

A Comprehensive and Novel Analysis of the Chandra X-ray Observatory Data for the Pictor A Radio Galaxy

A PhD Dissertation

by

mgr Rameshan THIMMAPPA
rameshan@oa.uj.edu.pl

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**The Faculty of Physics, Astronomy and Applied Computer Science
of the Jagiellonian University
Kraków, Poland**

Supervisor: dr hab. Łukasz STAWARZ
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Dedicated to
My mother Padhmamma and my father Thimmappa

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Abstract

Pictor A, recognized as the archetypal powerful radio galaxy of the FR II type, is not only one of the brightest radio sources in the sky, but is also particularly prominent in the X-ray domain. Importantly, the extended structure of Pictor A is characterized by the large angular size of the order of several arcminutes. This structure could be therefore easily resolved by the modern X-ray telescopes, in particular by the *Chandra* X-ray Observatory. As such, Pictor A is a truly unique object among all the other radio galaxies.

The main goal of my scientific research carried out during the last years, and summarized in this dissertation, is a comprehensive and novel re-analysis of all the available archival *Chandra* data for Pictor A. One of the main difficulties in this respect, is that the *Chandra* observations spread over the past decades have targeted different regions in the source with various exposures and off-axis angles. In addition, those regions do vary dramatically in their X-ray output and appearance, from the extremely bright and point-like (unresolved) nucleus, to the low-surface brightness but considerably extended lobes. Keeping in mind the above-mentioned difficulties and challenges, for each region within the Pictor A system and each pointing selected for the analysis, we studied in detail the *Chandra* point-spread function, and the emission spectrum within the 0.5 – 7.0 keV range, performing, whenever possible, image deconvolution, timing analysis, and spectral modeling.

In particular, in our studies we have focused on the following three main research problems: (I) an approach to the X-ray spectroscopy of the active nucleus in Pictor A radio galaxy, carried out in a regime of a severe instrumental pile-up; (II) investigating the X-ray structure of the termination shocks of relativistic jets in Pictor A, the so-called “hotspots”, by means of detailed image deconvolution and timing analyses; and (III) investigating correlations between the X-ray and radio emission features within the extended lobes of the source.

The main novel results of our comprehensive analysis, regard (i) a possibility for a presence of a broad fluorescent iron line in the nuclear spectrum of the source, (ii) a sub-structure of the Western hotspot in Pictor A in X-rays, as well as (iii) the discovery of the tens-of-kpc long X-ray filament within the Eastern lobe of the radio galaxy. For the hotspot, we present for the first time the *deconvolved* total intensity, revealing clearly the Mach disk-structure of the termination shock at sub-pixel ($\simeq 0.25$ arcsec) scale, and indicating that an efficient acceleration of ultra-relativistic electrons (up the TeV energies and more), takes place exclusively within a rather thin layer of the very front of the termination shock. For the lobe’s X-ray filament, we demonstrate an anti-correlation between the X-ray surface brightness and polarized radio intensity, suggesting a presence of a magnetized thermal plasma only partly mixed with the non-thermal radio-emitting particles within the lobe, combined with the reversals in the lobe’s net magnetic field.

Contents

Abstract	iii
Acknowledgments	xviii
1 Introduction	1
1.1 The Instruments	3
1.1.1 Radio-to-Submillimeter Range	3
1.1.2 Infrared and Optical Ranges	7
1.1.3 X-ray Range	8
1.1.4 γ -ray Range	11
1.2 <i>Chandra</i> X-Ray Observatory	13
1.2.1 The Advanced CCD Imaging Spectrometer (ACIS)	14
1.2.2 Standard Data Processing (SDP)	16
1.2.3 Data Analysis Software	18
1.3 Active Galactic Nuclei	19
1.3.1 AGN Phenomenology	19
1.3.2 Broad-band Emission Spectra of AGN	22
1.3.3 Radio Galaxies	24
1.4 Radiative Processes	29
1.4.1 Synchrotron Radiation	30
1.4.2 Inverse-Compton Scattering	32
1.4.3 Thermal Bremsstrahlung	33

1.5	Pictor A: From Radio to γ -rays	35
1.5.1	Radio emission	35
1.5.2	IR & Optical emission	38
1.5.3	X-ray emission	39
2	Active Nucleus in Pictor A: Data Analysis in the Regime of Instrumental Pile-up	41
2.1	Introduction	41
2.2	Data Analysis	42
2.2.1	Spectral Modelling	43
2.2.2	Surface Brightness Profiles	49
2.3	Conclusions & Future Work	54
3	Western Hotspot of Pictor A: Image Deconvolution and Variability Analysis	55
3.1	Introduction	55
3.2	Chandra Data	57
3.3	Data Analysis	58
3.3.1	Spectral modeling	58
3.3.2	PSF modeling	60
3.3.3	Image Deconvolution	63
3.4	Discussion: Results of the Analysis	64
3.5	Conclusions	69
4	Eastern Lobe of Pictor A: Spectral Analysis and X-ray/Radio Correlations	73
4.1	Introduction	73
4.2	X-ray and Radio Data	75
4.2.1	Chandra Observations and Data Processing	75
4.2.2	VLA Observations and Radio Maps	78
4.3	Analysis Results	80

4.3.1	Chandra Spectral Analysis	81
4.3.2	The Surface Brightness Profile	84
4.4	Discussion and Conclusions	85
5	Summary and Main Conclusions	89
	References	93

List of Figures

1.1	The accessible range of the electromagnetic spectrum. Note that the boundaries between different ranges are not well defined. (Credit: Bradt 2004). . .	3
1.2	The electromagnetic spectrum – the atmospheric band view (‘windows’). (Credit: Burke & Graham-Smith 2009).	4
1.3	Schematic diagram of the <i>Chandra</i> spacecraft with the main components labeled. (Credit: NASA/CXC/SAO & J.Vaughan)	13
1.4	The structure of the ACIS (Credit: NASA/CXC/SAO).	14
1.5	A schematic diagram of the ACIS focal plane. Note ACIS-S (S3) and ACIS-I (I3) are the aimpoints.	15
1.6	The encircled fractional power versus the radius of point source with HRMA plus ACIS at 1 keV observation of PG 1634-706.	16
1.7	Schematic mapping of the AGN phenomenon. (Credit: Blandford 1990). . .	20
1.8	Basic types and classes of AGN based on observational criteria. (Credit: Dermer & Giebels 2016).	20
1.9	Schematic representation of the AGN phenomenon in the unified scheme. (Credit: Beckmann & Shrader 2012).	22
1.10	A sketch of the broad-band continuum observed in many types of AGN. (Credit: Carroll & Ostlie 1996).	23
1.11	A zoom to the AGN accretion disk X-ray continuum (Credit: Fabian & Miniutti 2005).	24
1.12	Left:: <i>Chandra</i> X-ray image of the M87 radio galaxy with the X-ray jet extending to the right. Right: The zoom toward the central $10 r_g$ (where, r_g is the gravitational radius of a black hole) obtained by the EHT. (Credit: X-ray: NASA/CXC/Villanova University/J. Neilsen; Radio: Event Horizon Telescope Collaboration.)	25

1.13	Left: The <i>Chandra</i> X-ray image of the distant radio quasar PKS 1127–145, revealing the jet that extends at least a million light years from the core. (Credit: NASA/CXC/ A.Siemiginowska / J.Bechtold). Right: A composite image of <i>Chandra</i> X-ray (blue) and VLA radio (red) observations showing the inner 4,000 light years of a jet in the nearby radio galaxy Centaurus A. (Credit: X-ray: NASA/CXC/Bristol U./M. Hardcastle et al.; Radio: NRAO/AUI/NSF/Bristol U./ M. Hardcastle.)	26
1.14	Top: Cygnus A X-ray contours obtained with the ROSAT HRI, superimposed on the 327 MHz VLA color image (Harris et al. 1994); Bottom: Cygnus A X-ray image by the CXO (Wilson et al. 2000).	28
1.15	Synchrotron radiation produced when relativistic electrons gyrate in a magnetic field. (Credit: NASA/CXC/SAO)	30
1.16	A power-law spectrum of the synchrotron radiation produced by a power-law energy distribution of ultra-relativistic electrons. A single electron spectrum is shown at the top right (Credit: Carroll & Ostlie 1996)	31
1.17	Inverse-Compton process: low-energy photon gains energy when scattered off energetic electron. (Credit: NASA/CXC/SAO)	32
1.18	Bremsstrahlung: emission resulting from the interaction of free electrons with the fluctuating electrostatic potential of background protons. (Credit: NASA/CXC/SAO)	33
1.19	Top: The radio VLA image of Pictor A, revealing an unresolved core, two extended filamentary lobes, and two hotspots. Middle: The X-ray <i>Chandra</i> image of Pictor A, revealing a bright nucleus, a pair of long jets terminating in the two hotspots, and a diffuse X-ray cocoon overlapping with radio lobes. Bottom: The composite VLA radio (red) and <i>Chandra</i> X-ray image (blue) of Pictor A. (Credit: X-ray courtesy of NASA/CXC/Univ of Hertfordshire/ M.Hardcastle et. al.; radio courtesy of CSIRO/ATNF/ATCA.)	36
1.20	Multi-epoch TANAMI images of Pictor A nuclear region, revealing expansion of compact knots from a stationary core, with mildly relativistic apparent speeds. (Credits: Angioni et al. 2019)	37
1.21	The <i>Chandra</i> image of the Western hotspot in Pictor A in the 0.5–5.0 keV range (binned to pixels of 0.123 arcsec on a side and smoothed with a Gaussian of $\sigma = 1$ pixel to give an effective resolution of ~ 0.7 arcsec). Contours are from the 5 GHz ATCA map with 1.7 arcsec resolution (yellow), and from the 15 GHz VLA map. (Credit: Hardcastle et al. 2016).	40

2.1	The collection of all the available <i>Chandra</i> pointings on the Pictor A nucleus, marked in all the panels by a green circle with 60 px radius. All the corresponding ObsIDs are given in the panels.	42
2.2	ACIS-S 0.5–7 keV image of the central parts of Pictor A, for the first ObsID 346. The AGN source extraction region (< 6 px), and the background region (10–30 px, omitting the jet), are denoted by green contours.	44
2.3	Model (power-law) fluxes and photon indices, calculated for the individual <i>Chandra</i> observations of Pictor A nucleus within the 0.5–7.0 keV energy range, based on the applied simple power-law model including <code>jdpileup</code> . Top: Flux vs. date of observation; middle: photon index vs. date of observation; bottom: flux vs. photon index.	45
2.4	The <i>Chandra</i> 0.5–7.0 keV spectra of the Pictor A nucleus, for ID 346 and ID 17574, fitted with a single power-law model including the Galactic absorption and the instrumental pile-up. The corresponding model parameters are given in Table 2.1.	46
2.5	The <i>Chandra</i> 0.5–7.0 keV spectrum of the Pictor A nucleus for ID 346, fitted with a single power-law model including Galactic absorption and the instrumental pile-up, as well as the redshifted ($z = 0.035$) Gaussian line with the position fixed at 6.4 keV and the width $\sigma_\ell = 1$ keV.	48
2.6	The X-ray surface brightness profile of the Pictor A central region, obtained from ObsID 346. The cyan curve denotes the table model for the core PSF (with freed amplitude), the green curve corresponds to the β -profile component, the blue horizontal line denotes the constant background, and the solid grey curve gives the total “Take #1” PSF+beta1d+constant model fitted to the data. The corresponding residuals are given in the lower panel.	50
2.7	Observations ID 346, 12039, 14357, and 14222, selected for the “Take #2” analysis of the X-ray surface brightness profile within the central regions of Pictor A, denoted on each panel by a red circle (0–60 px from the core). The source extraction regions for the spectral analysis (< 6 px), and the corresponding background extraction regions (10–20 px), are denoted by green circles.	52

2.8	The X-ray surface brightness profile of the Pictor A central region, obtained from ObsID 346, ID12039, ID14357 and ID14222. The cyan curves denote the table model for the core PSF (with freed amplitude), the green curves correspond to the β -profile component, the blue horizontal line denotes the constant background (only for ObsID 346), the magenta curves denote the extra Gaussian component, and the solid grey curves give the total “Take #2” PSF+beta1+gauss1d(+constant) model fitted to the data. The corresponding residuals are given in the lower panel.	53
2.9	Deconvolved <i>Chandra</i> image of the Pictor A nucleus (ObsID 346), with 1 px resolution.	54
3.1	<i>Left panel:</i> ACIS-S image of the W hotspot of Pictor A radio galaxy, within the energy range 0.5 – 7 keV for the ObsID 3090 (with 1 px binning and field point sources removed). The source extraction region for the spectral modeling is denoted by the green solid circle (20 px radius), and the background annular region by green dashed circles (30 – 60 px). <i>Right panel:</i> the PSF simulated for the ObsID 3090 (as discussed in Section 3.3.2).	57
3.2	The 0.5 – 7.0 keV spectra of the W hotspot of Pictor A, for ID 346 (gray diamonds) and 17574 (black circles), both fitted with the single power-law model moderated by the Galactic column density. Parameters of the model are given in Table 3.1.	59
3.3	The 0.5 – 7.0 keV energy flux (upper panel) and the photon index (lower panel) for the W hotspot of Pictor A, determined from single absorbed power-law model (see Table 3.1). The energy flux is given in the units of 10^{-13} erg $\text{cm}^{-2} \text{s}^{-1}$	60
3.4	The enclosed count fraction as a function of the radius aperture for the simulated PSFs for ObsIDs 346 (upper panel) and 3090 (lower panel). For each ObsID we performed 100 PSF simulations, and each curve corresponds to one particular PSF realization. The horizontal green, blue, and red lines (from bottom to top), correspond to 1σ , 2σ , and 3σ count fractions, respectively.	61
3.5	The deconvolved <i>Chandra</i> images of the W hotspot in Pictor A at 1 px resolution. Each image results from averaging over the restored images for 100 PSF realizations using the LRDA on the exposure-corrected maps. The color scale gives the count rate (cts s^{-1}).	62
3.6	The deconvolved <i>Chandra</i> images of the W hotspot in Pictor A at 0.5 px resolution. Each image results from averaging over the restored images for 100 PSF realizations using the LRDA on the exposure-corrected maps. The color scale gives the count rate (cts s^{-1}).	62

3.7	The deconvolved exposure-corrected <i>Chandra</i> image of the W hotspot in Pictor A at 0.5 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF, with the radio (3.6 cm wavelength, beam size $0.''77 \times 0.''17$, position angle -0.4°) VLA contours superimposed (left panel) and optical F606W filter (5918Å, 90% encircled energy within radius 0.35'') <i>Hubble</i> Space Telescope ACS/WFC contours superimposed (right panel). Radio contours are spaced with a factor of $\sqrt{2}$ between 0.552 and 70.71% of the peak intensity of $215 \text{ mJy beam}^{-1}$. Optical contours are spaced with a factor of $\sqrt{2}$ between 0.008 and 3 cts s^{-1}	63
3.8	A comparison between the <i>Chandra</i> image of the W hotspot in Pictor A resulting from merging all the analyzed ObsIDs (left panel), and the deconvolved exposure-corrected image at 0.5 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF (right panel). In both panels, the VLA 3.6 cm radio contours are superimposed (see Figure 3.7).	64
3.9	The deconvolved exposure-corrected <i>Chandra</i> image of the W hotspot in Pictor A at 1.0 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF. Source regions used for the extraction of the next counts — “hotspot total” (HS), “hotspot North” (N), and “hotspot South” (S) — are denoted by the circle and the two smaller ellipses.	65
3.10	Histograms of the net count rates calculated for the selected regions HS (top panel), N (middle panel), and S (lower panel) within the W hotspot in Pictor A, on the deconvolved exposure-corrected <i>Chandra</i> images for the ObsID 3090, for 100 random realizations of the PSF.	67
3.11	The net count rate measured for the selected regions HS (top panel), N (middle panel), and S (lower panel) within the W hotspot in Pictor A on the deconvolved exposure-corrected <i>Chandra</i> images (see Table 3.2), as a function of the observing time.	68
3.12	Integrated intensity profiles along the major axis of the N region displayed on Figure 3.9, for the ObsID 346 and 3090 (upper and lower panels, respectively), at either 1 px or 0.5 px resolution (left and right panels, respectively). Each curve on the panels corresponds to a single realization of the PSF for a given ObsID.	70
3.13	Histograms of the net count rates calculated for the HS region on the deconvolved exposure-corrected <i>Chandra</i> images of the W hotspot in Pictor A, at 1 px resolution, for all the analyzed ObsIDs. Each panel corresponds to 100 random realizations of the PSF for a given ObsID.	72

3.14	Integrated intensity profiles along the major axis of the N region displayed on Figure 3.9, for all the analyzed ObsIDs, at 0.5 px resolution. Each curve on the panels corresponds to one single realization of the PSF for a given ObsID.	72
4.1	Top: Merged counts image of the Pictor A radio galaxy, for the selected eight <i>Chandra</i> observations listed in Table 4.1, in the energy range 0.5–7.0 keV, with native 0.492'' pixels. Note a much reduced exposure toward the E lobe when compared to the W lobe. Middle: Exposure-corrected merged <i>Chandra</i> image, smoothed with 3σ Gaussian radius, revealing the bright core, the jet extending to the North-West from the core, the W hotspot, the weak counterjet to the South-East, 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 <i>wavdetect</i> tool using the minimum PSF method; different sizes of the point/compact sources across the field, reflect the varying PSF and/or sources extension.	76
4.2	Top: The VLA spectral index map of Pictor A radio galaxy, between L and C bands, with the <i>total intensity</i> L-band (1.45 GHz) contours superimposed, at 10'' resolution. Bottom: The VLA rotation measure (RM) map between L and C bands, with the <i>polarized intensity</i> L band contours superimposed, at 10'' resolution.	77
4.3	Top: A zoomed view of the RM distribution within the E hotspot region in Pictor A, with the polarized intensity L band contours superimposed, at 10'' resolution. Bottom: A zoomed view of the 0.5–7.0 keV emission of the E hotspot region in Pictor A, with the 1.45 GHz polarized intensity contours (white) superimposed. The 0.5–7.0 keV <i>Chandra</i> image is smoothed with 3σ Gaussian radius. Radio contours start from 3σ confidence level. Regions selected for the <i>Chandra</i> data analysis are labeled and indicated by green contours.	79
4.4	The background-subtracted <i>Chandra</i> 0.5–7.0 keV spectrum for the selected source region A, binned with $S/N = 3$ and fitted with a power-law model (top panel), APEC model (middle panel), and a two-component power-law+APEC model (bottom panel). See Table 4.3 for the corresponding best-fit model parameters.	83
4.5	The confidence contours for the model parameters kT and Γ for the two-component power-law+APEC model applied to the selected source region A.	84

4.6	The exposure-corrected 0.5–7.0 keV merged <i>Chandra</i> image of the entire structure of Pictor A, smoothed with 3σ Gaussian radius, with the 1.45 GHz VLA total and polarized intensity (3σ) contours superimposed (red and white, respectively). The two elongated yellow 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.	85
4.7	Top: The Profile 1 rectangular region, rotated by $\theta = 335^\circ$, and divided into 16 vertical boxes. Middle: The X-ray photon fluxes per unit area (filled circles), and the polarized radio flux spectral densities (empty circles), integrated over each box. Bottom: The X-ray photon fluxes per unit area (filled circles), and the total radio flux spectral densities (empty circles), integrated over each box.	86
4.8	Top: The Profile 2 rectangular region, rotated by $\theta = 360^\circ$, and divided into eight vertical boxes. Middle: The X-ray photon fluxes per unit area (filled circles), and the polarized radio flux spectral densities (empty circles), integrated over each box. Bottom: The X-ray photon fluxes per unit area (filled circles), and the total radio flux spectral densities (empty circles), integrated over each box.	87

List of Tables

1.1	The optical and near-IR telescopes with > 8 m apertures.	8
1.2	The most important past, present, and future X-ray missions.	10
1.3	The most important past & present space-born γ -ray missions.	12
1.4	The characteristics of ACIS instrument.	15
1.5	Classification of AGN based on their optical and radio properties.	21
2.1	The best-fit parameters for the nuclear spectrum of Pictor A, assuming a power-law model (including <code>jdpileup</code>).	43
2.2	The pileup fraction for ObsID 346.	47
2.3	Best-fit model parameters for the Pictor A nuclear spectrum, corresponding to the power-law model including <code>jdpileup</code> and red-shifted ($z = 0.035$) Gaussian line, for ObsID 346.	48
2.4	Parameters of the multi-component model applied to the X-ray surface brightness profile of the Pictor A central regions (Take #1).	50
2.5	Parameters of the multi-component model applied to the X-ray surface brightness profile of the Pictor A central regions (Take #2).	52
3.1	Observational Data and Spectral Fitting Results	56
3.2	Net Count Rates of the W Hotspot in Pictor A and its Two Subregions, from the Deconvolved Images	66
4.1	<i>Chandra</i> observations used in our analysis of the E lobe in Pictor A	74
4.2	Power-law fitting results for the selected regions within the E lobe	80
4.3	Spectral fitting results for the source region A.	82

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எப்பொருள் எத்தன்மைத் தாயினும் அப்பொருள்
மெய்ப்பொருள் காண்பது அறிவு.

– திருக்குறள் (355) ~ கி.மு முதல் நூற்றாண்டு

The mark of wisdom is to see the reality
Behind each appearance.

– Thirukkural (355) ~ First century B.C

Chapter 1

Introduction

The study of Active Galactic Nuclei (hereafter AGN) plays an important role in the field of astrophysics, since first identifications of active galaxies as a general and distinct class of astronomical objects at optical wavelengths. The first attempt for an explanation of the AGN phenomenon in this context, was given by [Fath \(1909\)](#), and later by [Seyfert \(1943\)](#). In 1930s, the radio astronomy was introduced ([Jansky 1933](#); [Reber 1940](#)), soon followed the first discovery of a bright, double-lobed radio counterpart to the active galaxy Cygnus A ([Jennison & Das Gupta 1953](#)), located at the redshift of $z = 0.05$ ([Baade & Minkowski 1954](#)). As later recognized by [Fanaroff & Riley \(1974\)](#), the large-scale radio morphology of this source is in fact representative for luminous radio galaxies of the “classical double”, or the “FR II” type (see section 1.3.3). Such galaxies, in addition to the double lobes, contain also bright unresolved core coinciding with the nucleus of a host galaxy, and a pair of jets extending from the core down to the termination “hotspots” located at the edges of the lobes, where the radio surface brightness of the entire structure peaks. This morphology allowed to develop a general understanding of radio galaxies, where the active galactic nucleus (core) supplies continuous energy to the lobes through bi-polar well-collimated outflows (jets), which terminate by forming extended shock waves (observed as hotspots) when colliding with the external intergalactic medium ([Blandford & Rees 1974](#); [Scheuer 1974](#); [Hargrave & Ryle 1974](#)).

In it now generally accepted, that Super Massive Black Holes (SMBHs), i.e. black holes with masses $M \sim 10^{6-10} M_{\odot}$ appear in the nuclei of every large galaxy, including our own Galaxy¹. And this is the enhanced accretion of a surrounding matter onto such SMBHs, which powers the nuclear activity of radio galaxies, and of all the other types of AGN (see section 1.3). We can also estimate the total number of extragalactic radio sources with total luminosities $L_{\text{rad}} \geq 10^{38} \text{ erg s}^{-1}$ — for which a substantial fraction is constituted by jetted AGN — as about 10^9 ([Padovani 2016](#)). This is therefore a very numerous, and energetically

¹Solar mass $M_{\odot} \simeq 1.989 \times 10^{30} \text{ kg}$

CHAPTER 1. INTRODUCTION

relevant, population of astronomical objects, and hence studying and understanding such is important for our comprehensive understanding of the Universe in general. The observations and theories of various aspects of the SMBH activity, including the radiative properties and classification of AGN, the physics of relativistic jets in AGN, or finally the feedback processes in the co-evolution of SMBHs and their host galaxies, were reviewed in a number of excellent articles, including [Bridle & Perley \(1984\)](#); [Begelman et al. \(1984\)](#); [Rees \(1984\)](#); [Mushotzky et al. \(1993\)](#); [Antonucci \(1993\)](#); [Ho \(2008\)](#); [Fabian \(2012\)](#); [Hickox & Alexander \(2018\)](#); [Blandford et al. \(2019\)](#); [Hardcastle & Croston \(2020\)](#).

During my research, I have also used extensively several textbooks on the topics such as (i) general concepts in modern astronomy and astrophysics, including ‘*High Energy Astrophysics*’ by [Longair \(2011\)](#), ‘*Astronomy Methods – A Physical Approach to Astronomical Observations*’ by [Bradt \(2004\)](#), ‘*An Introduction to Galaxies and Cosmology*’ by [Jones & Lambourne \(2004\)](#), ‘*Astrophysical Concepts*’ by [Harwit \(2006\)](#), or ‘*An Introduction to Modern Astrophysics*’ by [Carroll & Ostlie \(2006\)](#); (ii) more specifically, the theory of radiative transfer and emission processes, including ‘*Radiative Processes in Astrophysics*’ by [Rybicki & Lightman \(1986\)](#), and ‘*Radiative process in high energy astrophysics*’ by [Ghisellini \(2013\)](#); (iii) various aspects of the physics of AGN and black hole activity, including ‘*Active Galactic Nuclei*’ by [Blandford \(1990\)](#), ‘*Active Galactic Nuclei*’ by [Beckmann & Shrader \(2012\)](#), or ‘*The Formation and Disruption of Black Hole Jets*’ by [Contopoulos et al. \(2015\)](#); finally, (iv) the modern X-ray astronomy, including ‘*Handbook of X-ray Astronomy*’ by [Arnaud et al. \(2011\)](#), ‘*The Restless Universe: Understanding X-ray Astronomy in the Age of Chandra and Newton*’ by [Schlegel \(2002\)](#), and ‘*The Chandra X-ray Observatory: Exploring the high energy universe*’ by [Wilkes & Tucker \(2019\)](#).

