obtain $2\sigma_{RM} \lambda^2 \sim 7$ at $\lambda = 21$ cm, and $\sim 0.05$ at $\lambda = 6$ cm, meaning that the 21 cm lobes’ radio emission may be substantially depolarized by the thermal magnetized gas within the filament.

Clearly, a thermal model for the X-ray filaments within extended lobes of radio galaxies is not the only plausible scenario. For example, keeping in mind that such lobes may be acceleration sites of ultra-high-energy cosmic rays (UHECRs; see the discussion in, e.g., Hardcastle et al. 2009; O’Sullivan et al. 2009), one could speculate following Stawarz et al. (2013) that the flux of UHECRs through the lobes may produce uncompensated currents, which locally alter both the magnetic field configuration and the electron heating/acceleration conditions, via cosmic ray current-driven instability. In this model it would, however, remain rather unclear why an enhancement in the nonthermal electron population, manifesting as an enhancement in the X-ray surface brightness via inverse Comptonization of the cosmic microwave background photons, should be associated with a lower radio polarization and/or with a decrease in the RM value. This demonstrates that a proper discrimination between various models and plausible scenarios proposed for the internal structure of the extended lobes in radio galaxies and quasars requires not only a deep X-ray imaging of the lobes on arcsecond scales, but also the accompanying detailed radio polarimetry with a comparable high-resolution.

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