Early history of the AGN research:

- 1908** Edward Fath finds strong emission lines from H, O, and Ne in the nuclear spectrum of NGC 1068
- 1915** Albert Einstein’s *General Theory of Relativity*
- 1916** Karl Schwarzschild solution of the Einstein equation, describing a black hole
- 1918** Herber Curtis discovered the first astrophysical jet in M 87 (“...a curious straight ray... bound to the nucleus by a thin line of matter...”)
- 1924/29** General realization, led by Edwin Hubble, that “nebulae” like NGC 1068 or M 87 are extragalactic objects, representing distant galaxies
- 1939** Grote Reber discovers the radio source Cygnus A
- 1943** Carl Seyfert identifies a class of galaxies with strong, broad emission lines and luminous blue nuclei (known nowadays as “Seyfert galaxies”)
- 1954** Walter Baade & Rudolph Minkowski identify the optical counterpart to Cygnus A at $z = 0.057$
- 1963** Maarten Schmidt identifies the redshifted $z = 0.158$ emission lines in the spectrum of the “quasi-stellar object” 3C 273
- 1964** Zeldovich & Novikov and Salpeter speculate about supermassive black holes powering quasars
- 1968** Donald Lynden Bell states that many galactic nuclei may consist “collapsed old quasars”
- After:** AGNs became a focus of a widespread research...

1.1 The Instruments

Nowadays, we are privileged to have a number of excellent telescopes enabling us to perform detailed spectroscopy, imaging, and monitoring of AGN at various segments of the electromagnetic spectrum (see Figure 1.1).

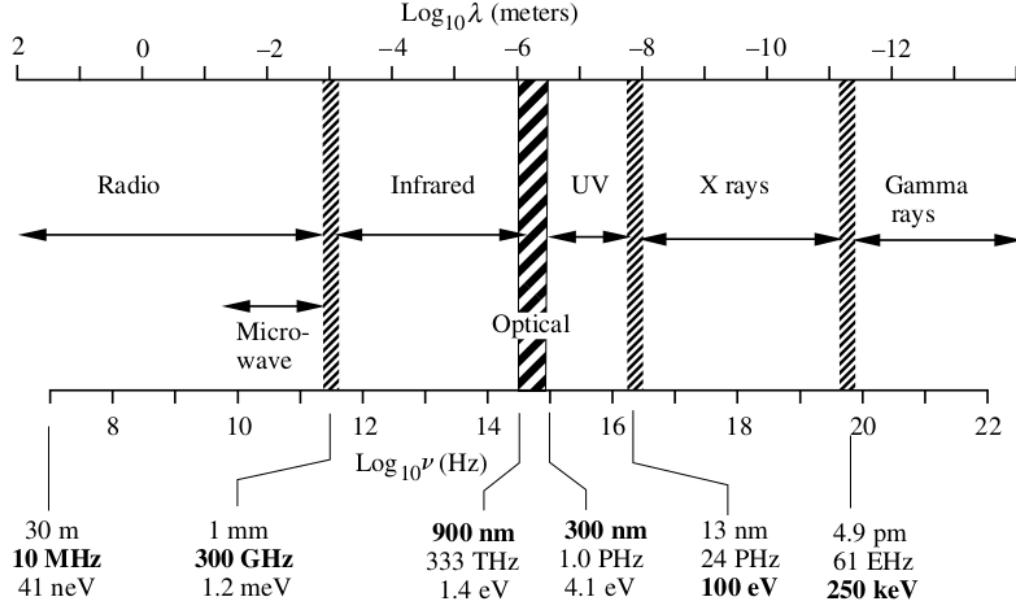


Figure 1.1: The accessible range of the electromagnetic spectrum. Note that the boundaries between different ranges are not well defined. (Credit: [Bradt 2004](#)).

1.1.1 Radio-to-Submillimeter Range

The Earth's ionosphere is transparent for the radio wavelengths within the range, roughly, from 30 MHz to 300 GHz (see Figure 1.2), so that the astronomical objects can be studied at such wavelengths by ground-based antennas. Radio waves can penetrate through the interstellar gas and dust, allowing us to see more deeply into galaxies and molecular clouds, as well as galactic nuclei. In general, in the radio domain, we can study the thermal emission processes from the interstellar dust and cold interstellar plasma (free-free emission), as well as non-thermal emission processes related to relativistic electrons, in particular their synchrotron emission when embedded within strong magnetic fields.

In 1935 – Karl G. Jansky built a directional array at 20 m (at 15 MHz frequency) and discovered cosmic radio waves. In particular, he detected our own Galaxy as the main source of the background, and also observed that this radiation comes from energetic electrons of the interstellar medium ([Jansky 1935](#)). In 1937, the first reflecting radio telescope was constructed by Grote Reber ([Reber 1944](#)). Later, during World War II (in 1942), radio emission from the Sun has been identified for the first time by James Hey. In the early

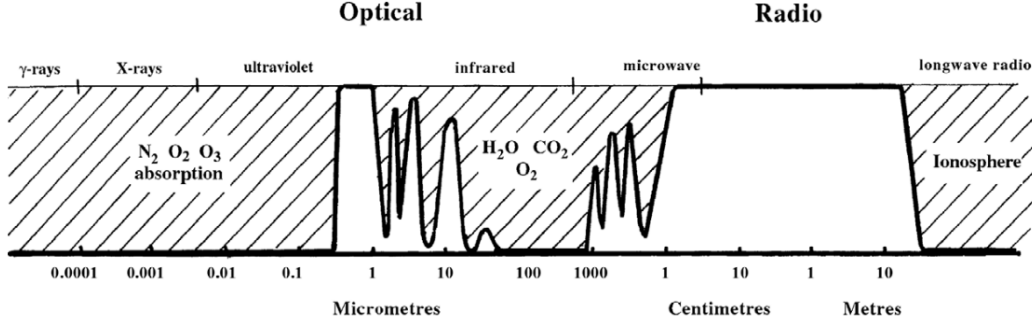


Figure 1.2: The electromagnetic spectrum – the atmospheric band view (‘windows’). (Credit: [Burke & Graham-Smith 2009](#)).

survey of the radio sky, the source Cygnus A was detected by [Hey et al. \(1946\)](#). In 1948, John Bolton, Martin Ryle and Graham Smith discovered the two most powerful radio sources in the sky, namely Taurus A (the Crab Nebula) and Cassiopeia A. In 1951, the 21 cm hydrogen line discovered at the same time in the USA, The Netherlands, and Australia. It was previously predicted by Jan Oort and H. van der Hulst. This hydrogen line emission played a major role to form the new field of astro-chemistry. During 1954, the evolution of interferometer techniques was used to locate the exact position of cosmic radio sources, and also to resolve their large-scale structure, like for example the two giant lobes of Cygnus A. In 1958, Martin Ryle lead an effort to compile the list of extra-galactic radio sources detected in the Cambridge surveys. In 1962, also Martin Ryle used aperture synthesis technique for the interferometer and Henry Palmer linked long baselines to observe the cosmic radio sources. In 1964, the isotropic cosmic microwave background (CMB) detected by Arno Allan Penzias and Robert Woodrow Wilson; the Nobel Prize was awarded for this discovery in 1978, the second time to radio astronomers. The first Nobel Prize was awarded to radio astronomers in 1974, for the discovery of pulsars in 1967.

Single-aperture antennas are built from metal wires or rods, i.e. dipoles, Yagis and log periodics at longer wavelengths (≤ 500 MHz), depending on the aimed sensitivity and angular resolution of the instrument. Below I provide a short summary of the main single-dish radio telescopes widely used for the AGN study over the last decade:

- In 1957, the 76 me Lovell Telescope was commissioned and operated by the University of Manchester. This telescope operates at 408 MHz & 6 GHz frequencies, and now plays as a part of the eMERLIN radio imaging array.
- In 1961, Parkes 64 m diameter radio telescope was started and is still one of the largest single-dish telescopes in the southern hemisphere. It can observe radio waves in the range 7 mm– 4 m, with a resolution of $\geq 10''$.
- In 1974, RATAN-600 telescope (Radio Astronomical Telescope of the Academy of Sciences) was launched, that contains a 576 m diameter circle of rectangular radio reflectors and a set of secondary reflectors and receivers, based at an altitude of

CHAPTER 1. INTRODUCTION

970 m. It can resolve $1'$ in the horizontal plane, at 8 cm (3.75 GHz) with an effective collecting area of 1000 m^2 (11000 ft^2).

- The Green Bank Telescope (GBT): The Robert C. Byrd Green Bank Telescope is a 100 m diameter dual offset Gregorian reflector radio telescope, which operates in the range $\sim 300 \text{ MHz}$ – 100 GHz .
- The Max-Planck-Institut für Radio-astronomie (MPIfR) is 100 m radio antenna used to facilitate protection from Radio Frequency Interference (RFI), located in a valley near Bad Münstereifel-Effelsberg around 40 km south-west of Bonn. It can observe radio emission in the astrophysical objects at 300 MHz – 96 GHz frequency range.
- In 2016, the Five-hundred-metre Aperture Spherical Telescope (FAST) was launched; this is the world's largest filled-aperture radio telescope and the 2nd-largest single-dish aperture, after the RATAN-600 telescope.

The modern computing technology helped to develop an aperture synthesis in the 1970s and 1980s, which led to many operating radio interferometric arrays that contain at least eight telescopes expanding over a few kilometers or more, with an angular resolutions of $\sim 0.1'' - 1''$. Based on this techniques, the following telescope arrays have been constructed:

- In 1970, the Westerbork Synthesis Radio Telescope (WSRT) was opened containing fourteen 25 m dishes. The WRST setup into a linear array arranged on a 2.7 kilometres (1.7 mi) East-West line.
- Very Large Array (VLA) Telescope: It contains 27 indistinguishable 25 m dishes, each dishes inter connected with an optical-fibre data network, which are organised in a Y-configuration. The arms of the Y are $\sim 21 \text{ km}$ long, provides a long baseline over 36 km. It can operate between in the range of 74 MHz – 50 GHz .
- Multi-Element Radio Linked Interferometer Network (eMERLIN) was constructed between 1970s and 1990. It contains more extended arrays and has six telescopes (five - 25 m and one 32 m in diameter), with a long baseline of $\sim 200 \text{ km}$ and has the higher angular resolution at a given frequency.
- In 1988, the Australia Telescope Compact Array (ATCA) was started, which includes six 22 m dishes (five dishes are movable) distributed along 6 km East–West baseline.
- In 1995, the Giant Metre-Wave Radio Telescope (GMRT) was designed to operate at longer wavelengths (from 50 MHz to 1.4 GHz) frequency. This contains thirty 45 m dishes in fixed locations, which has baselines up to 25 km.
- In 2007, the Allen Telescope Array (ATA) was constructed, and has forty-two 6 m offset parabolic dishes with baselines to 300 m. This configuration can carry out wide-area surveys over $(1 - 10 \text{ GHz})$ frequencies.
- In 2018, the Australia SKA Pathfinder (ASKAP) was completed, which has thirty-six 12 m dishes with baselines up to 6 km. The main goal of this project is to make

CHAPTER 1. INTRODUCTION

observations around 1 GHz (including redshifted atomic hydrogen) along with the WSRT.

- The Karoo Array Telescope (MeerKAT), contains sixty four 13.5 m dishes with maximum baseline of 8 km. In the southern hemisphere, this is the most sensitive radio telescope.
- First and the largest modern low frequency phased array telescope was the international Low-Frequency Array (LOFAR), located in The Netherlands (maximum baselines ~ 100 km), after 2017 with partner stations in Poland, Sweden, Germany, France, Ireland and UK (maximum baselines ~ 1500 km). LOFAR operates in two bands: at low (10 – 80 GHz) and high (120 – 240 GHz).

Radio interferometers with very long baselines have also been developed, with the main goal of imaging various astronomical objects at milli-arcsec resolution. This Very-Long-Baseline Interferometry (VLBI) occurred to be particularly useful in the AGN research, as it allowed us to probe the innermost regions of active galaxies, namely the closest vicinity of SMBHs where relativistic radio jets are formed. There are several VLBI arrays spread all over the world on different continents, and recently involving also space satellites placed on the Earth’s orbit. The Very Long Baseline Array (VLBA) is one of the most prominent arrays in this context, including ten 25 m telescopes with 45 baselines. Among these ten telescopes, eight located in the USA with one-Hawaii & one-St Croix, Virgin Islands. These telescopes can operate with the VLA and span 8000 km, which results angular resolution ≤ 1 mas, and the operational band (330 MHz – 43 GHz).

The most recent effort in this direction, is to achieve the angular resolution of the order of tens micro-arcseconds (and below!), by combining radio antennas spreading the entire globe. This has been just achieved by the Event Horizon Telescope (EHT) which, in 2019, published the first image (“shadow”) of the SMBH in the center of M 87 (Virgo A) radio galaxy.

In addition, during the last years a few high-resolution interferometers operating at millimeter and submillimeter range, have been operational, targeting predominantly galaxies with vigorous starformation, and starforming molecular clouds within our Galaxy. Those include:

- The Submillimeter Array (SMA), which contains an eight 6 m diameter dishes connected with the baseline of 509 m long. This radio interferometer is located near the summit of Maunakea in Hawaii. It operates at 180–420 GHz frequencies.
- Atacama Large Millimeter Array (ALMA), operational since 2011, and located at the Atacama dessert in Chile, at the altitude of 5000 m; it operates within the frequency range 31–950 GHz. ALMA includes sixty-four 12 m antennas, which can be moved into different configurations of baselines from 150 m to 16 km.

CHAPTER 1. INTRODUCTION

1.1.2 Infrared and Optical Ranges

Above the millimeter/sub-millimeter range, i.e. at infrared frequencies, the observations of astrophysical objects become difficult or even impossible to carry out from the ground, because of the Earth's atmosphere, which itself may be a source of infrared photons due to the molecular line emission. For that reason, the infrared observations, in particular those in the mid- and far-infrared ranges, have to be done using space-born observatories. Typically, the lifetime of such is limited due to the required efficient cooling of the detectors. Nonetheless, a number of good-quality infrared space observatories have been launched since the 80ies of the previous century, providing an extremely rich amount of information regarding the cosmic dust. This includes hot dust covering – or in some case even completely hiding – nuclei of active galaxies.

- In 1983, the Infrared Astronomy Satellite (IRAS) was launched, orbiting 900 km high above the Earth's atmosphere. The 0.6 m telescope was cooled to liquid He temperatures. The designed detectors were made to observe from $12\text{ }\mu\text{m}$ – $100\text{ }\mu\text{m}$.
- In 1995, after the success of IRAS, the European Space Agency (ESA), in a collaboration with Japan and the United States, has launched the 0.6 m Infrared Space Observatory (ISO). The ISO operated until 1998, and produced images with much improved sensitivity and 1000 times better resolution than the IRAS.
- In 2003, the NASA's *Spitzer* Space Telescope was launched, with 0.85 m diameter and focal length 10.2 m. This is the most recent and largest IR observatory ever launched. The *Spitzer* can observe in the range $3\text{ }\mu\text{m}$ – $180\text{ }\mu\text{m}$, with the angular resolution of a few/several arcseconds.
- In 2009, the Wide-field Infrared Survey Explorer (WISE) was launched, which has 0.4 m and provides an all-sky survey at $3.4\text{ }\mu\text{m}$, $4.6\text{ }\mu\text{m}$, $12\text{ }\mu\text{m}$ and $22\text{ }\mu\text{m}$, up to 500 times more sensitive than the IRAS survey.

At optical wavelengths, the Earth's atmosphere starts to be transparent again, enabling sensitive and high-resolution observations of astronomical objects using ground-based facilities. This is this “most familiar” part of the electromagnetic spectrum, as it is accessible for the human eye ($\sim 4000 - 7000\text{ }\text{\AA}$). Obviously, there is a very long history of the optical astronomy. In the beginning, Galileo has built a refracting telescope using lenses, in which the light can travel via lenses to form an image. Then, Newton designed and constructed a reflecting telescope using mirrors as the primary optical component. Currently, both – refractors and reflectors – are in use, in a number of smaller and medium-size optical telescopes spread all over the Earth. The best-quality ground-based optical (and near-infrared) observations, are currently enabled by large telescopes, located at higher latitudes above the sea level. With such, an unprecedented sensitivity and the sub-arcsec angular resolution, can be easily achieved. In the following Table 1.1 we provide a list of currently operational optical observatories with an aperture of 8 m or more, adopted from [Harwit \(2006\)](#).

CHAPTER 1. INTRODUCTION

Table 1.1:: The optical and near-IR telescopes with > 8 m apertures.

Name	Size (m)	Site	First Light
Gemini North	8.1	Mauna Kea, Hawaii	1999
Gemini South	8.1	Cerro Pachn, Chile	2002
Subaru	8.2	Mauna Kea, Hawaii	1999
Very Large Telescope (VLT)-Antu	8.2	Cerro Paranal, Chile	1998
Very Large Telescope (VLT)-Kueyen	8.2	Cerro Paranal, Chile	1999
Very Large Telescope (VLT)-Melipal	8.2	Cerro Paranal, Chile	2000
Very Large Telescope (VLT)-Yepun	8.2	Cerro Paranal, Chile	2000
Large Binocular Telescope (LBT)	8.4×2	Mt. Graham, Arizona	2005
Hobby-Eberly Telescope (HET)	9.2	McDonald Observatory, Texas	1999
Keck I	10	Mauna Kea, Hawaii	1993
Keck II	10	Mauna Kea, Hawaii	1996
Gran Telescopio Canarias (GTC)	10.4	La Palma, Canary Islands	2005
Southern African Large Telescope (SALT)	11	Sutherland, South Africa	2005

In addition to those ground-based large telescopes, one should also mention the well-known space-born optical observatories, and in particular the biggest of them all, the NASA's space mission *Hubble* Space Telescope (HST). Launched in 1990, and named after Edwin Hubble, the HST has a 2.4 m diameter and focal ratio $f/24$. It operates from 120 nm up to $1\mu\text{m}$ (near-UV to near-IR, respectively), using the RitcheyChretien (RT) reflector type.

The future in this field belongs to The James Webb Space Telescope (JWST or Webb), which is a large space telescope with a 6.5 m primary mirror, operating within a range from longer-wavelength optical down to mid-infrared. This telescope will be launched on an Ariane 5 rocket from French Guiana in October 2021. The *Webb* will become the prime observatory for the coming decades, with thousands of astronomers serving worldwide for the mission.

1.1.3 X-ray Range

Various astrophysical objects are now confirmed sources of the X-ray emission, including individual stars, supernova remnants, accretion disks in X-ray binaries and active galactic nuclei, as well as entire galaxies and galaxy clusters. X-ray photons could be produced as a bremsstrahlung emission of a ionized hot gas with temperatures $10^6 - 10^9$ K, fluorescent emission, or via non-thermal processes involving ultra-relativistic electrons (synchrotron emission and inverse-Compton scattering). Earth's atmosphere is however an efficient X-ray absorber, and so the X-ray observations have to involve solely space-borne missions.

There is a surprisingly long history behind the development of the X-ray astronomy. In 1946, first V2 rocket was launched at the Naval Research Laboratory (NRL) with an altitude of 150 km, led by Herbert Friedman, aiming to measure solar X-ray radiation

CHAPTER 1. INTRODUCTION

(Friedman et al. 1951), even though the first successful detection of stellar X-rays came only in 1963. In 1962, Riccardo Giacconi and his team developed an *Aerobee* rocket at American Science & Engineering (AS&E), which has successfully detected the first celestial X-ray source Scorpius X-1 (Giacconi et al. 1962), as well as the Crab Nebula containing the supernova remnant and the pulsar (Bowyer et al. 1964). Since the discovery of Sco-1, there is a continuous progress in the technology, theory and observational analysis, which made the X-ray astronomy a leading scientific field in astrophysics research in general. In 2002, Riccardo Giacconi was awarded the Nobel Prize in Physics for pioneering the research field of X-ray astronomy.

In 1970, the *Uhuru* X-ray satellite was launched and made the first comprehensive survey of the X-ray sky, which acquires 50,000 s exposure time per day. Among the other sources, the *Uhuru* telescope has discovered a number of binary systems containing either black holes (such as Cyg X-1), or neutron stars (e.g., Cen X-3) (Giacconi et al. 1971). These X-ray observations provided a much improved view of the X-ray emitters in the local Universe. The corresponding X-ray luminosities are $10^{36} - 10^{38} \text{ erg s}^{-1}$, i.e. of the order of the gravitational energy of a gas in-falling on compact objects such as stellar-mass black holes (Schreier et al. 1972). Another major discovery of the *Uhuru* was the existence of very hot (temperatures $\sim 10^6 - 10^7 \text{ K}$) plasma in galactic clusters, constituting a huge reservoir of the baryonic matter, far exceeding the one related to the cluster's galaxies (Gursky et al. 1972).

In 1978, the *Einstein* Observatory (HEA0-2) was launched to study predominantly solar X-rays, but also supernova remnants, clusters of galaxies, and other fainter sources, with the angular resolution of the order of a few/several arcseconds. This has prevailed the importance of a high-resolution X-ray telescopes, that has opened the new path for the development of the *Chandra* X-ray Observatory (Giacconi & Gursky 1974; Giacconi et al. 1979; Giacconi & Tananbaum 1980; Tucker & Giacconi 1985; Giacconi & Rosati 2008). The *Chandra* telescope operates (formally) with an energy band of 0.08–10 keV, with the capabilities of providing sub-arcsec ($\sim 0.492''$) X-ray images, locating X-ray sources at high precision, detecting extremely faint sources, and enabling a high-resolution ($\sim 100 \text{ eV}$) spectroscopy of astrophysical sources. These well-established specifications make the instrument the most powerful X-ray tool for exploring the high-energy Universe. A more detailed description of the *Chandra* X-ray Observatory is given in Section 1.2 below.

The operation of the NASA's *Chandra*, followed the other European and Japanese X-ray missions in the 90ies of the last century, including the ROSAT and ASCA; it was also accompanied by the operation of similarly successful satellites Suzaku, Swift, and XMM-Newton, with comparable or complementary characteristics (regarding, e.g., energy and timing resolution, effective area, or the covered energy range). Recently, a number of smaller X-ray missions have been launched into the Earth's orbit as well, including the NuSTAR, or ASTROSAT. Those are all summarized in Table 1.2, adopted from (Bambi 2020). None of those, however, matches the superb *Chandra*'s angular resolution.

CHAPTER 1. INTRODUCTION

Table 1.2:: The most important past, present, and future X-ray missions.

Mission	Launched	End of mission	Instruments
Röntgen satellit (ROSAT)	1990	1999	XRT (0.1-2 keV)
Advanced Satellite for Cosmology and Astrophysics (ASCA)	1993	2000	GIS (0.7-10 keV) SIS (0.4-10 keV)
Rossi X-ray Timing Explorer (RXTE)	1995	2012	ASM (2-10 keV) PCA (2-60 keV) HEXTE (15-250 keV)
Suzaku	2005	2015	XRS (0.3-12 keV) XIS (0.2-12 keV) HXD (10-600 keV)
Hitomi	2016	2016	SXS (0.4-12 keV) SXI (0.3-12 keV) HXI (5-80 keV)
Chandra X-ray Observatory (CXO)	1999	–	ACIS (0.2-10 keV) HRC (0.1-10 keV) LETG (0.08-2 keV) HETG (0.4-10 KeV)
XMM-Newton	1999	–	EPIC-MOS (0.15-15 keV) EPIC-pn (0.15-15 keV) RGS (0.33-2.5 keV)
Swift	2004	–	BAT (15-150 keV) XRT (0.2-10 keV)
Monitor of All-sky X-ray Image (MAXI)	2009	–	SSC (0.5-10 keV) GSC (2-30 keV)
Nuclear Spectroscopic Telescope Array (NuSTAR)	2012	–	FPMA (3-79 keV) FPMB (3-79 keV)
ASTROSAT	2015	–	SXT (0.3-80 keV) LAXPC (3-80 keV) CZTI (100-300 keV)
Neutron star Interior Composition Explorer (NICER)	2017	–	XTI (0.2-12 keV)
Hard X-ray Modulation Telescope (HXMT)	2017	–	HE (20-250 keV) ME (5-30 keV) LE (1-15 keV)
Spektrum-Roentgen-Gamma (Spektr-RG)	2019	–	eROSITA (0.3-10 keV) ART-XC (0.5-11 keV)
X-Ray Imaging and Spectroscopy Mission (XRISM)	2022(?)	–	Resolve (0.4-12 keV) Xtend (0.3-12 keV)
Enhanced X-ray Timing Polarization (eXTP)	2027(?)	–	SFA (0.5-20 keV) LAD (1-30 keV)
Advanced Telescope for High Energy Astrophysics (ATHENA)	early 2030's(?)	–	X-IFU (0.2-12 keV) WFI (0.1-15 keV)

CHAPTER 1. INTRODUCTION

1.1.4 γ -ray Range

Photons with γ -ray energies cannot propagate freely within the Earth’s atmosphere, and so the γ -ray observations of astronomical objects have to be carried out, in principle, using space-born observatories. This, however, becomes more and more challenging in the Very High Energy (VHE) range of the γ -ray spectrum, due to more and more limited statistics of the photons with energies exceeding tens of GeV, even in the case of the brightest γ -ray sources on the sky. On the other hand, such energetic photons, when interacting with the Earth’s atmosphere, produce showers of secondary particles, which may be observed from the ground. In particular, within the ~ 0.1 -100 TeV range, observations of the Cherenkov emission of the showers occurs to be the most effective method enabling for a precise reconstruction of the energy and the arrival direction of the incident photon. Stereoscopic systems of the Cherenkov telescopes optimized for the showers’ detection, overcome the “flux vs. effective area of the detector” limitation of the space-born γ -ray instruments.

The following Table 1.3 lists the most important γ -ray missions from past and present, adopted from (Bambi 2020). The ground-based stereoscopic systems of the Imaging Atmospheric Cherenkov Telescopes (IACT) currently in operation, on the other hand, include:

- The High Energy Stereoscopic System (H.E.S.S.), located in Namibia, which contains four 13 m diameter IACT, arranged 120 m side length from each other in square structure, plus one larger telescope with a 28 m mirror located in the centre of the array. It can detect the VHE γ -rays in the range between 100 GeV to tens of TeV energy. It acquires 5° complete field of view and has angular resolution of $\lesssim 0.1^\circ$.
- The Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC), located in Canary Islands (Spain), which contains two 17 m diameter IACTs to observe VHE γ -rays ($\gtrsim 30$ GeV).
- The Very Energetic Radiation Imaging Telescope Array System (VERITAS), located at the Fred Lawrence Whipple Observatory in southern Arizona (USA), which contains four 12 m diameter IACTs covering the photon energy range between 85 GeV and 30 TeV.

At this moment, the next-generation system of IACTs, called simply The Cherenkov Telescope Array (CTA), is being build simultaneously in the northern and southern hemispheres, including more than 100 telescopes. It is expected to provide the most sensitive and high-resolution observations of cosmic γ -ray sources, for which the first truly meaningful population studies have been enabled only relatively recently, thanks to the all-sky survey of the *Fermi*-LAT satellite. Among such sources, one should mention a variety of Galactic pulsars and pulsar wind nebulae, supernova remnants, and binary systems, as well as starburst galaxies, gamma-ray bursts, and – last but not least – various types of AGN, predominantly blazars, for which non-thermal emission of relativistic jets dominates the entire radiative output.

CHAPTER 1. INTRODUCTION

Table 1.3:: The most important past & present space-born γ -ray missions.

Mission	Launched /	End of mission	Instruments
GRANAT	1989	1999	SIMGA (30-1300 keV) PHEBUS (0.1-100 MeV) KONUS-B (0.01-8 MeV) TOURNESOL (0.002-20 MeV)
Compton Gamma Ray Observatory (CGRO)	1991	2000	OSSE (0.06-10 MeV) COMPTEL (0.8-30 MeV) EGRET (20-3000 MeV) BATSE (0.015-110 MeV)
International Gamma-Ray Astrophysics Laboratory (INTEGRAL)	2002	–	SPI (0.02-8 MeV) IBIS (0.015-10 MeV)
Astrorivelatore Gamma ad Immagini LEggero (AGILE)	2007		GRID (30 MeV-50 GeV) MC (0.25-200 MeV)
Fermi gamma ray space telescope	2008	–	LAT (20 MeV-300 GeV) GBM (8 keV-30 MeV)

1.2 *Chandra* X-Ray Observatory

In 1976, first proposal of the *Chandra* X-ray Observatory (CXO) was submitted to NASA, under the title of Advanced X-ray Astrophysics Facility (AXAF).² It was later named after the Nobel-prize winning astronomer, **S. Chandrasekhar**, who is credited with the first detailed calculations of black hole critical mass limits. On 23rd July 1999, the CXO was launched by NASA's Space Shuttle Columbia, with Eileen Collins commanding. *Chandra* spacecraft, shown in Figure 1.3, rotates around the Earth on elliptically orbit with ~ 63.5 hr period, the apogee height $\sim 140,000$ km and the perigee height $\sim 16,000$ km. Even after 20 years, the *Chandra* operation (still ongoing) remains excellent. With well-calibrated instruments, the extended observation baseline allows temporal studies over timescales from milliseconds to years.

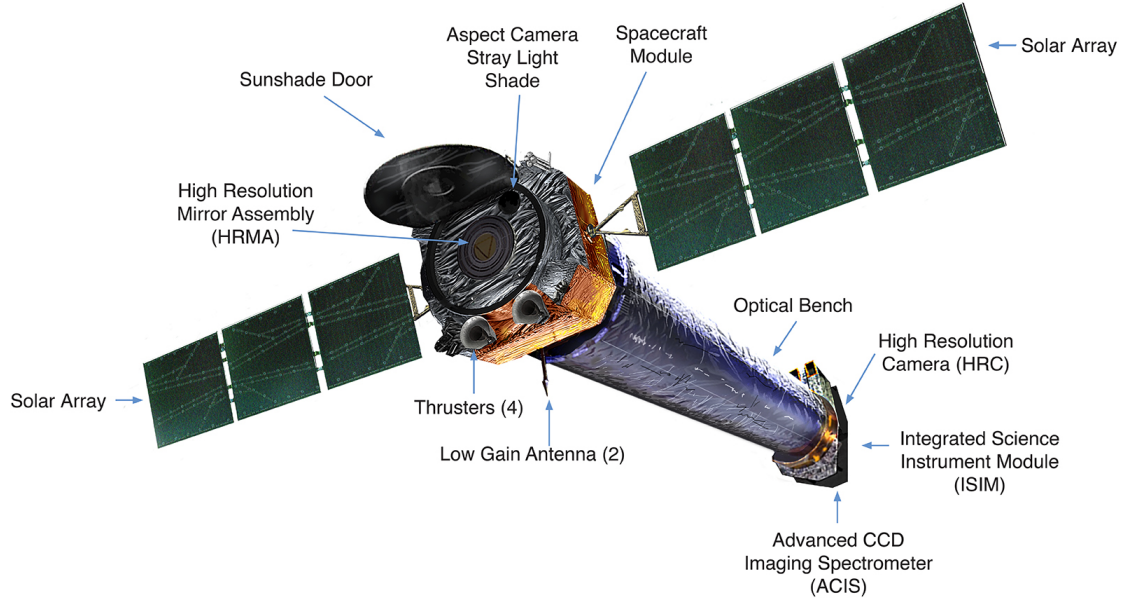


Figure 1.3: Schematic diagram of the *Chandra* spacecraft with the main components labeled. (Credit: NASA/CXC/SAO & J.Vaughan)

The key feature of *Chandra* is the great advanced angular resolution, with sub-arcsec FWHM. *Chandra*'s High Resolution Mirror Assembly (HRMA) has 10 m focal length and consists of four pairs of nested grazing-incidence mirrors along with their support structure (Burke et al. 1997). The thick mirrors are polished and provides an angular resolution of $0.492''$ on axis, which allows *Chandra* to collect $\sim 80 - 95\%$ of incoming X-rays within a circular region of $1''$ radius. *Chandra*'s angular resolution is therefore an order of magnitude

²<https://cxc.harvard.edu>

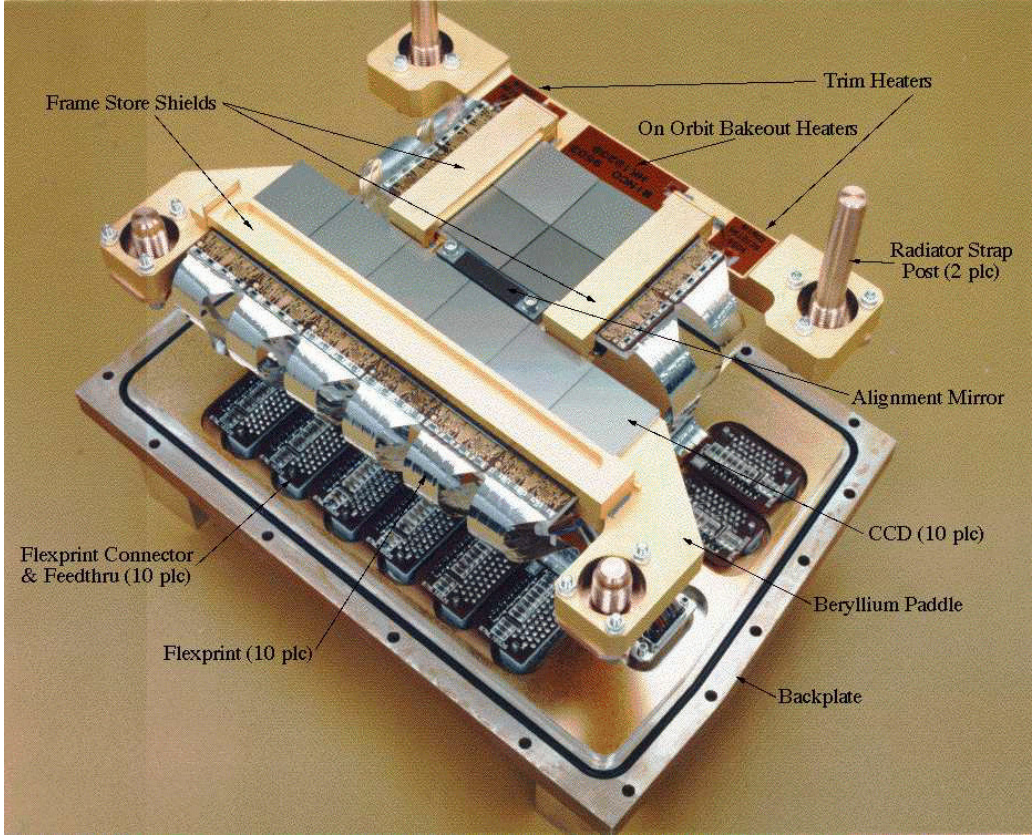


Figure 1.4: The structure of the ACIS (Credit: NASA/CXC/SAO).

greater than the first orbital X-ray telescope *Einstein* (Giacconi et al. 1979). *Chandra* includes two Science Instrument Modules, the Advanced CCD Imaging Spectrometer (ACIS; Garmire 1997) and the High Resolution Camera (HRC; Murray et al. 1997). Both instrument made of a spectroscopic array (HRC-S and ACIS-S, used in combination with transmission gratings) alongside with array of imaging (HRC-I and ACIS-I) intended for wide field imaging.

1.2.1 The Advanced CCD Imaging Spectrometer (ACIS)

The ACIS is a focal plane instrument used for measuring the position, energy and time of incoming X-ray photons. The structure and configuration of the ACIS is shown in Figures 1.4 and 1.5, and its basic parameters³ are summarized in Table 1.4. The ACIS contains two arrays of 1024×1024 pixel CCDs. (i) The imaging array, ACIS-I consists of a 2 by 2 array of front-illuminated CCDs, providing a $17' \times 17'$ wide field of view optimized for spectrally resolved, high-resolution ($\lesssim 0.5''$) imaging. (ii) The spectroscopy array, ACIS-S

³<https://cxc.harvard.edu/proposer/POG/html/chap6.html>

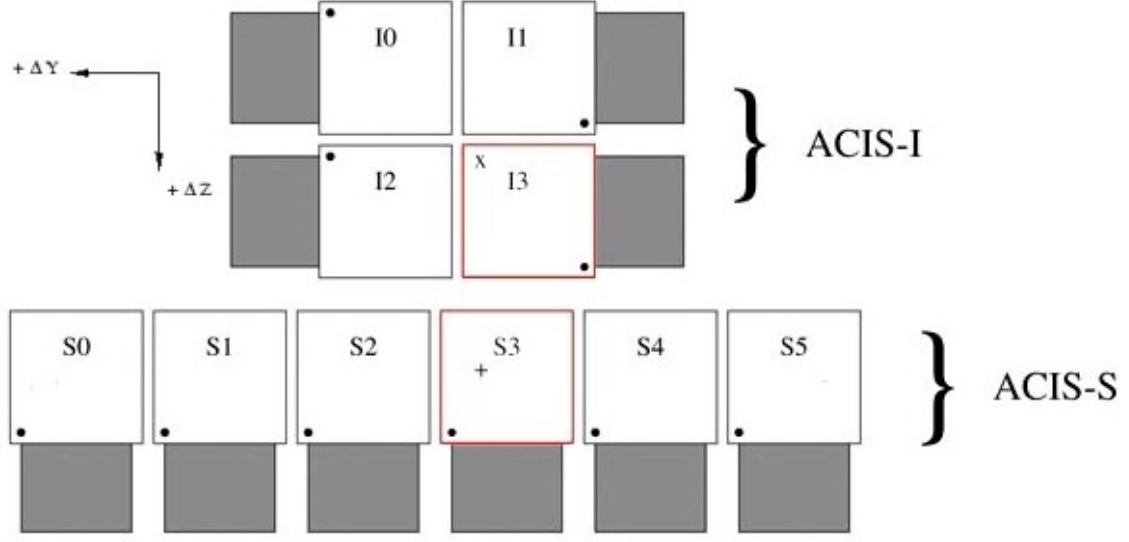


Figure 1.5: A schematic diagram of the ACIS focal plane. Note ACIS-S (S3) and ACIS-I (I3) are the aimpoints.

consists of a 6 by 1 array of charged coupled devices (CCDs), including 4 front-illuminated and 2 back-illuminated CCDs (S3 & S0). The ACIS-S array presents a $8' \times 51'$ field of view. Front-illuminated (FI) CCDs have the gate electrodes which focusing towards the incoming photons, providing them a significantly higher quantum efficiency (than back-illuminated CCDs) at photon energies of $\gtrsim 3$ keV. Back-illuminated CCDs have the gate electrodes facing away from the incoming photons, offering them greater quantum efficiency (than FI CCDs) at photon energies of $\lesssim 1$ keV. The ACIS four-dimensional data set provides X-ray images, low-resolution spectra and light curves for any source or region in the image.

Table 1.4:: The characteristics of ACIS instrument.

Focal-plane arrays		
Illumination Method		2 CCDs are back-side illumination (BI) 8 CCDs are front-side illumination (FI)
Charge Transfer Method		Frame Transfer
Number of pixels in each chip		1024 by 1024 pixels
Pixel Size		$24 \mu\text{m}$ (corresponding to 0.492 ± 0.0001 arcsec)
Frame transfer time		$41 \mu\text{sec}$
Frame time		0.2 to 10.0 sec (nominally 3.2 sec)
Operating temperature		-90 to -120 °C (nominally -120 °C)
Quantum Efficiency	FI chip	$\gtrsim 80\%$ (3.0 – 5.0 keV) $\gtrsim 30\%$ (0.8 – 8.0 keV)
	BI chip	$\gtrsim 80\%$ (0.8 – 6.5 keV) $\gtrsim 30\%$ (0.3 – 8.0 keV)
Arrays	ACIS-I	4 CCDs in a square configuration
	ACIS-S	6 CCDs in a linear configuration
Field of view	ACIS-I	16.9 by 16.9 arcmin ²
	ACIS-S	8.3 by 50.6 arcmin ²

The spatial resolution for the on-axis point source is constrained with the physical size of the CCD pixel of the ACIS, rather than by the HRMA. The fraction of encircled energy with respect to radius is shown in the Figure 1.6 for an on-axis point source. Around 90 percent of the X-rays are included within a diameter of 4 pixels ($\sim 2''$) at 1.49 keV and 5 pixels ($\sim 2.5''$) at 6.4 keV.

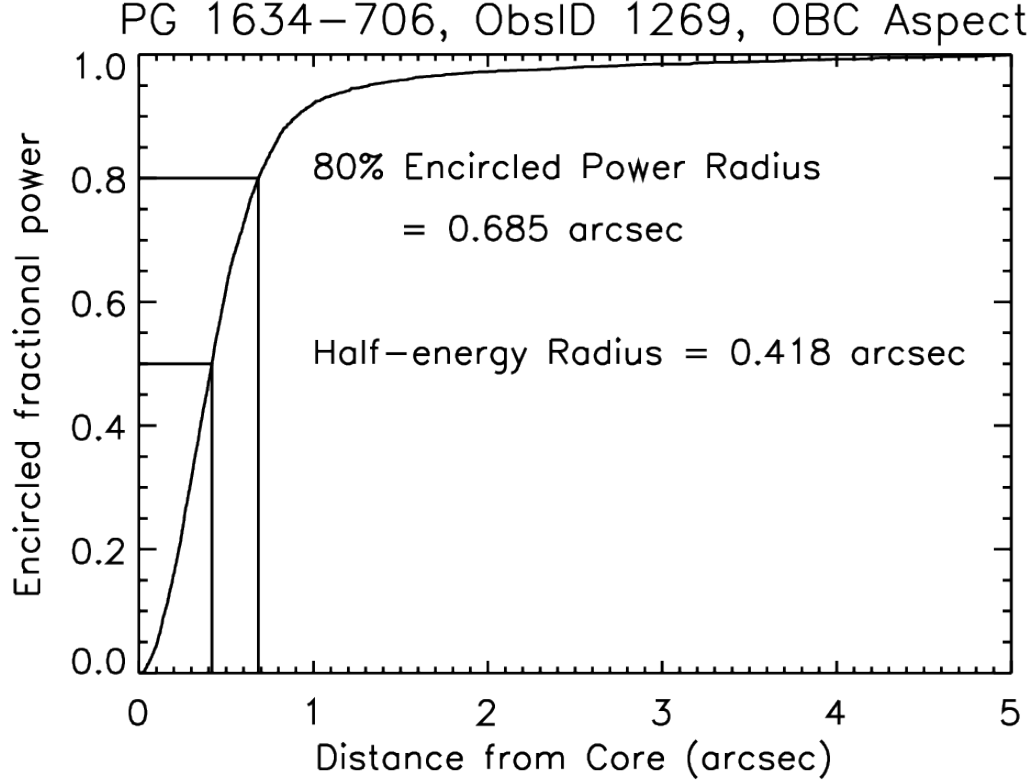


Figure 1.6: The encircled fractional power versus the radius of point source with HRMA plus ACIS at 1 keV observation of PG 1634-706.

1.2.2 Standard Data Processing (SDP)

The *Chandra* observations are downloaded from the satellite then processed, archived, and delivered to the proposing team. The CXC Data System's Operation team performs standard data processing for all the *Chandra* observational data. This includes several steps, each one built on the results of the preceding level. A well-defined set of data products for each level is transferred to the archive.

Level 0 processing extracts time-tagged information from the telemetry stream into multiple parallel streams for each science instrument and spacecraft subsystem;

CHAPTER 1. INTRODUCTION

Level 0.5 determines the as-run instrument configuration and on-sky science time to ensure that all received science data are included;

Level 1 performs the main scientific data calibration, to map the X-ray event positions from the individual detector elements (i.e., the individual CCDs for ACIS) onto a single, uniform “idealized” detector pixel grid on the focal plane and corrects for spatial distortions. The SDP determines the appropriate calibration product to apply based on the observation date and engineering data (e.g., focal-plane temperature); the last step will be the good time intervals (GTIs), during which all science data collected are within valid limits on all spacecraft and instrument subsystems, are defined for each data set;

Level 2 is the final step of SDP in which the science data within GTIs are extracted and any bad data filtered out; this is followed by an automated validation and verification (V&V) process to ensure that the observation was performed as requested by the observer and data processing did not encounter any errors; in most cases, level 2 data files should be used for data analysis.

All data products are recorded in the astronomical standard file name, ‘Flexible Image Transport System’ (FITS) format and comply with International Virtual Observatory Alliance (IVOA) standards that facilitate interoperability with data from other observatories and wavebands, and High Energy Astrophysics Science Archive Research Center (HEASARC) standards that promote compatibility with high-energy astrophysics data analysis packages, such as CXC’s portable CIAO data analysis package.

Science data processing is fully automated, with *Chandra* data being available to the observer after the observation is completed. The Chaser archive interface⁴ provides search and retrieval capabilities for all public data in the archive. Proprietary data sets, i.e., those within a year of the completion of SDP, are only available to the original proposing teams.

Level 3 products are determined for all the significant *Chandra* sources derived by merging all public data sets from the archive for each region of sky, to generate the *Chandra* Source Catalog (CSC)⁵.

CSC 2.0, including all the data up to 2014, was released in 2019.

⁴<https://cda.harvard.edu/chaser/>

⁵<https://cxc.cfa.harvard.edu/csc/>

1.2.3 Data Analysis Software

The *Chandra* X-ray Center (CXC) provides a powerful, flexible, multidimensional set of data analysis software ‘Chandra Interactive Analysis of Observations’ (CIAO)⁶. We used the CIAO package for processing and analysis of the *Chandra* data for the Pictor A radio galaxy, noting that the software could also been useful for analysing the data from other, non-X-ray missions. CIAO includes a set of advanced data manipulation tools – the Data Model (DM) tools – which operate both on ASCII text files and on FITS images and binary tables. CIAO version 4.12 is used for our analysis work presented in this thesis. We also use the X-ray data analysis software package HEASOFT, which is implemented by the High Energy Astrophysics Science Archive Research Center (HEASARC) of the NASA’s Goddard Space Flight Center ⁷. We also use the Sherpa package version 4.12, which is a Python language-based, model-parameter-fitting program, developed for the spectral and spatial fitting of *Chandra* data, but with widely applicable functionality, including advanced Bayesian fitting methods.

Finally, we used MARX simulation tool⁸, which is designed and controlled by the MIT/CXC/HETG group to simulate the on-orbit performance of the CXO. MARX offers a comprehensive ray-trace simulation for *Chandra* telescope. It includes precise models for the High Resolution Mirror Assembly(HRMA) of *Chandra*, the gratings HETG and LETG, as well as the focal plane detectors. The MARX program uses for simulating sources’ point spread functions (PSFs), including both mirror and detector properties.

For image-based analysis, the SAOImage DS9 program⁹ has been developed alongside CIAO, and integrated with it, including a GUI-based analysis menu supporting a variety of *Chandra* analysis tasks. DS9 can be used independently from CIAO, and is widely used by the astronomical community for visualization and analysis of non-Chandra data.

⁶<http://cxc.harvard.edu/ciao/>

⁷<http://heasarc.gsfc.nasa.gov/lheasoft/>

⁸<https://space.mit.edu/cxc/marx/>

⁹<https://ds9.si.edu/site/Home.html>

1.3 Active Galactic Nuclei

My research summarized in this thesis, intends to expand our knowledge of the particular radio galaxy Pictor A, widely considered the archetypal Radio-loud and luminous (high-power) active galaxy, by means of the detailed analysis of the *Chandra* X-ray Observatory data, combined with the radio and optical observations. In this way, we hope to understand better various physical processes that take place in extended lobes, relativistic jets, and nuclei of active galaxies in general.

With its angular resolution of $\sim 0.5''$, the CXO is the only instrument able to resolve the extended lobes and jets of Pictor A. Hence, *Chandra* imaging allows us to investigate spatial and energy distributions of the lobes' and jets' ultrarelativistic electrons, producing the observed X-ray photons via synchrotron and inverse-Compton emission processes, and in this way to diagnose the large-scale structure of the lobes' magnetic field. The X-ray emission of the unresolved nucleus of the target, on the other hand, is dominated by the accretion disk in the system, with a significant contribution from the bremsstrahlung emission of the hot gas present within the interstellar medium of the host galaxy. Our understanding of all such components is still insufficient in many respects, for example regarding the structure of the jets' termination shocks, or of the accretion disk corona. The quality and quantity of the available X-ray observations is however already good enough, in principle, to constrain model parameters. My aim is to fill some of the gaps in our understanding of the AGN phenomenon, by way of providing new insights into the X-ray radiative output of Pictor A, radio galaxy.

1.3.1 AGN Phenomenology

AGN constitute now a well established class of astronomical objects, which has been observed throughout the entire available electromagnetic spectrum — i.e., from radio frequencies $\lesssim 100$ MHz up to VHE γ -rays with photon energies ≥ 100 GeV — over the past 100 years. Many different classes and types of AGN have been identified over the last decades, and general AGN unification schemes have been developed as well, aiming for a comprehensive view on the AGN phenomenon behind the observed variety and diversity.

The basics of the AGN phenomenology could be presented in different ways, for example, by mapping various AGN components depending on the frequency range of the dominant radiative output, and the characteristic size, as shown in Figure 1.7. This mapping demonstrates a huge range in spatial scales involved, from $\lesssim 10^{25}$ cm characterizing the lobes in giant radio galaxies, down to $\gtrsim 10^{12}$ cm corresponding to event horizons of SMBHs in lower-mass AGN. Based on the band-specific characteristics of the AGN emission (predominantly radio and optical properties), and reflecting to some extent historical development, AGN can be further divided into a variety of types, such as Seyfert galaxies, quasars, radio galaxies and blazars, as presented in Figure 1.8 and listed in Table 1.5 from

Tadhunter (2016).

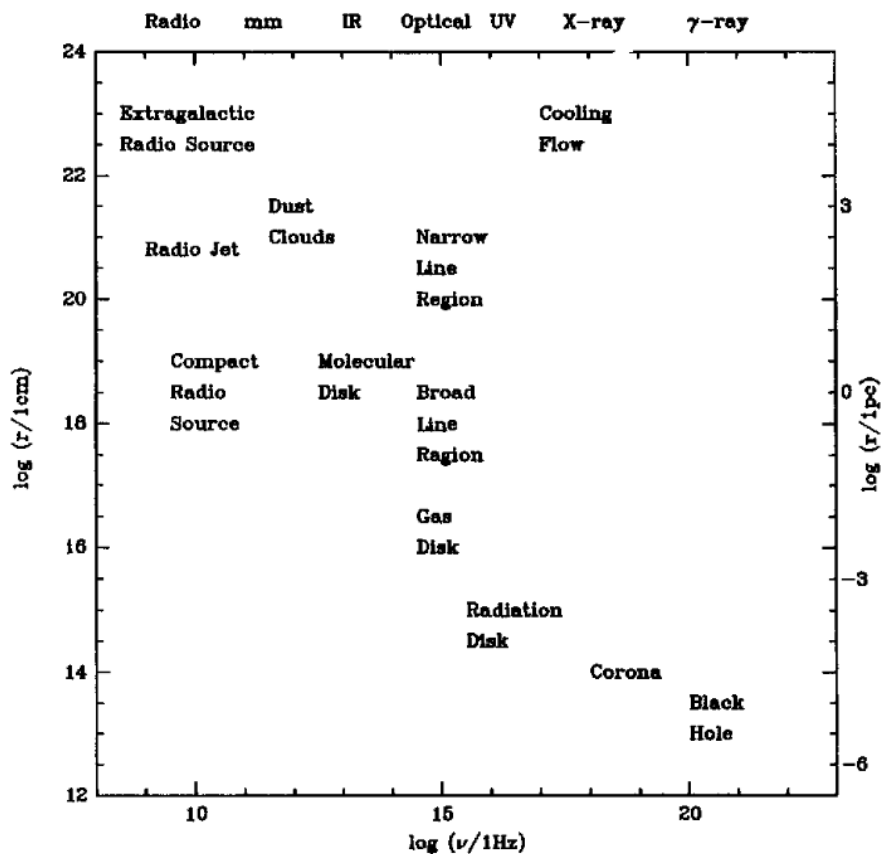


Figure 1.7: Schematic mapping of the AGN phenomenon. (Credit: Blandford 1990).

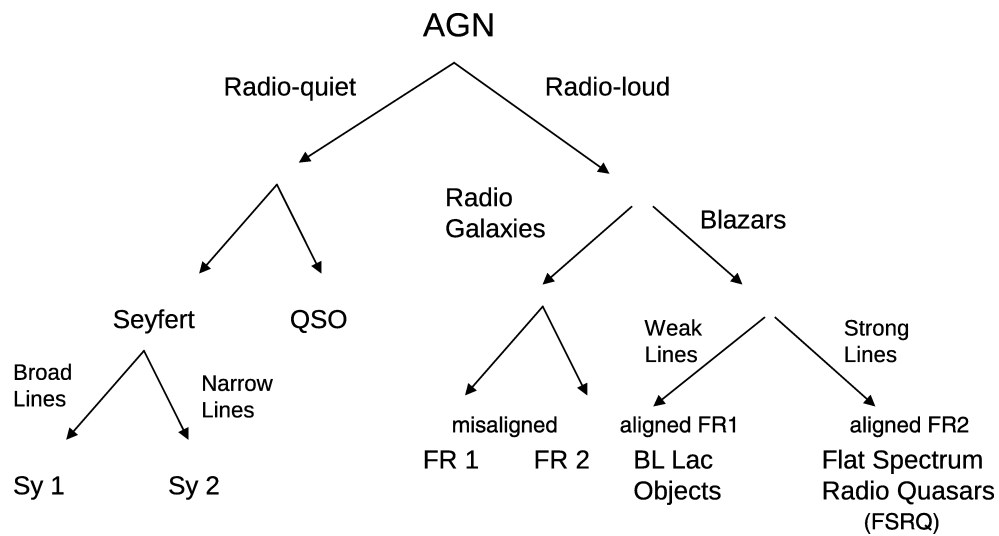


Figure 1.8: Basic types and classes of AGN based on observational criteria. (Credit: Dermer & Giebels 2016).

CHAPTER 1. INTRODUCTION

Table 1.5:: Classification of AGN based on their optical and radio properties.

Abbreviation	Expansion	Definition	Density [Gpc^{-3}]	L_{bol} [erg s^{-1}]
LINER	Low-Ionization Nuclear Emission-line Region	Weak Seyfert-like galaxy	$\sim 10^{6.5}$	$< 10^{42}$
Sy 2	Seyfert galaxy type 2	AGN with narrow permitted & forbidden lines	$\sim 10^{5.3}$	$> 10^{42}$
Sy 1	Seyfert galaxy type 1	AGN with broad permitted & narrow forbidden lines	$\sim 10^{5.0}$	$> 10^{42}$
QSO	Quasi-Stellar Object	Powerful AGN that outshines its host galaxy	$\sim 10^{2.5}$	$> 10^{45}$
WLRG	Weak-Line Radio Galaxy	radio galaxy analog to LINER	$\sim 10^4$	$< 10^{42}$
NLRG	Narrow-Line Radio Galaxy	radio galaxy analog to Sy 2	$\sim 10^{1.2}$	$> 10^{42}$
BLRG	Broad-Line Radio Galaxy	radio galaxy analog to Sy 1	~ 10	$> 10^{42}$
QSR	Quasi-Stellar Radio source	QSO with strong radio emission	$\sim 10^{-1.5}$	$> 10^{45}$

From the historical perspective, the first observational evidence for the enhanced emission lines in the nuclei of some galaxies, were found by Edward A. Fath (1880-1959). Later, Carl K. Seyfert (1911-1960) announced that a small percentage of galaxies had unusually bright nuclei. These sources, recognized by their broad emission lines produced by atoms in a wide range of ionization states, are nowadays known as “Seyfert galaxies”, and are broadly divided into two main sub-classes. Seyfert 1 type galaxies have very broad emission lines, that include permitted lines (H I, He I, He II) and forbidden (narrow) lines (O III). Seyfert 1 type galaxies also have “narrow” permitted lines, although these are still broad compared to the spectral lines displayed by normal galaxies. The width of lines are consistent with Doppler broadening, which indicates that the permitted lines originate from the sources with speeds between 1,000 and 5,000 km/s, while the forbidden lines correspond to speeds of approximately 500 km/s. Seyfert 2 type galaxies have only narrow lines (both allowed and forbidden), with a characteristic speed of ~ 500 km/s. Sources with both broad and narrow permitted lines, are often classified as an intermediate type Seyfert 1.5. It is important to highlight this spectral classification, since the most pronounced X-ray emitters among galaxies in general, are Seyferts of types 1 and 1.5. The X-ray emission of such is, in addition, variable, and can change on timescales from years to hours. In contrast, the Seyfert 2 galaxies are much weaker emitters in the soft X-ray band, though they may be quite bright at hard X-rays; this indicates that the ‘missing’ soft X-rays are absorbed by intervening material with high and very high hydrogen column densities between 10^{22} and 10^{24} cm^{-2} .

In general, there is a wide-spread consensus on the idea that all the spectral and morphological diversity exhibited by AGN, could be understood in a framework of a relatively simple unification scheme, in which all the AGN are intrinsically similar, or at least represent a continuous distribution in the most basic parameters (namely: the accretion rate, and the jet production efficiency), and only appear differently to the observer, depending on the viewing angle with respect to the accretion disk/jet axis. Various versions of the unification scheme are presented in numerous review articles and textbooks, and often sum-

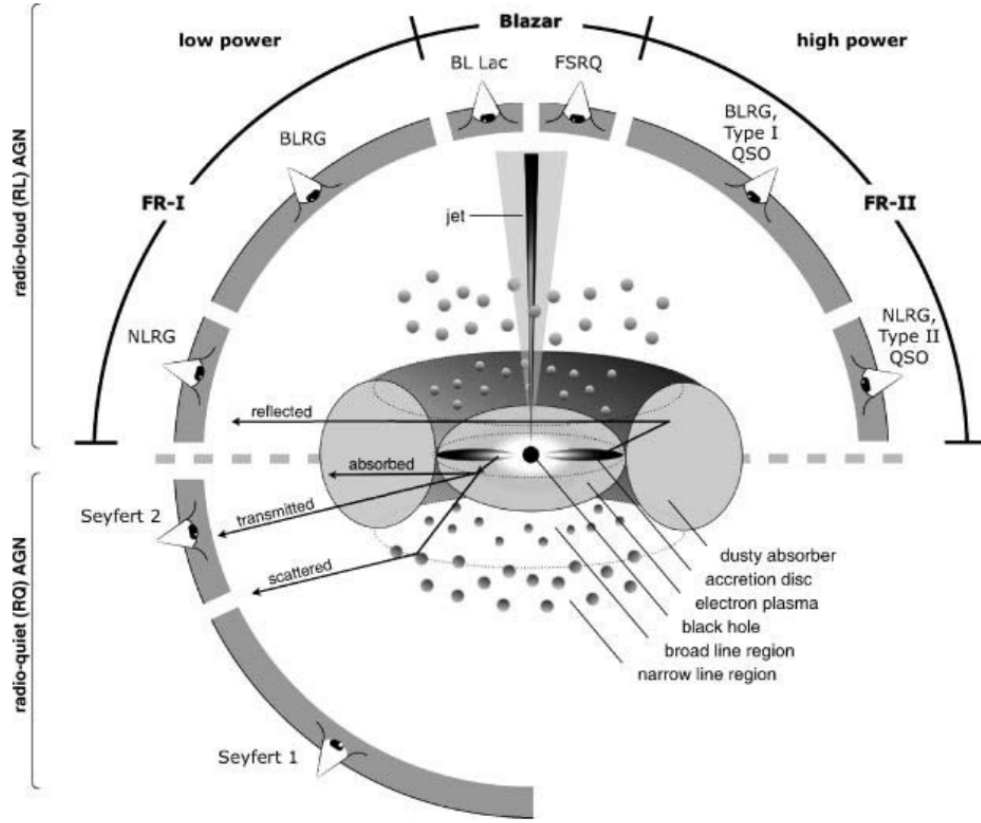


Figure 1.9: Schematic representation of the AGN phenomenon in the unified scheme. (Credit: [Beckmann & Shrader 2012](#)).

marized in a form of diagram such as the one given in Figure 1.9 following [Beckmann & Shrader \(2012\)](#). The key features in all of such scenarios, are the anisotropic obscuration of the nucleus by hot circumnuclear dust (“dusty torus”), combined with strongly anisotropic and Doppler-boosted emission of relativistic jets.

1.3.2 Broad-band Emission Spectra of AGN

The schematic diagram of the broad-band AGN continuum, from radio up to the X-ray range, is shown in Figure 1.10. It highlights the main radiative components in a generic spectrum of high-luminosity AGN (such as Seyfert 1s, BLRGs, or QSOs). There, a power-law radio continuum originates from a synchrotron emission of jets and lobes in the case of “Radio-loud” (i.e., jetted) AGN, and from a combination of a free-free and synchrotron emission of massive nuclear outflows in “Radio-quiet” AGN. Only around 10% of AGN is Radio-loud at a given epoch. The “Big Blue bump”, on the other hand, dominating at optical-to-UV frequencies, represents the direct radiative output of a standard (geometrically-thin/optically-thick) accretion disk. A significant fraction of this direct disk emission ($\sim 10\%$) is repro-

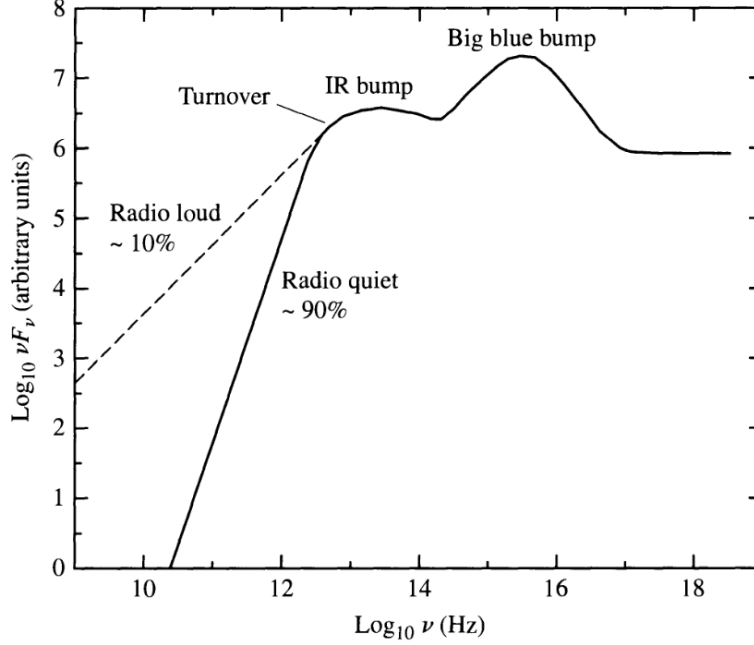


Figure 1.10: A sketch of the broad-band continuum observed in many types of AGN. (Credit: [Carroll & Ostlie 1996](#)).

cessed by the circumnuclear hot dust, and re-emitted at infrared frequencies, forming in this way the observed “IR bump”. At the same time, hot corona of accretion disks, up-scatter the $\sim 1 - 10\%$ of the UV photons from the disk into the X-ray range.

The X-ray continua of high-power AGN, can be parametrized by a power-law function,

$$F_E \propto E^{-\Gamma} \quad (1.1)$$

where E is the photon energy, and F_E is the photon flux spectral density (in the units of, e.g., $\text{cts s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$). The average value of the corresponding photon-index in the local Universe is $\Gamma = 1.9$, with a typical spread within the range $1.5 - 2.0$ ([Nandra & Pounds 1994](#); [Bianchi et al. 2009](#); [Piconcelli et al. 2005](#)). This non-thermal power-law spectrum arises due to multiple inverse-Compton up-scatterings of accretion disk photons off Maxwellian-distributed hot electrons present within the corona (e.g., [Guilbert & Rees 1988](#); [George et al. 1990](#); [George & Fabian 1991](#); [Matt et al. 1991](#); [Nandra & George 1994](#)).

The more exact decomposition of the AGN X-ray continuum, as shown in Figure 1.11, includes in addition also the Compton reflection hump, and the “soft X-ray excess”. The former component originates when a part of the X-ray emission of the corona reflects from the accretion disk surface. Note that such a reflection is expected to be accompanied by the formation of the iron fluorescent line, at the rest-frame photon energies of 6.4 keV (in the case of a neutral reflector and negligible GR effects related to the SMBH gravitational potential; see in this context [Reynolds & Nowak 2003](#)). The origin of the soft X-ray excess is still under the debate.

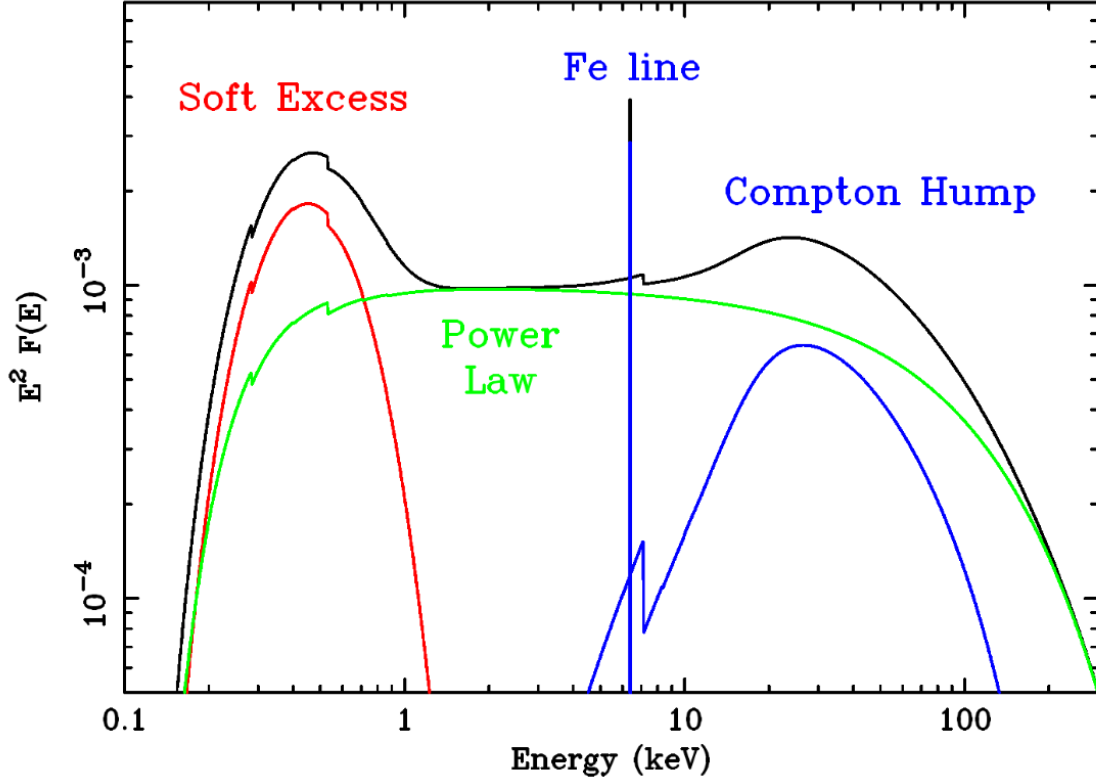


Figure 1.11: A zoom to the AGN accretion disk X-ray continuum (Credit: [Fabian & Miniutti 2005](#)).

1.3.3 Radio Galaxies

In the framework of the most general AGN unification scheme, Radio Galaxies are simply Radio-loud (jetted) AGN observed at intermediate and larger viewing angles with respect to the jet axis.¹⁰ We note that the direction of the **jets** traces the rotational axis of a spinning black hole, and of the accretion disk. Each radio galaxy contains a point-like **radio core**, which coincides with the nucleus of its host. The nuclei of radio galaxies share many characteristics with Seyferts or LINERs, depending on the corresponding accretion rates. In particular, based on the optical spectral properties of their nuclei, high-power radio galaxies, can be divided into two sub-classes, namely Broad-Line Radio Galaxies (BLRGs), and Narrow-Line Radio Galaxies (NLRGs), in the direct analogy to Seyfert 1s and Seyfert 2s, respectively.

In 1974, B. L. Fanaroff and J. M. Riley noted that Radio-loud AGNs (included in the 3rd Cambridge Catalog) could be categorized into two types based on their total radio

¹⁰Radio-loud AGN observed at small and very small viewing angles with respect to the jet axis, are called “Blazars”.

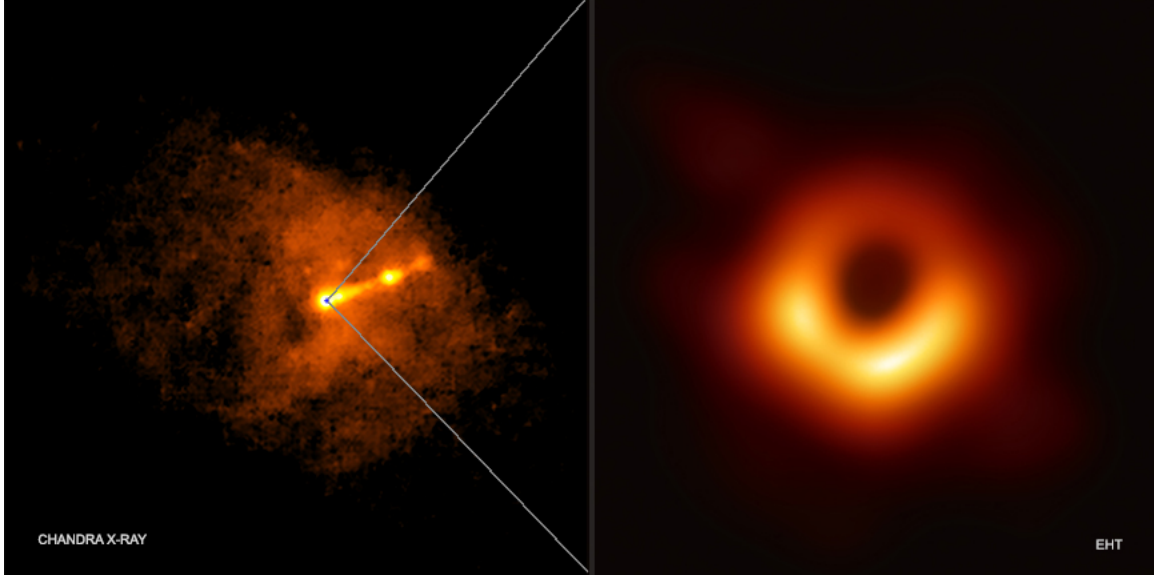


Figure 1.12: Left:: *Chandra* X-ray image of the M87 radio galaxy with the X-ray jet extending to the right. **Right:** The zoom toward the central $10 r_g$ (where, r_g is the gravitational radius of a black hole) obtained by the EHT. (Credit: X-ray: NASA/CXC/Villanova University/J. Neilsen; Radio: Event Horizon Telescope Collaboration.)

luminosity and large-scale morphology (Fanaroff & Riley 1974). In the case of “type I” (FR I) objects, the ratio of the distance between the brightest spots of radio emission on either side of the center (excluding the central source) to the full extent of the radio source is less than 0.5. In “type II” (FR II) class objects, the aforementioned ratio is greater than 0.5. Generally, FR I galaxies have two recognizable radio jets, while FR II galaxies often exhibit only a single detectable jet (the counterjet is either very weak or undetectable) terminating in a bright **hotspot**, in addition to two prominent **lobes** positioned at both sides of the nucleus. Furthermore, FR I galaxies have typically curved jets, while FR II galaxies have jets that tend to be straight. There is a clear separation between FR I and FR II types in terms of the specific luminosity: sources having a specific luminosity less than $10^{25} \text{ W Hz}^{-1}$ at 1.4 GHz are identified as FR Is, and otherwise as FR IIs.

The Fanaroff & Riley division correlates – at least to some extent – with the optical classification of the nuclear activity: the optical nuclei of FR II radio sources are typically classified as high-excitation objects (i.e., QSRs, BLRGs, or NLRGs), while the optical nuclei of FR I radio sources are typically classified as low-excitation objects (i.e., LINER/WLRGs), although recently many outliers have been identified in this respect. *Pictor A* is one of the prime examples of an FR II type radio galaxy (a “classical double”), with the high-excitation nucleus of the BLRG type.

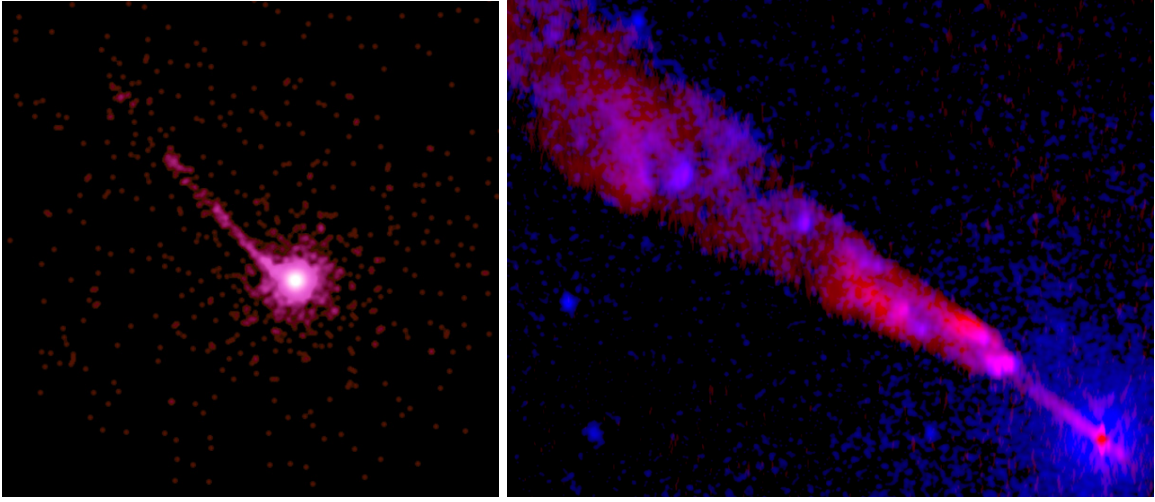


Figure 1.13: Left: The *Chandra* X-ray image of the distant radio quasar PKS 1127–145, revealing the jet that extends at least a million light years from the core. (Credit: NASA/CXC/ A.Siemiginowska / J.Bechtold). **Right:** A composite image of *Chandra* X-ray (blue) and VLA radio (red) observations showing the inner 4,000 light years of a jet in the nearby radio galaxy Centaurus A. (Credit: X-ray: NASA/CXC/Bristol U./M. Hardcastle et al.; Radio: NRAO/AUI/NSF/Bristol U./ M. Hardcastle.)

Radio Cores

The unresolved cores of radio galaxies, coincide with SMBHs in the systems. Previous studies have shown that the cosmological evolution of SMBHs in general – their growth and activity duty cycle – is tightly connected to the cosmological evolution of host galaxies (see, e.g., [Richstone 1998](#); [Ferrarese & Merritt 2000](#); [Kormendy & Gebhardt 2001](#); [Ferrarese 2002](#); [Kormendy et al. 2009](#)). The observational studies of the SMBH activity in the population of local radio galaxies, carried out by means of modelling the nuclear emission spectra at radio, optical, and X-ray frequencies, are plentiful (e.g., [Best et al. 2005](#); [Balmaverde & Capetti 2006](#); [Capetti & Balmaverde 2006](#); [Chiaberge et al. 2005](#); [Nagar et al. 2005](#); [Filho et al. 2006](#); [Gallo et al. 2008](#)). However, only very recently, the Event Horizon Telescope (EHT) resolved the radio core in the nearby radio galaxy M 87 at the angular scale of micro-arcseconds, and in this way produced the first radio “image” of the active SMBH ([Event Horizon Telescope Collaboration et al. 2019a,b](#)), shown in Figure 1.12.

Large-scale Jets

The jets in radio galaxies, extending from radio cores up to terminal hotspots located at tens and hundreds of kpc distances from the centers, have been widely studied at radio frequencies throughout the last decades of the previous century [Bridle & Perley \(1984\)](#).

CHAPTER 1. INTRODUCTION

One of the most important discoveries of *Chandra* in the beginning of this century, was the detection of an intense X-ray emission of the kpc-scale jets in both FR I and FR II sources (Harris & Krawczynski 2006; Worrall 2009)¹¹. The example of such are shown in Figure 1.13. Note that *Chandra* is the only instrument that could resolve and image such structures at X-ray frequencies, due to the unprecedented arcsec resolution and high sensitivity of the instrument.

Jets in FR II radio galaxies have small opening angles, and magnetic field that aligns parallel to the jet axis. The radio brightness asymmetry between counter-jet and the jet is greater than a factor 4, implying that inside the jets, magnetized plasma is moving with relativistic speeds; as a result, the jet emission is relativistically beamed and strongly anisotropic.

Terminal Hotspots and Lobes

The hotspots are compact (linear size < 1 kpc) termination regions of large-scale jets in FR II sources. Those structures are understood as mildly-relativistic shocks formed when high-kinetic power but low-density relativistic jets interact with the dense ambient (intergalactic) medium. The extended lobes are formed as a backflow of the jet matter passing through the termination shocks. Harris et al. (1994) was the first to detect the X-ray emission from hotspots of the powerful radio galaxy Cygnus A, using the ROSAT HRI (see the upper panel in Figure 1.14). The *Chandra* X-ray Observatory confirmed the preliminary ROSAT results (Wilson et al. 2000), and resolved the entire complex structure of Cygnus A at X-rays in much more detail (including the intracluster environment, the extended lobes, and the large-scale jets; see the lower panel in Figure 1.14).

¹¹<https://hea-www.harvard.edu/XJET/>

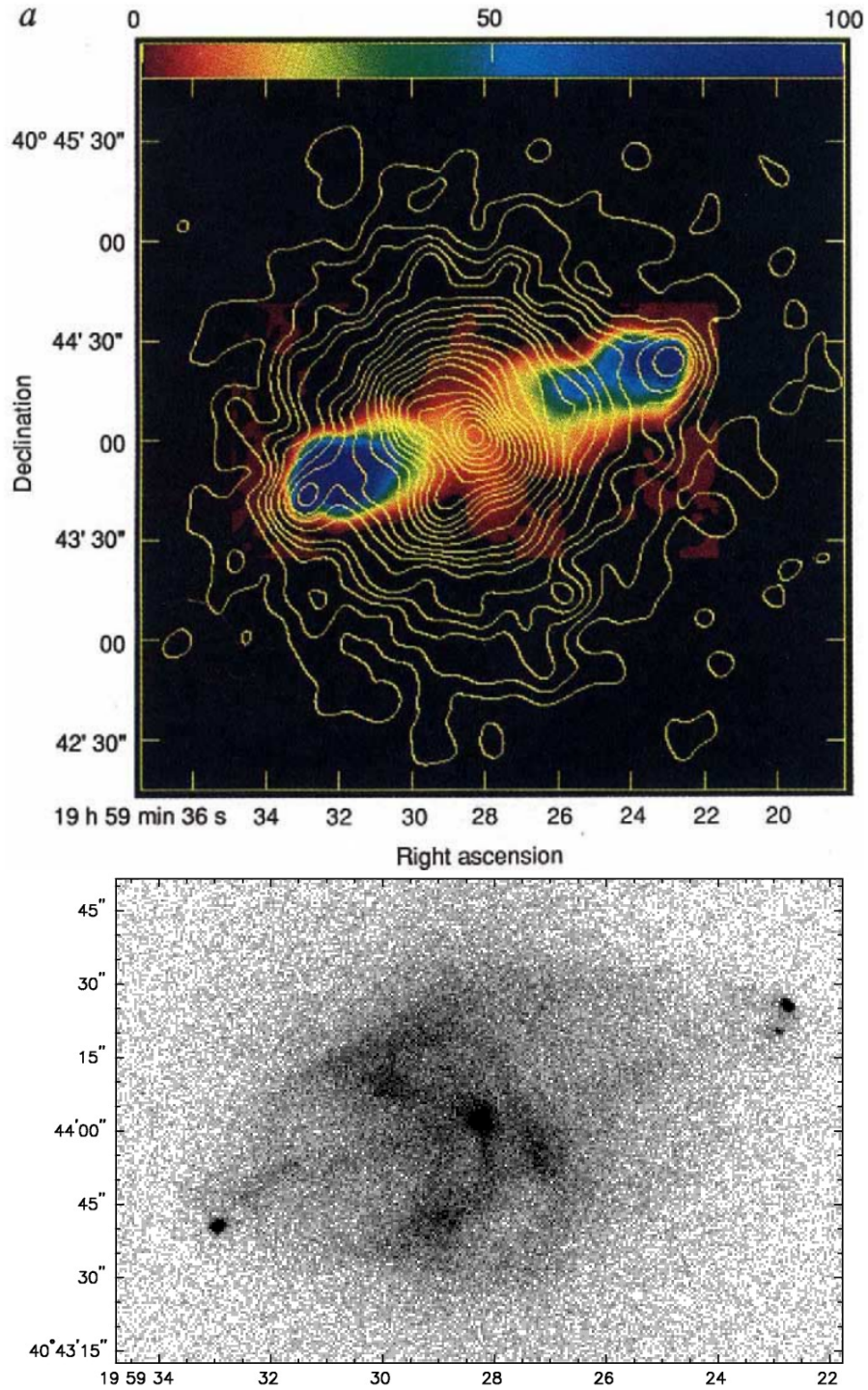


Figure 1.14: **Top:** Cygnus A X-ray contours obtained with the ROSAT HRI, superimposed on the 327 MHz VLA color image ([Harris et al. 1994](#)); **Bottom:** Cygnus A X-ray image by the CXO ([Wilson et al. 2000](#)).

1.4 Radiative Processes

In this section, we briefly discuss various radiative processes that are of importance for the production of cosmic X-ray photons. Both thermal and non-thermal processes may play a role in this respect, depending on the particular physical conditions characterizing a given source. Thermal radiation refers here to the emission of particles with a Maxwellian distribution, and non-relativistic velocities. Non-thermal radiation, on the other hand, involves particles, usually electrons (or electron-positron pairs), with very high energies that are far from a thermal equilibrium and typically have power-law distribution of momenta/energies.

Thermal radiation from a plasma with a temperature T , in particular the thermal bremsstrahlung (free-free) radiation, has a spectrum that peaks at photon energies $\varepsilon \equiv h\nu \sim kT$, where h is the Planck constant, ν is the frequency of the electromagnetic wave, and k is the Boltzmann constant. Beyond the peak frequency, the radiation spectrum falls off exponentially, so that the production of X-rays with energies of the order of $\varepsilon \sim 1$ keV, requires plasma temperatures of the order of

$$T \sim \varepsilon/k \sim 10^7 \text{ K}. \quad (1.2)$$

In addition to the bremsstrahlung continuum, thermal plasma produces also emission lines, depending on its ionization and metallicity states; those lines become the dominant radiative cooling mechanisms for the gas with temperatures $< 10^6$ K (Peterson & Fabian 2006).

Non-thermal X-ray radiation in the Universe is often produced via the synchrotron process involving ultra-relativistic electrons. Here relativistic effects boost the cyclotron orbital frequency of the electron by a factor γ^2 , where

$$\gamma \equiv \frac{1}{\sqrt{1 - (v/c)^2}} \equiv \frac{E_e}{m_e c^2} \quad (1.3)$$

is the electron Lorentz factor, v is the electron velocity, E_e is the total (rest plus kinetic) electron energy, c stands for the speed of light, and m_e for the electron mass (note that $m_e c^2 \simeq 511$ keV). In particular, the production of a synchrotron X-ray photon with energy $\varepsilon \sim 1$ keV, requires electrons with Lorentz factor

$$\gamma \sim 3 \times 10^5 B_G^{-1/2}, \quad (1.4)$$

where B_G is the magnetic field intensity B in Gauss units.

Another significant production mechanism of cosmic X-ray radiation, is the inverse-Compton scattering, in which ultra-relativistic electron with Lorentz factor $\gamma \gg 1$ boost the energy of the incoming lower-energy photon ε_0 again by a factor γ^2 (in the Thomson regime), so that

$$\gamma \sim \sqrt{\varepsilon/\varepsilon_0}. \quad (1.5)$$

For example, inverse-Compton upscattering of the target Cosmic Microwave Background (CMB) photon ($\varepsilon_0 \simeq 1$ meV) to the X-ray band ($\varepsilon \simeq 1$ keV) requires electrons with $\gamma \sim 10^3$.

1.4.1 Synchrotron Radiation

Synchrotron radiation is produced when ultra-relativistic electrons experience acceleration in a uniform and static magnetic field (see Figure 1.15). The synchrotron theory has been developed by [Schwinger \(1949\)](#), then applied to the cosmic sources of radio emission by [Alfvén & Herlofson \(1950\)](#); for the early ‘history’ of the synchrotron radiation see [Shklovskii \(1960\)](#). The most outstanding property of this emission is that it is strongly polarized, a trait that makes it distinguishable from thermal and other non-thermal radiation mechanisms, and that allows the observer to deduce the configuration of magnetic fields in remote cosmic sources. And since the presence of high-energy electrons and magnetic fields are universal, synchrotron emission can be observed from many classes of astrophysical objects, including jets and extended lobes of AGN, Supernova Remnants (SNRs), interstellar medium of starforming galaxies, or even intracluster medium in some systems.

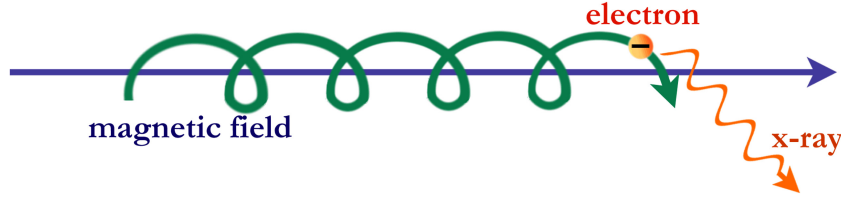


Figure 1.15: Synchrotron radiation produced when relativistic electrons gyrate in a magnetic field. (Credit: NASA/CXC/SAO)

Spectral distribution of the synchrotron emission of a single ultra-relativistic electron forms a continuum, peaked at frequencies

$$\nu \simeq \frac{3 e B \gamma^2}{4 \pi m_e c^2}, \quad (1.6)$$

where e is the electron charge. As a result, the synchrotron spectrum resulting from a power-law electron distribution,

$$n_e(\gamma) \propto \gamma^{-s}, \quad (1.7)$$

is also of a power-law form, in particular

$$j_\nu \propto \nu^{-\alpha} \quad \text{where} \quad \alpha = \frac{s-1}{2}, \quad (1.8)$$

and j_ν stands for the emissivity coefficient. This is illustrated in Figure 1.16. The overwhelming majority of cosmic radio sources are characterized by synchrotron spectral indices $\alpha_{\text{radio}} \sim 0.7$.

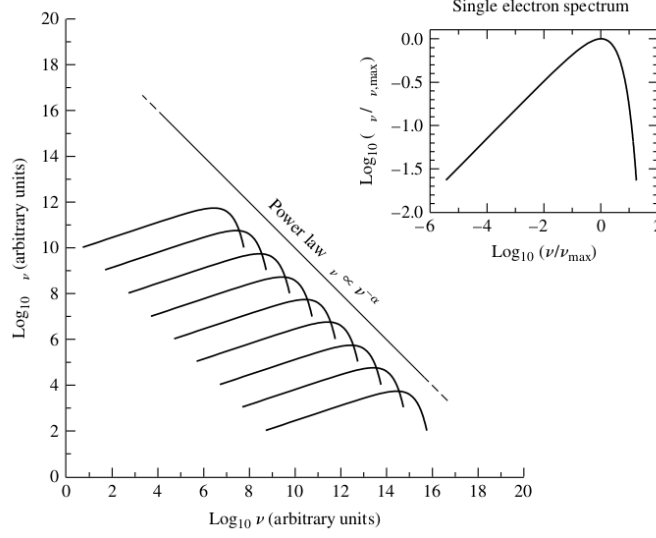


Figure 1.16: A power-law spectrum of the synchrotron radiation produced by a power-law energy distribution of ultra-relativistic electrons. A single electron spectrum is shown at the top right (Credit: [Carroll & Ostlie 1996](#))

Electrons emitting synchrotron photons are losing their energies, and the corresponding characteristic cooling timescale is

$$\tau_{\text{syn}} = \frac{\gamma m_e c^2}{\langle P \rangle_{\text{syn}}} \simeq 20 B_G^{-2} \gamma^{-1} \text{ yr}, \quad (1.9)$$

where $\langle P \rangle_{\text{syn}}$ is the pitch angle-averaged synchrotron power emitted by a single particle. Analysis of spectral breaks and cut-offs related to the synchrotron cooling in the radio continua of Radio-loud AGN, allows us to estimate the lifetimes of the corresponding radio structures, using the very equation 1.9; the resulting values range from $\sim 1,000$ yr in the case of compact lobes of your radio sources, up to ~ 100 Myr in the case of extended lobes of Giant Radio Galaxies (GRGs). We note in this context that, the AGN magnetic field intensity B ranges from $\lesssim 10^4$ G in the SMBH magnetospheres, and $\sim 0.1 - 1$ G in the innermost parts of relativistic jets, down to $\sim 10^{-4} - 10^{-3}$ G in the large-scale jets and hotspots, and even $\sim 10^{-6} - 10^{-5}$ G in the extended lobes. The typical level of the synchrotron polarization in AGN at radio wavelengths is typically 3 to 15%, indicating a partly ordered large-scale magnetic field component; the polarization persists toward higher frequencies, and peaks around $1 \mu\text{m}$ (the near-infrared band). The X-ray polarization properties of AGN are till now basically unexplored, due to instrumental limitations (i.e., due to the lack of high-sensitivity X-ray polarimeters).

For more detail on the theory of the synchrotron radiation and its application to astrophysics, see the review articles and textbooks by [Ginzburg & Syrovatskii \(1969\)](#), [Blumenthal & Gould \(1970\)](#), [Jackson \(1975\)](#), [Landau & Lifshitz \(1975\)](#), [Tucker \(1975\)](#), [Rybicki & Lightman \(1986\)](#), [Gould \(2005\)](#), and [Ghisellini \(2013\)](#).

1.4.2 Inverse-Compton Scattering

In the inverse-Compton (IC) scattering process, a lower-energy photon interacting with ultra-relativistic electron gains energy, at the expense of the electron. If the energy of the incoming photon in the electron rest frame (ERF) is smaller than the electron rest energy, i.e. when

$$\gamma \varepsilon_0 \ll m_e c^2, \quad (1.10)$$

the scattering proceeds in the Thomson regime, with the cross-section $\sigma_T \simeq 6.65 \times 10^{-25} \text{ cm}^2$. In this regime, the electron energy losses in a single scattering are very small, so that the scattering in the ERF is elastic (meaning $\varepsilon' \simeq \varepsilon'_0$, where primes denote the ERF), but the resulting final gain in the scattered photon energy is, due to relativistic transformations, huge,

$$\varepsilon \simeq \frac{4}{3} \varepsilon_0 \gamma^2 \quad (1.11)$$

(when averaged over the scattering angles). If the condition given in equation 1.10 is not satisfied, the scattering proceeds in the Klein-Nishina regime, with the significantly reduced cross-section due to quantum effects, $\sigma \ll \sigma_T$, so that the efficiency of the entire processes decreases dramatically.

Calculating the exact spectrum of the inverse-Compton emission resulting from a distribution of electrons up-scattering a distribution of soft photons, involves a multi-dimensional integral over the target photon and electron phase distributions, with a complicated kernel valid in both Thomson and Klein-Nishina regimes. This requires typically numerical calculations. However, some analytical solutions have also been found for the simplest cases. In particular, in the case of a power-law energy distribution of isotropic electrons, $n_e(\gamma) \propto \gamma^{-s}$, and a narrow energy distribution of isotropic soft photons (like that of a black body), the

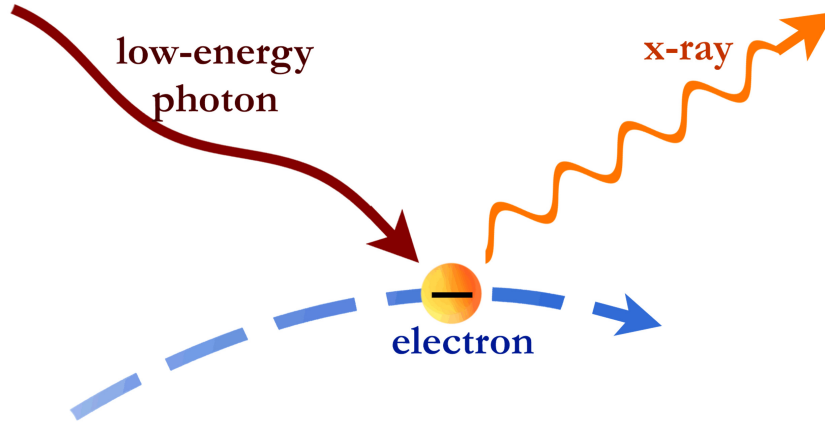


Figure 1.17: Inverse-Compton process: low-energy photon gains energy when scattered off energetic electron. (Credit: NASA/CXC/SAO)

CHAPTER 1. INTRODUCTION

resulting inverse-Compton emissivity in the Thomson regime is also of a power-law form, $j_\nu \propto \nu^{-\alpha}$, with $\alpha = (s - 1)/2$ similarly as in the case of the synchrotron emission. For further readings on the inverse-Compton process and its astrophysical applications, see e.g., [Blumenthal & Gould \(1970\)](#), [Rybicki & Lightman \(1986\)](#), and [Ghisellini \(2013\)](#).

In the specific context of Radio-loud AGN, one should note that the inverse-Compton up-scattering of the CMB photons has been proposed as the leading mechanism responsible for the production of the X-ray emission of the extended lobes of radio galaxies, already by [Harris & Grindlay \(1979\)](#). This scenario has been confirmed by several pioneering detections of non-thermal X-rays from the lobes of the nearest radio galaxies, such as Centaurus B or Fornax A, by early X-ray satellites, such as ROSAT or ASCA ([Kaneda et al. 1995](#); [Feigelson et al. 1995](#); [Tashiro et al. 1998](#)). More recently, *Chandra* and *XMM-Newton* have successfully resolved a number of extended lobes of radio galaxies and quasars at keV photon energies.

1.4.3 Thermal Bremsstrahlung

The deceleration of a charged particle deflected in an electrostatic potential of another charged particle, leads to a free-free, or bremsstrahlung emission. Massive target particle such as proton is accelerated only slightly and radiates a negligible amount compared to the electron, so in practice the process can be treated as the interaction of an electron with a fixed force field, see Figure 1.18.

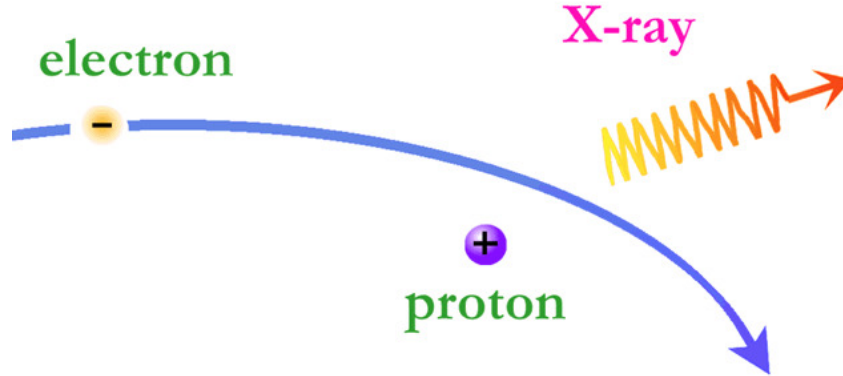


Figure 1.18: Bremsstrahlung: emission resulting from the interaction of free electrons with the fluctuating electrostatic potential of background protons. (Credit: NASA/CXC/SAO)

As mentioned in the previous section, in this process the characteristic (and maximum) energy of the emitted photon is of the order of the mean kinetic energy of the electrons (see equation 1.2), so that the production of the free-free X-ray photons requires gas temperatures $kT \sim \text{keV}$. Such temperatures are found in a wide range of cosmic sources such as accretion disks in stellar-mass black holes and neutron stars, stellar coronas, supernova

CHAPTER 1. INTRODUCTION

shock waves, and cluster of galaxies or hot galaxy halos. The total (frequency-integrated) power emitted in the bremsstrahlung process per unit volume of a homogeneous source, scales roughly as

$$\langle P/V \rangle_{\text{ff}} \sim 10^{-31} \left(\frac{T}{10^8 \text{ K}} \right)^{-1/2} \left(\frac{n_g}{10^{-4} \text{ cm}^{-3}} \right)^2 \text{ erg s}^{-1} \text{ cm}^{-3} \quad (1.12)$$

where n_g is the thermal gas number density (assuming for simplicity completely ionized electron-proton plasma; see, e.g., [Blumenthal & Gould 1970](#)). Thus, by detecting the free-free emission from an astrophysical system with a known volume V and a given luminosity distance d_L , one can constrain the corresponding thermal gas temperature and density, since the observed total energy flux related to the bremsstrahlung process, reads simply as

$$S_{\text{ff}} \sim \frac{1}{4\pi d_L^2} \times \langle P/V \rangle_{\text{ff}} \times V. \quad (1.13)$$

1.5 Pictor A: From Radio to γ -rays

Pictor A — the Broad-Line Radio Galaxy with the FR II-type large-scale radio morphology, located at the redshift $z = 0.035$ (Eracleous & Halpern 2004) — is one of the most prominent radio galaxies in the sky, that has become the prime target for detailed multiwavelength investigations in the recent decades, from radio to the X-ray ranges. More recently, it has been also confirmed as a source of high-energy γ -rays in the *Fermi*-LAT all-sky survey (Kataoka et al. 2011; Brown & Adams 2012; Ackermann et al. 2015).

In Figure 1.19 we present the radio and X-ray images of the source at arcsec ($\sim$ kpc) resolution. As follows from the figure, the radio/X-ray jet in Pictor A originates in the galaxy nucleus, and extends up to hundreds of kiloparsecs beyond the host galaxy to the West; the counter-jet is not prominent at radio frequencies (Perley et al. 1997), but can be spotted in deep X-ray maps by the CXO (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 the counter-jet (to the East); the Western hotspot is clearly detected and even resolved at radio, infrared, optical, and X-ray frequencies (Röser & Meisenheimer 1987; Thomson et al. 1995; Perley et al. 1997; Wilson et al. 2001; Werner et al. 2012; Isobe et al. 2017; Thimmappa et al. 2020b). The lobes appear in X-rays as a low-surface brightness cocoon surrounding the jets (Grandi et al. 2003; Migliori et al. 2007; Hardcastle et al. 2016).

1.5.1 Radio emission

Pictor A radio source was discovered and named by Stanley & Slee (1950). The discovery was soon later confirmed with better instruments (Mills 1952; Bolton et al. 1954; Mills et al. 1960), and in the 1960’s detailed observational studies of the source have been carried out using different radio telescopes (Morris et al. 1964). Located in the Southern Hemisphere, Pictor A appears as the 6th strongest source (based on the spectral flux density) in the 408 MHz all-sky survey of extragalactic radio sources (Robertson 1973). Its basic double radio structure was first reported by Maltby & Moffet (1962), and bright compact hotspots located at the lobes’ edges were first resolved by Schwarz et al. (1974). The polarization distributions were also studied by variant spacing interference polarimetry, including the twin-element interferometer of the Owens Valley Radio Observatory (Seielstad 1966, 1967). The compact radio core of Pictor A was first recognized by (Schwarz et al. 1974) at 1.4 GHz, and measured to be ~ 1 Jy bright at cm wavelengths, with the size $< 0.3''$ (Schilizzi 1976; Fomalont & Sramek 1976; Christiansen et al. 1977).

Later, the Australia Telescope Compact Array (ATCA) was used for 3 cm radio synthesis images of Pictor A (Simkin et al. 1999). Detailed VLA observations, on the other hand, including various polarization maps, were analyzed and presented by Perley et al. (1997). Those observational studies established that the radio emission of Pictor A — of all of its components, including the jets, hotspots, and lobes — is synchrotron in origin.



Figure 1.19: **Top:** The radio VLA image of Pictor A, revealing an unresolved core, two extended filamentary lobes, and two hotspots. **Middle:** The X-ray *Chandra* image of Pictor A, revealing a bright nucleus, a pair of long jets terminating in the two hotspots, and a diffuse X-ray cocoon overlapping with radio lobes. **Bottom:** The composite VLA radio (red) and *Chandra* X-ray image (blue) of Pictor A. (Credit: X-ray courtesy of NASA/CXC/Univ of Hertfordshire/ M.Hardcastle et. al.; radio courtesy of CSIRO/ATNF/ATCA.)

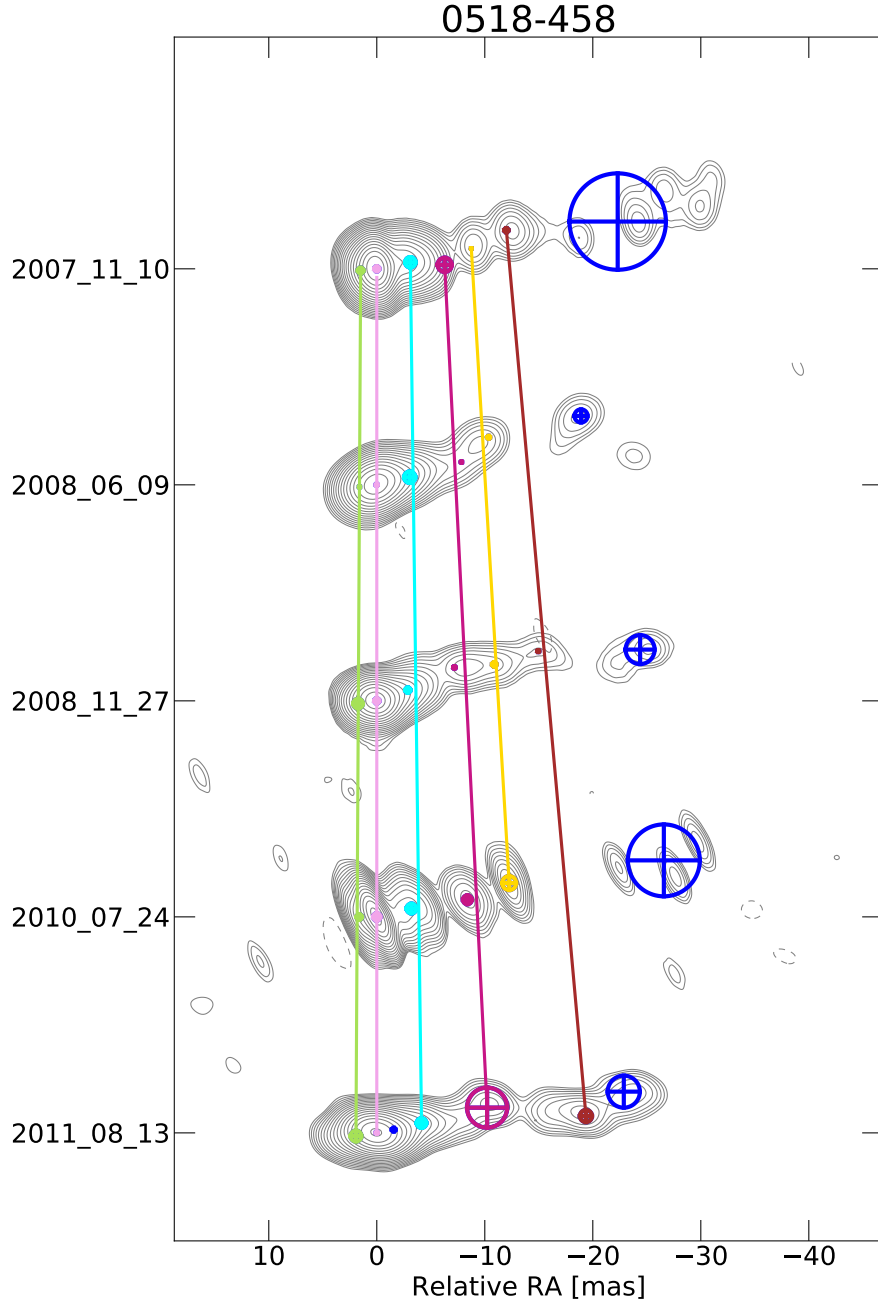


Figure 1.20: Multi-epoch TANAMI images of Pictor A nuclear region, revealing expansion of compact knots from a stationary core, with mildly relativistic apparent speeds. (Credits: [Angioni et al. 2019](#))

VLBI observations of the Pictor A radio core at 2.3 GHz and 8.4 GHz, revealed a parsec-scale jet structure and its morphological evolution, consistent with moderate jet viewing angles and at least slightly relativistic component speeds ([Tingay et al. 2000](#)). We note that, as one of the most prominent radio sources in the Southern Hemisphere detected

CHAPTER 1. INTRODUCTION

in γ -rays by *Fermi*-LAT, Pictor A is covered by the multiwavelength program Tracking Active Galactic Nuclei with Milliarcsecond Interferometry (TANAMI), including the high-resolution VLBI imaging (e.g., [Angioni et al. 2019](#), see Figure 1.20). Apart of the core, also the Western hotspot in the system has been imaged at radio wavelengths at mas resolution, using VLBA ([Tingay et al. 2008](#)). This revealed a presence of compact radio components embedded within the diffuse emission of the jet termination region.

Pictor A exhibit a very high level of the integrated polarization on a scale of 10 arcminutes at 20 GHz (polarized flux density ~ 0.50 Jy, with the total intensity of ~ 6 Jy; [Burke-Spolaor et al. 2009](#)). By combining observations of the Wilkinson Microwave Anisotropy Probe (WMAP) with that of *Planck*, [Chen et al. \(2013\)](#) established the flux density variability of the target at millimeter wavelengths.

1.5.2 IR & Optical emission

In the far/mid-infrared, Pictor A was observed with IRAS ([Golombek et al. 1988](#)), with the Multiband Imaging Photometer and the Infrared Spectrograph for *Spitzer* (MIPS and IRS, respectively; [Shi et al. 2005](#)), as well as with the Photodetector Array Camera and Spectrometer on the *Herschel* Space Observatory ([Meléndez et al. 2014](#)). In general, the nucleus of the source was found to have thermal emission components consistent with the presence of hot circumnuclear dust heated by the AGN, in agreement with the expectations from the general AGN unification scheme. The stellar velocity dispersion of the host calculated in near-infrared, $\sigma \simeq 145 \pm 20 \text{ km s}^{-1}$, gives the SMBH mass estimate of $\sim (4 \pm 2) \times 10^7 M_{\odot}$ ([Lewis & Eracleous 2006](#)).

High-resolution optical spectra of Pictor A, obtained by using either ground-based or space-born instruments including the *Hubble* Space Telescope, reveal a continuum emission with strong and broad emission lines, consistent with the BLRG classification of the AGN (e.g., [Marshall et al. 1979](#); [Glass 1981](#); [Heckman 1980](#); [Ward et al. 1982](#); [Carswell et al. 1984](#); [Filippenko 1985](#); [Halpern & Eracleous 1994](#); [Sulentic et al. 1995](#); [Simkin et al. 1999](#); [Allington-Smith et al. 2002](#); [Couto et al. 2016](#)).

The far/mid-infrared properties of the Western hotspot of Pictor A, were studied with the IRAC camera onboard the *Spitzer* Space Telescope, the Wide-field Infrared Survey Explorer (WISE), and with the Spectral and Photometric Imaging REceiver (SPIRE) on board *Herschel* ([Werner et al. 2012](#); [Isobe et al. 2017, 2020](#)). The optical emission from this feature has been also resolved in great detail with the *Hubble* Space Telescope ([Thomson et al. 1995](#)). A strong polarization of the hotspot at optical wavelengths ([Röser & Meisenheimer 1987](#)), along with a power-law form of the entire radio-to-IR/optical continuum, indicates a synchrotron origin of the observed broad-band emission of the structure (see the discussion in [Meisenheimer et al. 1989](#); [Isobe et al. 2020](#)). We note that the *Hubble* observations revealed also a tidal tail and a number of jet knots coinciding with the large-scale radio/X-ray jet ([Gentry et al. 2015](#)).

CHAPTER 1. INTRODUCTION

1.5.3 X-ray emission

Pictor A is a strong X-ray emitting radio source, detected already in the first full-sky survey of the HEAO-1 (Marshall et al. 1978, 1979). In addition to the central bright core, also the Western hotspot was marginally detected by the imaging proportional counter (IPC) of the *Einstein* Observatory, but remained practically unresolved from the strong nuclear emission (Röser & Meisenheimer 1987).

In 1986, Pictor A was observed with the EXOSAT observatory, on time-scales of a few minutes to a few hours (Singh et al. 1990). In 1996, the galaxy was studied with ASCA, with the main objective to detect the $K\alpha$ line in the X-ray nuclear emission spectrum of the target at 6.4 keV (Eracleous & Halpern 1998). No line was found, in contrast with several other analogous Seyfert-type AGN studied by ASCA, with the corresponding 99% confidence upper limit on the line’s equivalent width of the order of 100 eV. The general featureless power-law character of the nuclear continuum in Pictor A, extending with the photon index $\Gamma \sim 1.6\text{--}1.8$ up to 50 keV photon energies, was confirmed by the analysis of the *Beppo-SAX* observations from 1996, augmented by the ROSAT All-Sky Survey (Padovani et al. 1999). The hard X-ray data of Pictor A obtained from the Rossi X-Ray Timing Explorer (RXTE) in 1997, conformed to this picture as well (Eracleous et al. 2000). The ROSAT PSPC observations provide in addition the evidence of an extended component on a scale of $\lesssim 70''$.

After the launch of the CXO, Pictor A was included in the list of the first targeted radio galaxies. The *Chandra* observation revealed the unresolved nucleus in the source, the diffuse emission coinciding with the radio lobes, and most prominently the $\sim 2'$ -long X-ray jet extending to the West, and terminating in the very bright X-ray hotspot around 240 kpc from the nucleus (Wilson et al. 2001). The broad-band radio-to-X-ray continuum of the hotspot updated for the *Chandra* spectrum, could not be fitted in a satisfactory way with any standard model widely applied to the hotspots of other FR II galaxies, typically consisting of the synchrotron plus synchrotron self-Compton emission components with at most moderate beaming effects and equipartitional magnetic field intensity (see Figure 1.21 displaying the X-ray image of the hotspot).

The following *Chandra* pointings, enabled a detailed studies of the low-surface brightness diffuse X-ray emission of the lobes in Pictor A, consistent (at least in the zeroth-order approximation) with the inverse-Compton up-scattering of the CMB photons by the radio-emitting electrons (Hardcastle & Croston 2005; Kataoka & Stawarz 2005). This was further reinforced by the observations with the *XMM-Newton* satellite, characterized by a worse angular resolution than *Chandra*, but instead a larger effective area of the detector (and so a larger photon statistics; see Grandi et al. 2003; Migliori et al. 2007).

All the available *Chandra* data for Pictor A have been summarized and re-analyzed by Hardcastle et al. (2016). This included a significant ($\gtrsim 3\sigma$) and surprising flux variability from the large-scale jet, first noted in the CXO data by Marshall et al. (2010).

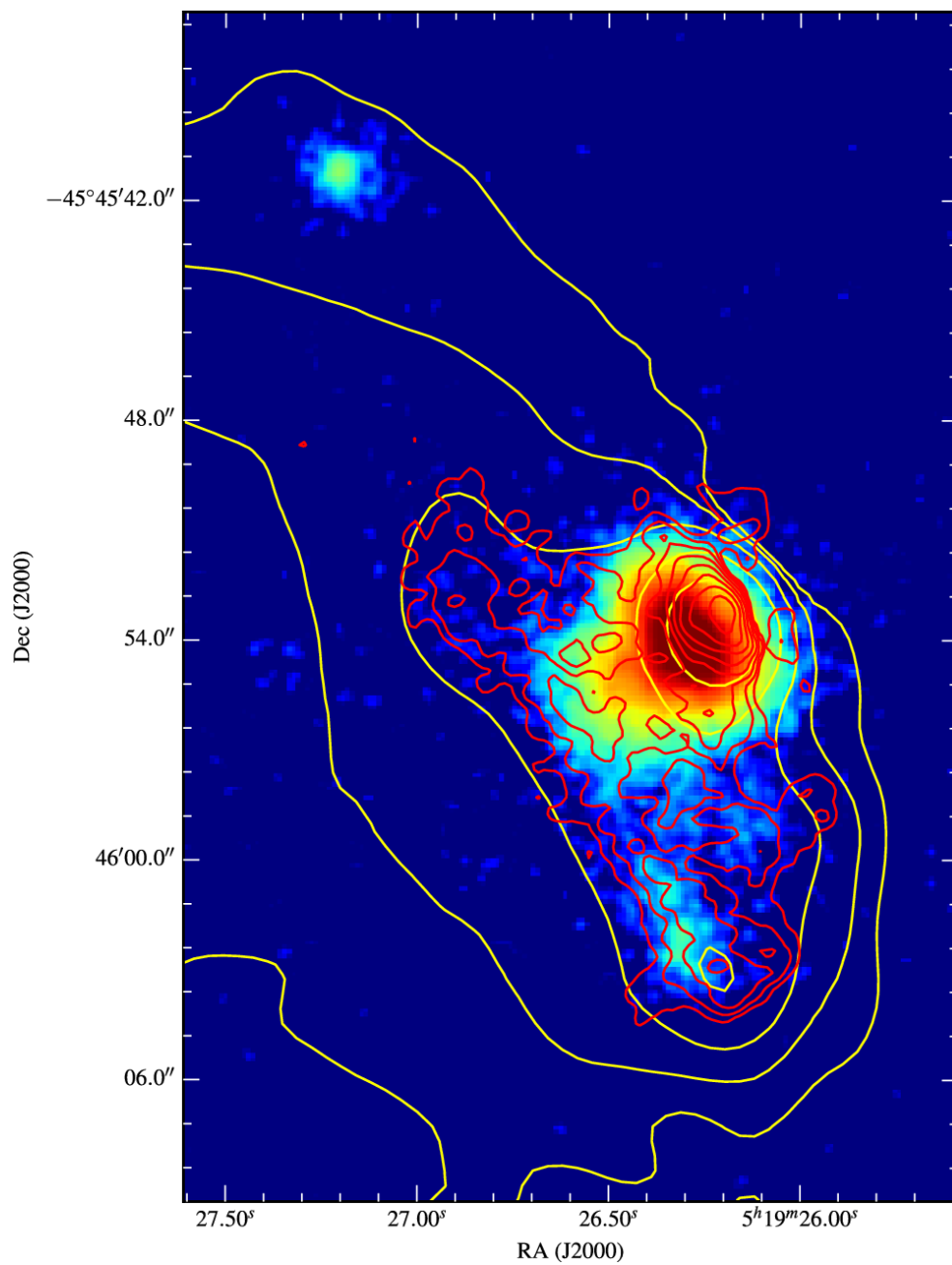


Figure 1.21: The *Chandra* image of the Western hotspot in Pictor A in the 0.5–5.0 keV range (binned to pixels of 0.123 arcsec on a side and smoothed with a Gaussian of $\sigma = 1$ pixel to give an effective resolution of ~ 0.7 arcsec). Contours are from the 5 GHz ATCA map with 1.7 arcsec resolution (yellow), and from the 15 GHz VLA map. (Credit: [Hardcastle et al. 2016](#)).

Chapter 2

Active Nucleus in Pictor A: Data Analysis in the Regime of Instrumental Pile-up

*This chapter includes some of the analysis results which originally appeared in ‘Preliminary analysis of the X-ray emission from the central regions of the Pictor A’ by **R. Thimmappa, Ł. Stawarz, V. Marchenko, & K. Balasubramaniam**; 2020, Proceedings of the International Astronomical Union, Volume 342, pp. 224-226 ([Thimmappa et al. 2020a](#))*

2.1 Introduction

During my research, we have analyzed the *Chandra* data for the Pictor A nucleus, aiming for a proper spectroscopy of the AGN in the system. In particular, we were hoping to ascertain the presence of the fluorescent iron line in the spectrum: until now, only the upper limits on the line’s equivalent width have been derived based on the observations with the previous X-ray telescopes ([Eracleous & Halpern 1998](#); [Padovani et al. 1999](#), see also Section 1.5.3). This is in contrast to the other radio galaxies of the BLRG type, for which the 6.4 keV iron line is often detected, in some cases (3C 120) even with the substantial broadening due to strong gravity effects (see [Kataoka et al. 2011](#), and references therein). However, several problems related to the quality of the available CXO data became apparent during the research:

- a) active nucleus (i.e., accretion disk and disk corona) in Pictor A is very bright in X-rays, so we have a problem of a severe instrumental pile-up in all the *Chandra* pointings;
- b) in addition to the AGN itself, also the hot gaseous halo of the Pictor A host galaxy

CHAPTER 2. ACTIVE NUCLEUS IN PICTOR A

is bright in X-rays (via bremsstrahlung emission); a significant fraction of this halo is included in the central PSF;

- c) the AGN emission is intrinsically variable on the timescale of months and years; moreover, various *Chandra* pointings spread overt the last decades have targeted the core in Pictor A with various ACIS configuration (off-axis angle) and exposure.

A large amount of the effort was directed into a proper recognition and characterization of those limitations. The first results of our analysis are presented below.

Throughout the chapter we assume the Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, for which the luminosity distance to the source is $d_L = 154 \text{ Mpc}$, and the conversion angular scale is $0.697 \text{ kpc arcsec}^{-1}$. The photon index Γ is defined as $F_\varepsilon \propto \varepsilon^{-\Gamma}$ for the photon flux spectral density F_ε and the photon energy ε .

2.2 Data Analysis

The *Chandra* telescope has observed Pictor A on 14 separate occasions over the past 15 years, for a total of 464 ks of the observing time. The pointings, all listed in Table 2.1, differ in the exposure time and off-axis angles, and this affects the quality of the available data for

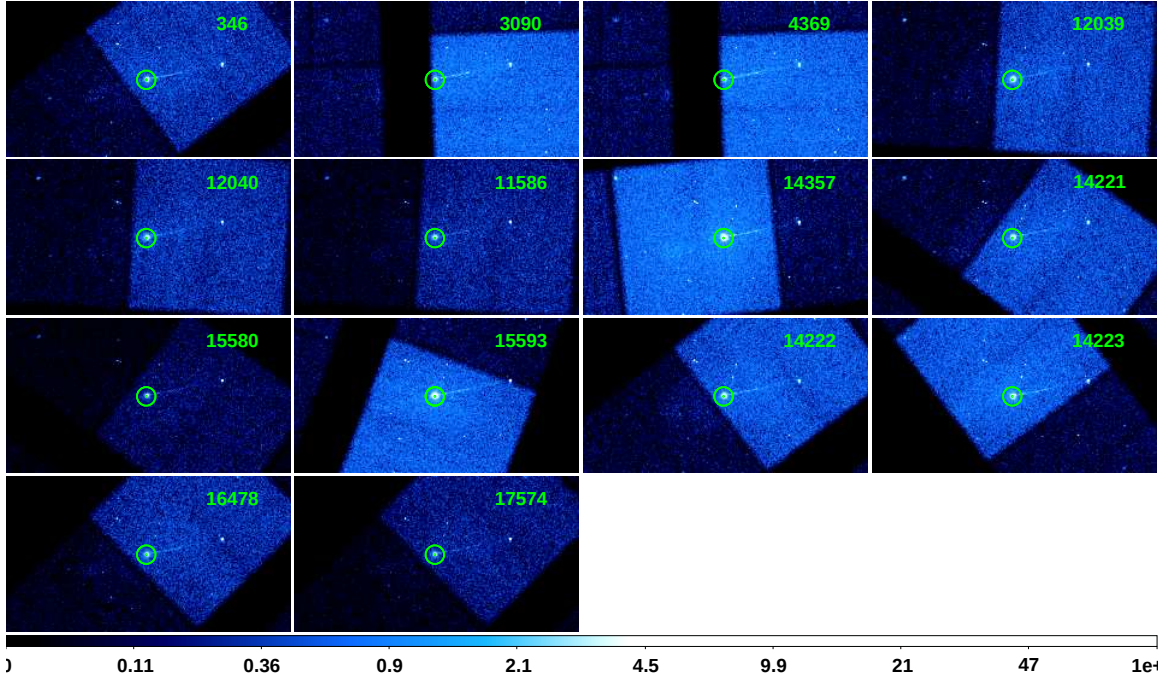


Figure 2.1: The collection of all the available *Chandra* pointings on the Pictor A nucleus, marked in all the panels by a green circle with 60 px radius. All the corresponding ObsIDs are given in the panels.

CHAPTER 2. ACTIVE NUCLEUS IN PICTOR A

Table 2.1:: The best-fit parameters for the nuclear spectrum of Pictor A, assuming a power-law model (including `jdpileup`).

Obs.ID	MJD	Exposure (ks)	θ (arcmin)	Γ	α	f	$F_{0.5-7.0}$ $e - 12$ cgs	χ^2/DOF	Counts
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
346	51561	25.8	0.73	$1.27^{+0.08}_{-0.06}$	$1.00^{--}_{-0.30}$	$0.94^{--}_{-0.04}$	$1.32^{--}_{-0.01}$	146/219	3581
3090	52534	46.4	4.07	$1.40^{+0.01}_{-0.01}$	$1.00^{--}_{-0.48}$	$0.89^{--}_{-0.04}$	0.46^{--}_{-}	310/380	21528
4369	52539	49.1	4.07	$1.43^{+0.01}_{-0.01}$	0.48^{--}_{-}	$0.86^{+0.13}_{-}$	0.32^{--}_{-}	286/376	23327
12039	55172	23.7	0.83	$1.47^{+0.09}_{-0.08}$	$0.32^{+0.16}_{-0.29}$	$0.86^{+0.06}_{-}$	2.47^{--}_{-}	119/204	3928
12040	55174	17.3	0.84	$1.64^{+0.10}_{-0.11}$	$0.83^{--}_{-0.66}$	$0.85^{+0.12}_{-}$	1.36^{--}_{-}	130/176	2757
11586	55177	14.3	0.83	$1.50^{+0.11}_{-0.11}$	$0.26^{+0.30}_{-0.24}$	$0.86^{+0.07}_{-}$	$1.77^{+0.02}_{-0.02}$	92/159	2236
14357	56095	49.3	1.11	$1.45^{+0.05}_{-0.06}$	$0.33^{+0.16}_{-0.24}$	$0.87^{+0.05}_{-}$	$2.06^{+0.07}_{-0.07}$	218/297	7954
14221	56237	37.5	1.07	$1.39^{+0.09}_{-0.05}$	$1.00^{--}_{-0.73}$	$0.89^{--}_{-0.01}$	$1.86^{+0.01}_{-0.01}$	226/287	5692
15580	56239	10.5	1.07	$1.25^{+0.28}_{-0.06}$	$1.00^{--}_{-0.72}$	$0.91^{--}_{-0.04}$	$1.83^{+0.10}_{-0.10}$	75/125	1608
15593	56527	49.3	1.19	$1.54^{+0.06}_{-0.05}$	$0.63^{+0.15}_{-0.48}$	$0.85^{+0.09}_{-}$	1.92^{--}_{-}	210/296	7554
14222	56674	45.4	0.86	$1.30^{+0.27}_{-0.02}$	$1.00^{--}_{-0.65}$	$0.89^{--}_{-0.01}$	$2.30^{+0.03}_{-0.03}$	262/359	7850
14223	56768	50.1	0.93	$1.29^{+0.29}_{-0.03}$	$1.00^{--}_{-0.70}$	$0.90^{--}_{-0.01}$	2.17^{--}_{-}	305/348	7814
16478	57031	26.8	0.84	$1.37^{+0.15}_{-0.05}$	$1.00^{--}_{-0.63}$	$0.88^{+0.10}_{-0.01}$	$2.87^{+0.01}_{-0.01}$	183/277	4905
17574	57032	18.6	0.84	$1.30^{+0.30}_{-0.04}$	$1.00^{--}_{-0.66}$	$0.89^{--}_{-0.66}$	$2.46^{+0.01}_{-0.01}$	149/223	3289

NOTES:

(1) ObsID of the pointing; (2) date of the observation; (3) total exposure; (4) off-axis angle for the nucleus; (5) photon index corresponding to the power-law fit, assuming $N_{\text{H,Gal}} = 4.12 \times 10^{20} \text{ cm}^{-2}$, and instrumental pile-up modeled with `jdpileup`; (6) grade migration parameter for the `jdpileup` model; (7) fraction of events falling into the pile-up region from the `jdpileup` model; (8) 0.5–7.0 keV flux of the power-law model component, in the units of $10^{-12} \text{ erg/cm}^2/\text{s}$; (9) chi-square statistic per DOF; (10) total number of counts within the 0.5–7.0 keV range from a circular region with a radius 6 px of the active nucleus.

various regions of the system, because the effective point spread function is a complicated function of the source flux and the source position in the detector. Figure 2.1 present the mosaic of the *Chandra* pointings of the Pictor A central regions. As shown, for ObsID 3090 and 4369, the nucleus is located at the very edge of the back-illuminated chip S3.

The other complication is that, due to a high flux of the Pictor A nucleus, the CXO spectra for the central parts of the source suffer from a significant pile-up problem. Due to this fact, in their analysis of the AGN variability in Pictor A, [Hardcastle et al. \(2016\)](#) has considered only the wings of the central PSF (from 6 px up to 29 px), excluding in this way the pixels piled up at more than the 1% level at any epoch. Still, due to the dependence of the PSF shape on the photon energy, the core spectra extracted in this way had to be corrected further via numerical simulations.

2.2.1 Spectral Modelling

We have reprocessed all the data by running the CIAO tool `chandra_repro`, and removed the readout streaks. For the spectral modelling, the source spectrum was extracted for each ObsID from a circular region with a radius of 6 px ($\simeq 3''$, for the conversion scale

$0''.492 \text{ px}^{-1}$), and the background region was extracted from an annulus of 10–30 px ($\simeq 5'' - 15''$) excluding the jet, as shown in Figure 2.2.

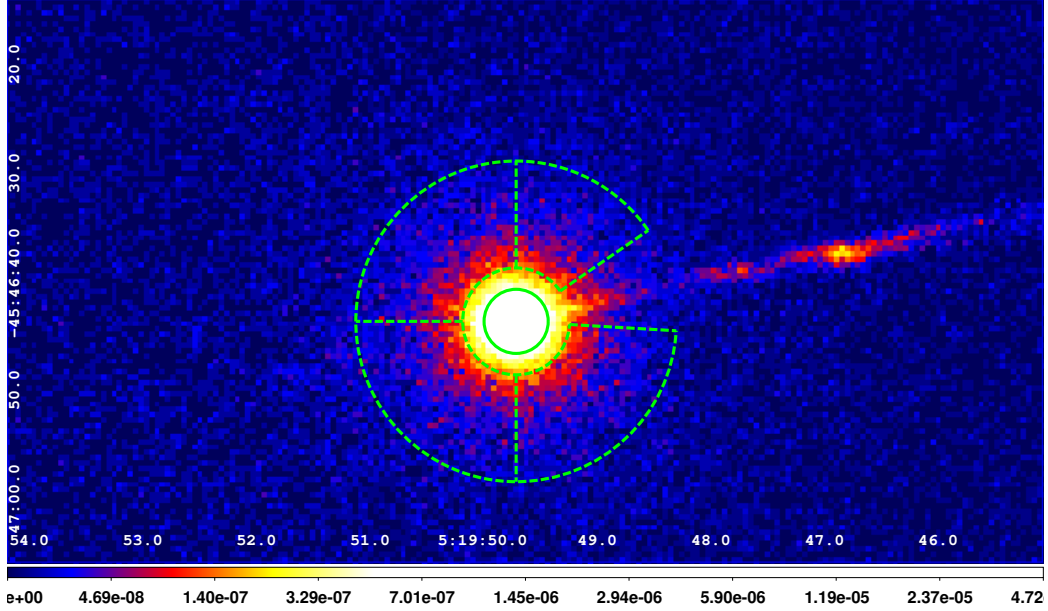


Figure 2.2: ACIS-S 0.5–7 keV image of the central parts of Pictor A, for the first ObsID 346. The AGN source extraction region (< 6 px), and the background region (10–30 px, omitting the jet), are denoted by green contours.

Spectral modeling was performed with the *Sherpa* package (Freeman et al. 2001). The background-subtracted source spectra were fitted within the 0.5–7.0 keV range, assuming a single power-law model `xsphabs*xspowerlaw`, including Galactic absorption in the direction of the source, with the corresponding column density $N_{\text{H,Gal}} = 4.12 \times 10^{20} \text{ cm}^{-2}$ (Kalberla et al. 2005). The pile-up function `jdpileup` has been added to the spectral model as well (see Davis 2001), and this constitutes one of the main differences with respect to the previous analysis presented in the literature. We note that the addition of an intrinsic absorption to the model, `xsphabs*zphabs*xspowerlaw`, does not affect any of the best-fit model parameters, or a quality of the fit, and returns the intrinsic hydrogen column densities orders of magnitude below the Galactic value, in agreement with the previous analysis by Hardcastle et al. (2016). The `chi2gehrels` fitting statistics and the Levenberg-Marquardt (i.e., `levmar`) optimization method were used. The resulting best-fit model parameters are summarized in Table 2.1 for all the pointings, and visualized in Figure 2.3.

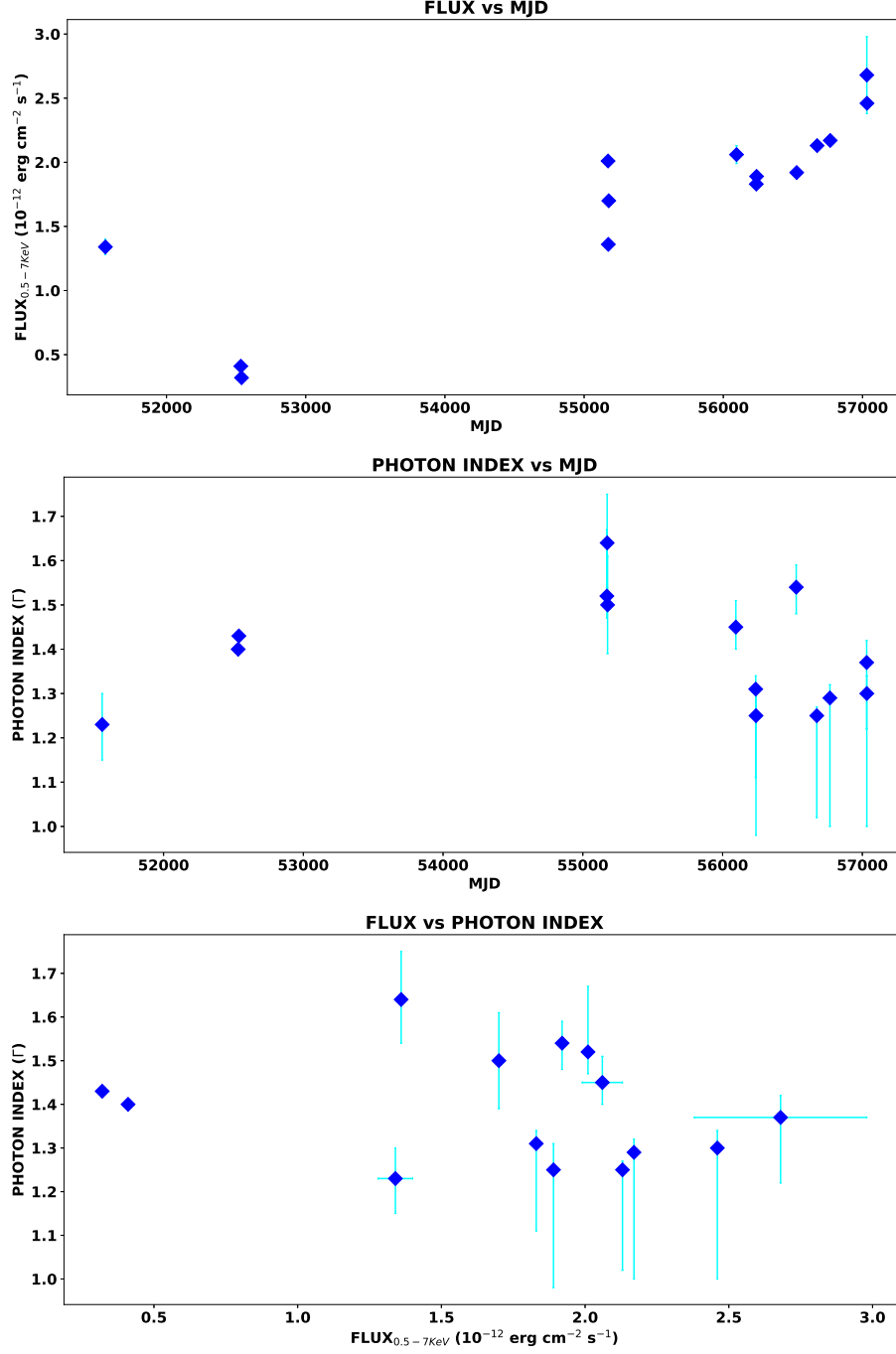


Figure 2.3: Model (power-law) fluxes and photon indices, calculated for the individual *Chandra* observations of Pictor A nucleus within the 0.5–7.0 keV energy range, based on the applied simple power-law model including *jdpileup*. **Top:** Flux vs. date of observation; **middle:** photon index vs. date of observation; **bottom:** flux vs. photon index.

As presented, the resulting flux of the source drops initially between the first pointing and the subsequent two observations (i.e., between 2000 and late 2002), and then increases systematically over the decade (from 2003 till 2015) by about one order of magnitude. The initial drop and the early flux increase phase, are both in a rough agreement with the analysis by [Hardcastle et al. \(2016\)](#), but the later increase (after 2012) is inconsistent with the results of those authors, who claimed a decreasing flux for this segment of the source lightcurve. In addition, our fluxes correspond to the isotropic luminosities within the range $L_{0.5-7.0} \simeq 4\pi d_L^2 \times F_{0.5-7.0} \sim (0.1 - 1) \times 10^{43} \text{ erg s}^{-1}$, which are lower than the corresponding luminosities estimated by [Hardcastle et al.](#). Finally, our modeled slopes, corresponding to the photon indices $\Gamma \sim 1.20 - 1.75$, are all significantly flatter than the slopes of the power-law continua emerging from the [Hardcastle et al.](#) analysis, namely $\Gamma \sim 1.80 - 2.05$.

In order to address the above-mentioned discrepancies, in Figure 2.4 we present for a comparison the *Chandra* spectra from ObsID 346 and 17574, along with the model fit curves and residuals. Note that the best-fit values of the photon index are in both cases very similar, namely $\Gamma \simeq 1.3$; the apparent difference in the low-energy segments of the spectra of the two pointings, is due to the CCDs' degradation (ObsID 346 was taken in 2000, i.e. during the initial phase of the *Chandra* mission, much earlier than the ObsID 17574 taken in 2015). In both fits, one can however clearly see very similar positive residuals in the high-energy segments of the spectra, starting from already 4.5 keV.

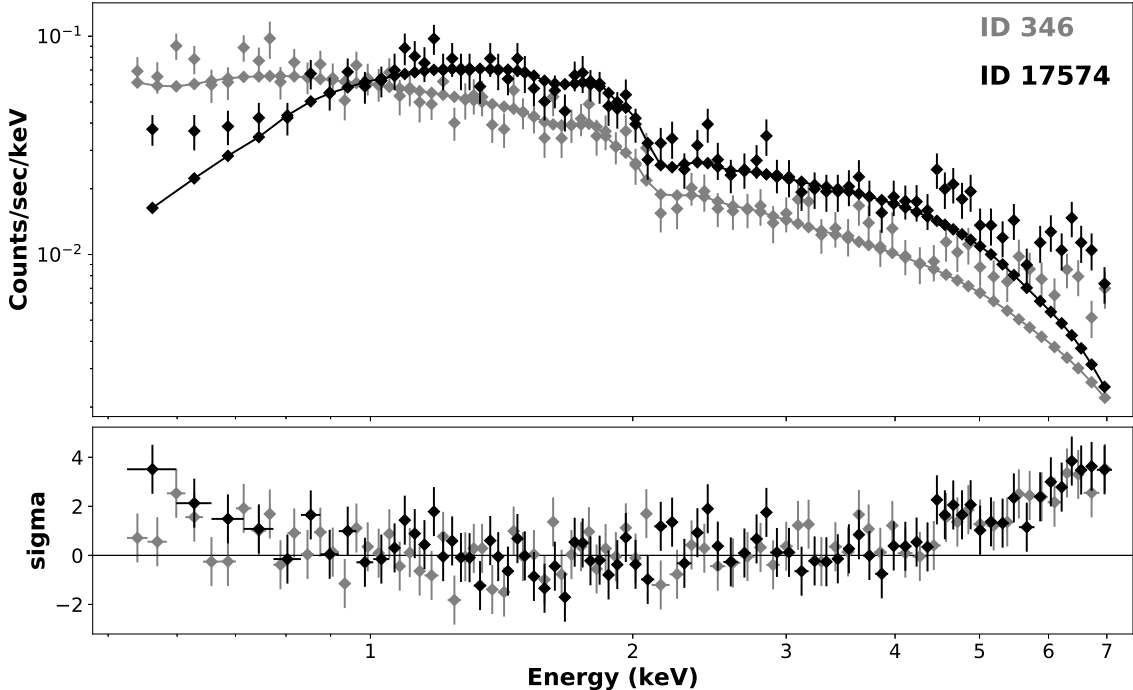


Figure 2.4: The *Chandra* 0.5–7.0 keV spectra of the Pictor A nucleus, for ID 346 and ID 17574, fitted with a single power-law model including the Galactic absorption and the instrumental pile-up. The corresponding model parameters are given in Table 2.1.

Table 2.2:: The pileup fraction for ObsID 346.

the number of piled photons	percentage in the pileup region	percentage in the total events
1	0.316102	0.751997
2	0.0861904	0.205045
3	0.0156675	0.0372725
4	0.002136	0.00508149
5	0.000232967	0.000554221
6	2.11741e-05	5.03726e-05
the total pileup fraction:	0.248003	

We believe that this high-energy excess is not real, and instead is simply related to the instrumental pile-up, which could not be characterized precisely and removed completely by the `jdpileup` model. This model contains in particular the two main parameters that are left to vary during the fitting procedure, namely

- α , which describes the “grade migration” in the detector, in terms of a probability that the piled event is not rejected as a “bad event”, but is instead retained as a single photon event with the summed energy;
- f , which gives the fraction of events to which the pile-up model is applied.

The best-fit values of those two parameters for each analyzed ObsID, are listed in Table 2.1. As given, the α parameter is in all the cases very high, indicating that the majority of the piled-up multiple-photon events are registered by the detector as single photons with very high energies (equal to the sum of the piled-up photon energies).

In order to look in more detail into this issue, in Table 2.2 we provide the fraction of the events which are calculated as piled For ID 346. This list indicates that: $\sim 32\%$ of the frames contained a single photon in the pileup region and $\sim 75\%$ of the events were single-photon events (the first row of the Table); only $\sim 9\%$ of the frames contained 2 photons in the pileup region and $\sim 21\%$ of the events were due to 2 photons (the second row of the Table); etc. The total pileup fraction is $\sim 25\%$.

The alternative explanation for the hard excess seen in the modelled spectra (over the applied simple power-law model including an approximate treatment of the instrumental pile-up), is that this excess is real, related to the fluoresce iron line in the radiative output of the Pictor A nucleus. We deem this possibility as unlikely, but nonetheless we explored it by adding a red-shifted ($z = 0.035$) Gaussian line (`xszgauss`) to the model spectrum. Because of the broadness of the hard excess, the line position had to be fixed during the fitting at 6.4 keV; we also considered different values of the line width σ_ℓ , between 10 eV and 1 keV. In fact, the best fit for which the hard excess is absent, could formally be obtained by freezing $\sigma_\ell = 1$ keV; in this fit, presented in Figure 2.5, and summarized in Table 2.3, the equivalent width of the line reads as $EW \sim 4$ keV.

CHAPTER 2. ACTIVE NUCLEUS IN PICTOR A

Table 2.3:: Best-fit model parameters for the Pictor A nuclear spectrum, corresponding to the power-law model including `jdpileup` and red-shifted ($z = 0.035$) Gaussian line, for ObsID 346.

Parameter	best-fit value
Pile-up α	$1^{+....}_{-0.38}$
Pile-up f	$0.94^{+....}_{-0.05}$
Photon index Γ	$1.41^{+0.15}_{-0.07}$
PL normalization	$1.75^{+20.51}_{-0.09} \times 10^{-4}$
Line position	6.4 keV (fixed)
Line width σ_ℓ	1 keV (fixed)
Line normalization	$7.50^{+4.25}_{-1.17} \times 10^{-5}$

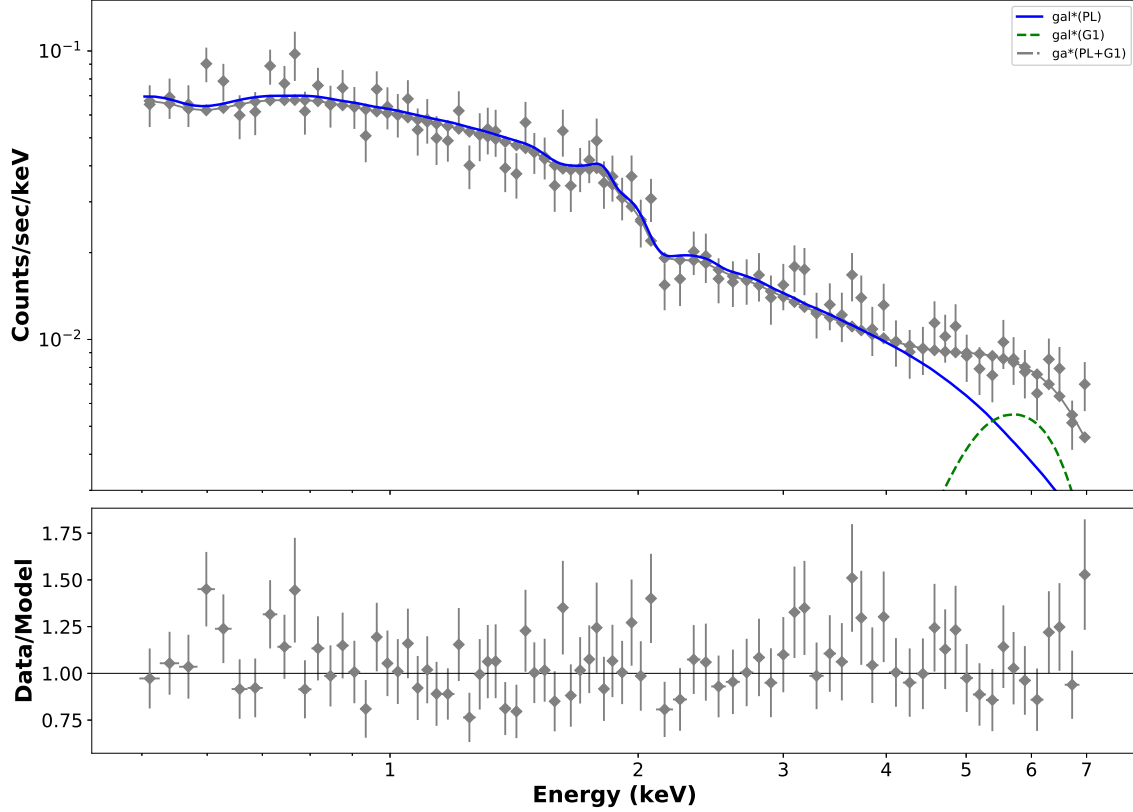


Figure 2.5: The *Chandra* 0.5–7.0 keV spectrum of the Pictor A nucleus for ID 346, fitted with a single power-law model including Galactic absorption and the instrumental pile-up, as well as the redshifted ($z = 0.035$) Gaussian line with the position fixed at 6.4 keV and the width $\sigma_\ell = 1$ keV.

2.2.2 Surface Brightness Profiles

For the analysis of the X-ray surface brightness profile within the central regions of the Pictor A system, one needs to simulate the Point Spread Function (PSF) of the unresolved nucleus with the MARX software (Davis et al. 2012), for a given source spectrum, flux, and position in the detector. This, however, is again complicated by a severe instrumental pile-up. We have approached this problem in two alternative takes (as suggested to us by the *Chandra* X-ray Center HelpDesk):

Take #1 by applying the pileup model `jdpileup` *only* during the spectral fitting, i.e. *before* the MARX simulations;

Take #2 by including the pileup effect *only* during the MARX simulations, and *not* during the spectral fitting.

Note that in the latter case, the input to the MARX simulations was the set of the model parameters emerging from a simple `xsphabs*xspowerlaw` fit with no pile-up correction.

Take #1

For the *Chandra* PSF simulations of the Pictor A nucleus, we used the Chandra Ray Tracer (ChaRT) online tool (Carter et al. 2003) and the MARX software (Davis et al. 2012). The source spectrum for the spectral specification in ChaRT was the background-subtracted 0.5–7.0 keV spectrum created separately for each observation, and fitted with a single power-law model including `jdpileup`, as described in the previous Section 2.2.1. Then the resulting rays from ChaRT were projected onto the detector through MARX simulations, taking into account all the relevant detector issues. Through this process, an event file was obtained, from which an image of the PSF was created. For each ObsID, we performed the PSF simulations, as described above, 50 times, as each particular realization of the PSF was different due to random photon fluctuations. The resulting PSF files were normalized to the observed count rate, and filtered with a bin size to 1. All the simulated 50 PSFs were then combined, so that the final table model for the PSF used for the surface brightness profile modelling, corresponds to the average over 50 independent PSF realizations.

For illustration purpose, here we present the resulting surface brightness analysis only for the first observation ID 346. The corresponding X-ray surface brightness profile of the central regions of Pictor A — up to $60 \text{ px} \simeq 30''$ from the core, i.e. $\sim 21 \text{ kpc}$ at the source distance — is shown in Figure 2.6. The profile was extracted from the exposure-corrected *Chandra* map, using concentric annular regions centered on the core (excluding the jet; see Figure 2.2). The profile was next fitted with the model including the central PSF (table, with the amplitude free to vary), the β -profile component (`beta1d`), and the constant background. The resulting best-fit model parameters are listed in Table 2.4.

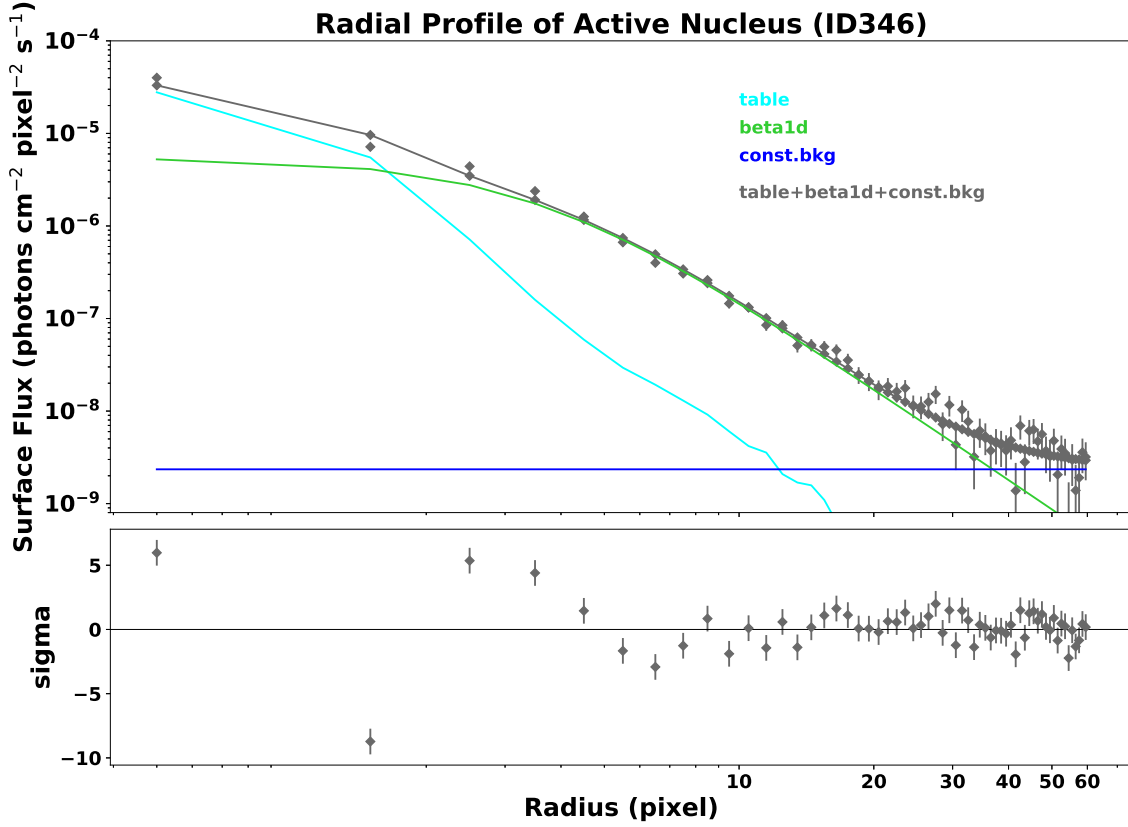


Figure 2.6: The X-ray surface brightness profile of the Pictor A central region, obtained from ObsID 346. The cyan curve denotes the table model for the core PSF (with freed amplitude), the green curve corresponds to the β -profile component, the blue horizontal line denotes the constant background, and the solid grey curve gives the total “Take #1” PSF+beta1d+constant model fitted to the data. The corresponding residuals are given in the lower panel.

Table 2.4:: Parameters of the multi-component model applied to the X-ray surface brightness profile of the Pictor A central regions (Take #1).

Parameter	ObsID 346
PSF (table) amplitude	0.40
β -profile core radius [px]	3.52
β -profile index β	0.72
β -profile amplitude	5.42e-06
constant background amplitude	2.35e-09

As follows, the X-ray surface brightness profile of the central regions of Pictor A could in this way be decomposed into various elements reasonably well, despite the fact that rather large residuals (mostly positive) are present within the central 6 px radius. These

CHAPTER 2. ACTIVE NUCLEUS IN PICTOR A

residuals imply, on the other hand, that the instrumental pile-up could not be modelled with sufficiently high accuracy in the adopted approach. The other main conclusion from the profile fitting is however that the component dominating the observed emission within the region between several pixels up to even 30 pixels from the core, is not that of the AGN, corresponding to the wings of the central PSF, but instead of a thermal emission of the hot gaseous halo within the host galaxy, represented by the β -profile component. Note that the value of the index $\beta \sim 0.7$, is as expected from such a hot gaseous halo profile (see, e.g., [Belsole et al. 2007](#), and references therein).

Take #2

In this approach, first we modified slightly the spectral analysis (needed as an input for the PSF simulations), by setting the background region as the 10–20 px annulus around the core (but keeping the source extraction region as before, namely 6 px radius circle centered on the nucleus). The source spectrum for the spectral specification in ChaRT was the background-subtracted 0.5–7.0 keV spectrum created separately for each observation and fitted with a single power-law model, *without* any pile-up correction. Only latter, during the MARX simulation process, we accounted for the pile-up effect. In this way event files were obtained, from which images of the PSF were created.

Here we present the resulting surface brightness analysis for the four exemplary ObsIDs 346, 12039, 14357, and 14222. For these, we performed the PSF simulations, as described above, 100 times. The resulting PSF files were normalized to the observed count rate, and filtered with a bin size to 1. All the simulated 100 PSFs were then combined, so that the final PSF table models correspond to the averages over 100 independent PSF realizations for each observation separately.

The X-ray surface brightness profiles were extracted as before from the exposure-corrected *Chandra* maps (see Figure 2.7), up to 60 px from the core. The profiles were fitted with the model including the central PSF (table, with the amplitude freed to vary), the β -profile component (beta1d), and the constant background; moreover, in order to reduce the residuals within the innermost regions, this time we have also added a Gaussian component (gauss1d), for which the position, width, and the amplitude, were all set free. We note that, because of the reduced photon statistics, for ObsIDs 12039, 14357, and 14222, the constant background component had to be set to 0 during the fitting. The results of the analysis are presented in Figure 2.8, and summarized in Table 2.5.

As follows, the inclusion of the additional Gaussian component does improve the quality of the fit, even though residuals (up to $\sim 5\sigma$) are still present within the innermost circumnuclear regions, with the exception of ObsID 14222. The presence of this Gaussian component, on the other hand, does not affect the slope of the β -profile, which in all the cases reads roughly as $\beta \sim 0.7$ (similarly as in Take #1), but increases slightly the core radius of the β -profile up to 6–7 px $\sim 2–2.5$ kpc, again with the exception of ObsID 14222.

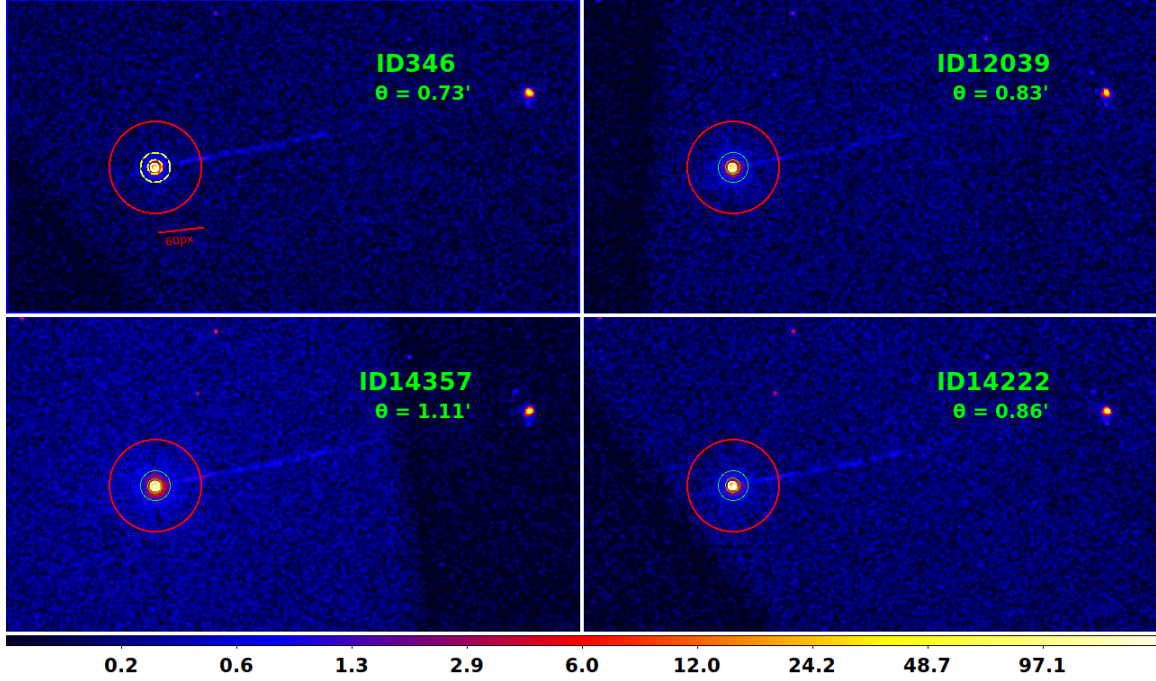


Figure 2.7: Observations ID 346, 12039, 14357, and 14222, selected for the “Take #2” analysis of the X-ray surface brightness profile within the central regions of Pictor A, denoted on each panel by a red circle (0–60 px from the core). The source extraction regions for the spectral analysis (< 6 px), and the corresponding background extraction regions (10–20 px), are denoted by green circles.

Table 2.5:: Parameters of the multi-component model applied to the X-ray surface brightness profile of the Pictor A central regions (Take #2).

Parameter	ID 346	ID 12039	ID 14357	ID 14222
PSF (table) amplitude	0.64	0.32	0.43	0.45
β -profile core radius [px]	5.7	7.2	6.3	2.6
β -profile index β	0.74	0.80	0.75	0.66
β -profile amplitude	1.56e-06	2.19e-06	2.37e-06	6.80e-06
Gaussian FWHM [px]	2.18	2.80	2.14	0.90
Gaussian position [px]	2.9	3.1	3.1	2.9
Gaussian amplitude	1.91e-06	2.73e-06	2.89e-06	3.75e-06
constant background amplitude	2.00e-09	0 (fixed)	0 (fixed)	0 (fixed)

This pattern is easy to understand: with no extra component, and given the fixed shape of the table model for the central PSF, the β -profile has to be more and more “peaked” to account for the excess emission seen at the distance of a few/several pixels from the core.

While it is possible that the additional Gaussian component represent a real feature, e.g., the inner segment of the jet (the jet knot) located ~ 3 px from the core, we believe that it is instead a manifestation of the instrumental pile-up, which could not be completely

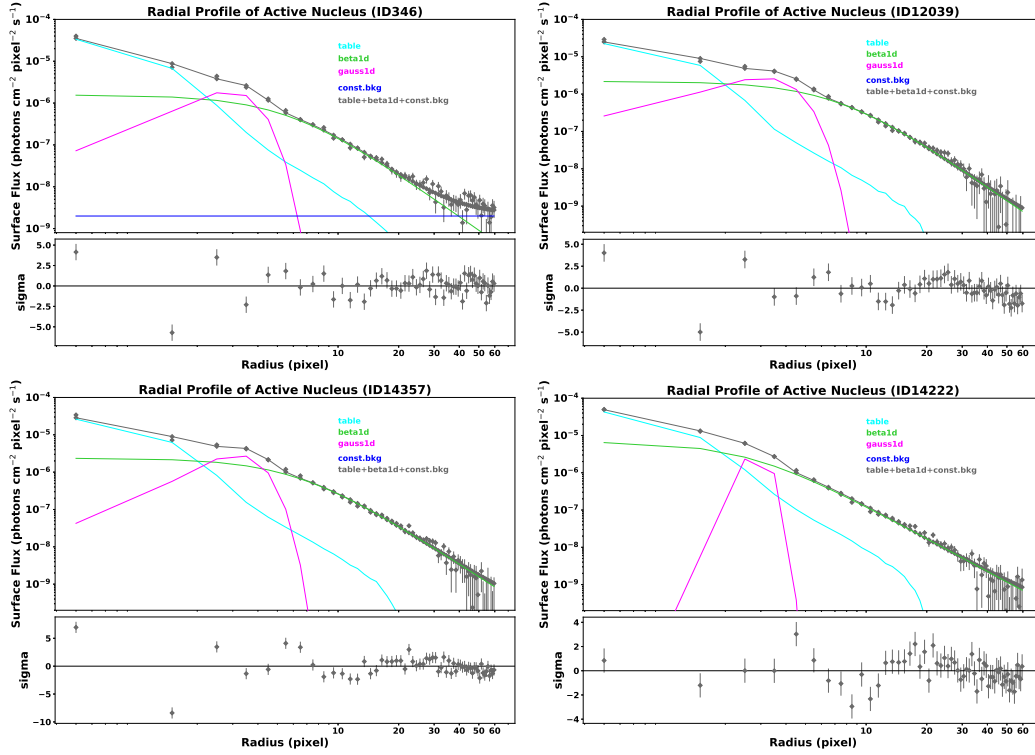


Figure 2.8: The X-ray surface brightness profile of the Pictor A central region, obtained from ObsID 346, ID12039, ID14357 and ID14222. The cyan curves denote the table model for the core PSF (with freed amplitude), the green curves correspond to the β -profile component, the blue horizontal line denotes the constant background (only for ObsID 346), the magenta curves denote the extra Gaussian component, and the solid grey curves give the total “Take #2” PSF+beta1+gauss1d(+constant) model fitted to the data. The corresponding residuals are given in the lower panel.

accounted for during the MARX simulation process. In order to verify this conclusion, based on the simulated PSF we performed the image deconvolution for ObsID 346, using the LucyRichardson Deconvolution Algorithm (LRDA), which is implemented in the CIAO tool `arestore`, in order to remove the effect of the PSF and to restore the intrinsic surface brightness distribution of the Pictor A central regions. The algorithm requires an image form of the PSF, and exposure-corrected maps of the source region. We performed 50 iterations of the PSF simulations, and produced 50 deconvolved images, which were next averaged. The resulting deconvolved image of the Pictor A nucleus from ObsID 346, with 1 px resolution, is presented in Figure 2.9. As shown, in addition to the central pixel (corresponding to the unresolved AGN) surrounded by a diffuse halo (corresponding to the hot gaseous atmosphere of the host) — both as expected from a properly deconvolved image — there is also an excess emission distributed within a ring with ~ 3 px from the central pixel. The ring-like morphology of this excess, supports our conclusion that it is an artifact of the instrumental pile-up effect.

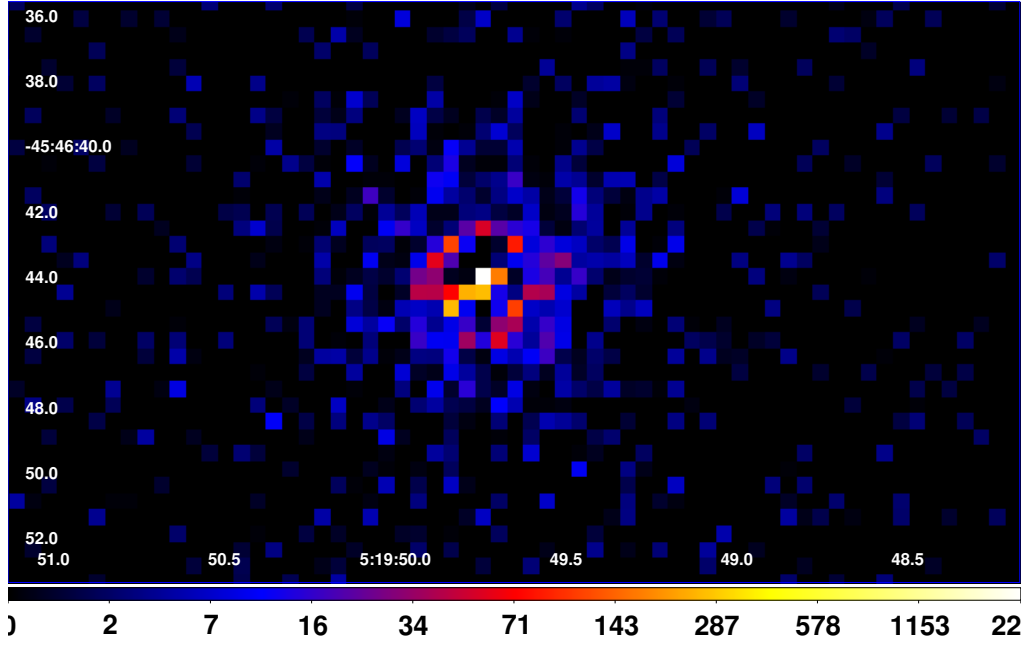


Figure 2.9: Deconvolved *Chandra* image of the Pictor A nucleus (ObsID 346), with 1 px resolution.

2.3 Conclusions & Future Work

Our approach to the analysis of the *Chandra* data for the active nucleus in Pictor A radio galaxy, and in particular to the spectral analysis in a regime of a strong instrumental pile-up, is alternative to the approach adopted by [Hardcastle et al. \(2016\)](#). While those authors analyzed the extended wings of the central PSF, and numerically corrected for the energy-dependence of the PSF, we have utilized the `jdpileup` model newly implemented in *Sherpa*. There are differences between our analysis results and the results obtained by [Hardcastle et al.](#), in particular regarding the slopes of the AGN power-law continuum, or the flux changes in the system. And while in the framework of our approach we were not able to completely remove/fully account for the instrumental pile-up effect, we believe that some of our findings are interesting enough to deserve a future, even more in-depth analysis. In particular, the two main conclusions emerging from our analysis are: (1) the contribution of the hot gaseous atmosphere of the host to the radiative output of the Pictor A nucleus, is very significant, and even dominates at distances of only several pixels from the center (up to ~ 30 px); as a result, one should be extremely careful when analyzing the extended wings of the central PSF in search of the AGN emission component free from the instrumental pile-up; (2) the available *Chandra* data allow, formally, for the presence of the very broad fluorescent iron line in the nuclear spectrum of Pictor A; we however deem this extremely exciting possibility as rather unlikely, due to the fact that the “grade migration” in the piled-up detector is a more probable cause of the observed hard X-ray excess in the 0.5–7.0 keV *Chandra* spectra of the system.

Chapter 3

Western Hotspot of Pictor A: Image Deconvolution and Variability Analysis

*This chapter originally appeared as ‘Chandra Imaging of the Western Hotspot in the Radio Galaxy Pictor A: Image Deconvolution and Variability Analysis’ by **R. Thimmappa, L. Stawarz, V. Marchenko, K. Balasubramaniam, C. C. Cheung, & A. Siemiginowska**; 2020, The Astrophysical Journal, Volume 903, Issue 2, id.109, 12 pp. ([Thimmappa et al. 2020b](#))*

3.1 Introduction

In classical radio galaxies, bright hotspots are formed when relativistic jets, emanating from Active Galactic Nuclei (AGN), terminate due to interactions with the intergalactic medium (IGM) at large distances (tens- and hundreds-of-kiloparsecs) from host galaxies. These hotspots mark, in particular, the position of the termination shocks, where jet bulk kinetic energy is converted to internal energy of the plasma transported by the jets, and next injected into the extended lobes ([Blandford & Rees 1974](#)). The interaction between a relativistic but “light” jet and a much denser ambient medium leads, in fact, to the formation of a double-shock structure, consisting of a non-relativistic forward shock propagating into the ambient medium, and a mildly-relativistic reverse shock propagating within the outflow (e.g., [Kino & Takahara 2004](#)). The intense non-thermal emission of the hotspots imaged from radio up to X-ray frequencies, is widely believed to originate in the near downstream of the reverse shock, where efficient acceleration of the jet particles to ultra-relativistic energies and magnetic field amplification likely take place (e.g., [Meisenheimer et al. 1989](#); [Stawarz et al. 2007](#); [Araudo et al. 2016](#)).

CHAPTER 3. WESTERN HOTSPOT OF PICTOR A

Table 3.1:: Observational Data and Spectral Fitting Results

ObsID	Date	MJD	Exposure	θ	Γ	red. χ^2	$F_{0.5-7.0\text{ keV}}$	Counts [†]
	d		[ksec]	[arcmin]			[$10^{-13}\text{ erg cm}^{-2}\text{ s}^{-1}$]	
346	2000-01-18	51561	25.8	3.50	2.01 ± 0.05	0.272	5.41 (+0.20 / - 0.45)	3461
3090	2002-09-17	52534	46.4	0.11	1.96 ± 0.03	0.377	5.64 (+0.03 / - 0.20)	5278
4369	2002-09-22	52539	49.1	0.11	1.99 ± 0.03	0.426	5.61 (+0.11 / - 0.15)	5564
12039	2009-12-07	55172	23.7	3.35	1.98 ± 0.06	0.260	5.71 (+0.02 / - 0.10)	2290
12040	2009-12-09	55174	17.3	3.35	2.07 ± 0.08	0.265	5.47 (+0.08 / - 0.25)	1710
11586	2009-12-12	55177	14.3	3.35	2.11 ± 0.09	0.212	5.39 (+0.21 / - 0.40)	1427
14357	2012-06-17	56095	49.3	3.07	2.05 ± 0.05	0.321	5.88 (+0.06 / - 0.14)	3043
14221	2012-11-06	56237	37.5	3.10	2.08 ± 0.05	0.356	5.84 (+0.01 / - 0.11)	3248
15580	2012-11-08	56239	10.5	3.10	2.08 ± 0.14	0.235	5.24 (+0.30 / - 0.21)	935
14222	2014-01-17	56674	45.4	3.30	2.00 ± 0.05	0.329	5.78 (+0.12 / - 0.10)	3428
16478	2015-01-09	57031	26.8	3.32	1.95 ± 0.08	0.232	5.30 (+0.15 / - 0.54)	1657
17574	2015-01-10	57032	18.6	3.32	2.04 ± 0.11	0.209	5.33 (+0.26 / - 0.21)	1187

[†] total number of 0.5 – 7.0 keV counts from a circular region with a radius 20 px centered on the hotspot.

In the majority of cases, relatively small angular sizes and fluxes of the hotspots, in cosmologically distant radio galaxies, preclude any detailed morphological analysis of the termination shocks, with the available instruments characterized by a limited sensitivity and arc-second angular resolution. For such, one can only apply a detailed spectral analysis and modeling of the broad-band spectral energy distribution, utilizing the integrated radio, infrared, optical, and X-ray flux measurements (e.g., [Meisenheimer et al. 1997](#); [Brunetti et al. 2003](#); [Georganopoulos & Kazanas 2003](#); [Hardcastle et al. 2004](#); [Tavecchio et al. 2005](#); [Werner et al. 2012](#)). Only in a few cases of the brightest and most extended hotspots, sub-arcsec imaging at high-frequency radio and near-infrared/optical frequencies have been performed; besides the famous Cygnus A example (see, e.g., [Carilli & Barthel 1996](#); [Pyrzas et al. 2015](#); [Dabbech et al. 2018](#)), these cases include 3C 445 ([Prieto et al. 2002](#); [Orienti et al. 2012, 2017](#)), and 4C +74.26 ([Erlund et al. 2010](#)).

The other particularly bright and extended hotspot can be found at the edge of the Western lobe of the nearest FR II type ([Fanaroff & Riley 1974](#)) radio galaxy, Pictor A, located at redshift $z = 0.035$ ([Eracleous & Halpern 2004](#)). The Western hotspot, which is much brighter than the Eastern hotspot located at the counter-jet side, and which is located at the projected distance of about 4 arcmin from the nucleus, has been investigated in detail: at cm radio wavelengths using the Very Large Array ([Perley et al. 1997](#)), at mid-infrared frequencies with the *Spitzer* Space Telescope ([Werner et al. 2012](#)) and the Wide-field Infrared Survey Explorer (WISE; [Isobe et al. 2017](#)), in near-infrared using ground-based data ([Meisenheimer et al. 1997](#)), at optical wavelengths with the Faint Object Camera onboard the *Hubble* Space Telescope ([Thomson et al. 1995](#)), and finally in X-rays with the *Chandra* X-ray Observatory ([Hardcastle et al. 2016](#), and references therein). The hotspot was also the subject of high-resolution radio imaging with the Very Long Baseline Array (VLBA; [Tingay et al. 2008](#)).

In this paper, we reanalyze all available *Chandra* data for the Western hotspots in

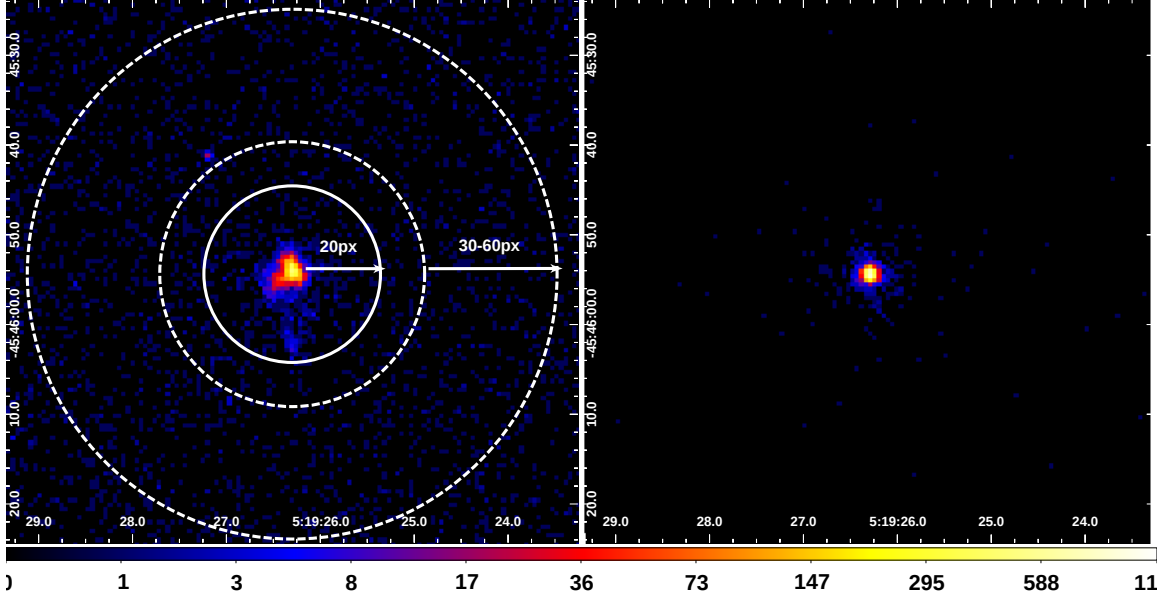


Figure 3.1: *Left panel:* ACIS-S image of the W hotspot of Pictor A radio galaxy, within the energy range $0.5 - 7$ keV for the ObsID 3090 (with 1 px binning and field point sources removed). The source extraction region for the spectral modeling is denoted by the green solid circle (20 px radius), and the background annular region by green dashed circles (30 – 60 px). *Right panel:* the PSF simulated for the ObsID 3090 (as discussed in Section 3.3.2).

Pictor A. The data consist of 12 pointings, spread over 15 years starting from 2000, each characterized by a different exposure and a different off-axis angle. Our study is complementary to the analysis presented in [Hardcastle et al. \(2016\)](#), in that we perform a detailed image deconvolution of the hotspot for each pointing in order to clearly resolve the hotspot structure and to investigate its flux variability, first reported by [Hardcastle et al.](#).

Throughout the paper we assume the Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, for which the luminosity distance to the source is 154 Mpc, and the conversion angular scale is $0.697 \text{ kpc arcsec}^{-1}$. The photon index Γ is defined as $F_\epsilon \propto \epsilon^{-\Gamma}$ for the photon flux spectral density F_ϵ and the photon energy ϵ .

3.2 Chandra Data

The Pictor A system has been observed with the Advanced CCD Imaging Spectrometer (ACIS), onboard *Chandra*, on 14 separate occasions over the past 15 years. The quality of the data for given regions of the source varies between the different pointings, due to the fact that the effective point spread function (PSF) is a complicated function of position in the imager, the source spectrum, and the exposure time. For our study we selected a 12-pointing subset of the ([Hardcastle et al. 2016](#)) study, with a total observing time of 364 ks;

we excluded the two pointings (ObsID 14223 and 15593) for which the hotspot was located very close to the chip gap on the detector. In Table 3.1 we list the ObsIDs, the dates and MJD of the observations, the exposure times, and the off-axis angles for the hotspot θ . Note that the best-quality data for the hotspot corresponds to the ObsID 3090 and 4369, due to a combination of relatively long uninterrupted exposures (exceeding 45 ksec) and small off-axis angles ($0.11 \simeq 7''$).

All data was reprocessed in a standard way with CIAO 4.10 (Fruscione et al. 2006), using the `chandra_repro` script and the Calibration database CALDB 4.7.8 recommended by the CIAO analysis threads. Pixel randomization was removed during the reprocessing and readout streaks were removed for all observational data. Point sources in the field were detected with the `wavdetect` tool and then removed for all analyzed ObsIDs. Throughout this paper, we selected photons in the 0.5–7.0 keV range. Counts and spectra were extracted for the source and the background regions from individual event files using the `specextract` script. Spectral fitting was done with the Sherpa package (Freeman et al. 2001).

The total number of counts obtained for the W hotspot ($> 30,000$) implies that calibration uncertainties dominate over statistical ones (see in this context Drake et al. 2006, Lee et al. 2011 and the related discussion in Hardcastle et al. 2016). We note that given the observed X-ray flux of the source, there is also a possibility for a pile-up in the detector (Davis 2001), in particular in ObsID 3090 and 4369, for which the W hotspot was located at the center of the S3 chip, and the resulting count rates were $\simeq 0.2 \text{ s}^{-1}$. Therefore, when performing the MARX simulation for the PSF modeling, we have accounted for the pile-up effect as well.

3.3 Data Analysis

3.3.1 Spectral modeling

For the spectral analysis, we have extracted the source spectrum in each ObsID from a circular region with a radius 20 px ($\simeq 10''$, for the conversion scale $0.492''/\text{px}$, and extracted the background spectrum from an annulus of 30 – 60 px ($\sim 15'' - 30''$), as illustrated in Figure 3.1 (left panel) for the ObsID 3090. The background-subtracted source spectra (with a total number of net counts ranging from about 900 for the ObsID 15580 up to about 5,000 for the ObsID 4369, see Table 3.1) were fitted within the 0.5 – 7.0 keV range, assuming a single power-law model moderated by the Galactic column density $N_{\text{H,Gal}} = 4.12 \times 10^{20} \text{ cm}^{-2}$ (Kalberla et al. 2005). Two examples of the fit, for the first exposure ObsID 346 and the last exposure ObsID 17574, are presented in Figure 3.2. The apparent difference between the low-energy segments of the spectra for the two pointings reflects, at least to some extent, the effective area of the detector at low photon energies decreasing with time (Plucinsky et al. 2018). The results of the spectral fitting performed, for all the analyzed pointings, are summarized in Table 3.1, and visualized in Figure 3.3.

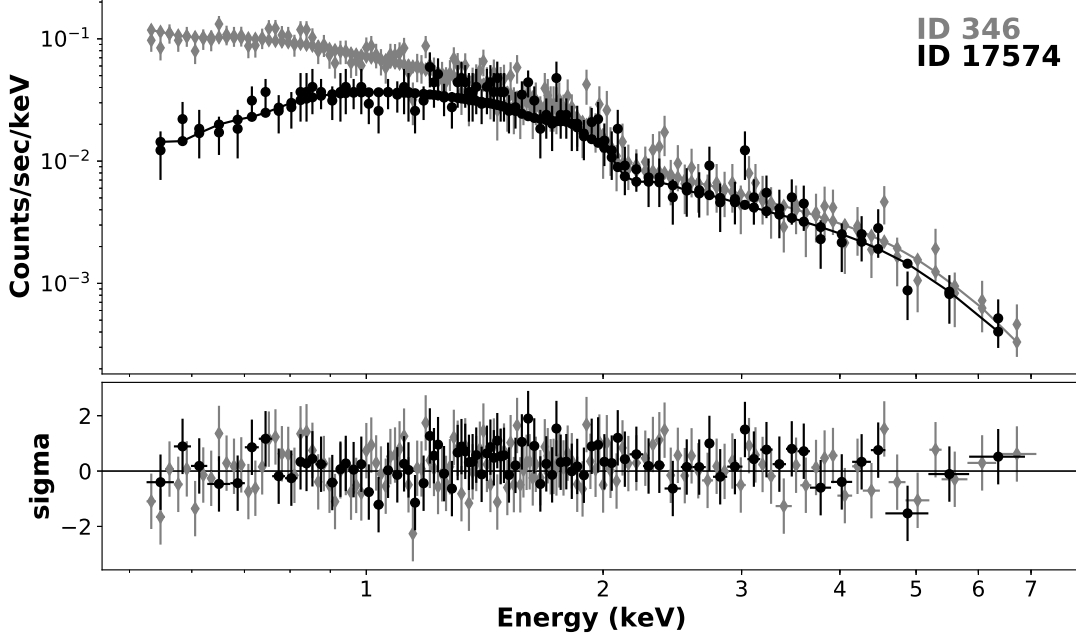


Figure 3.2: The 0.5 – 7.0 keV spectra of the W hotspot of Pictor A, for ID 346 (gray diamonds) and 17574 (black circles), both fitted with the single power-law model moderated by the Galactic column density. Parameters of the model are given in Table 3.1.

Overall, in our spectral analysis we see that the single power-law model provides a reasonable description of the source spectrum, and is sufficient for single pointings when being fitted separately. In addition, even though we do see some changes in the 0.5 – 7.0 keV flux of the target between successive pointings, the source variability cannot be claimed at a high significance level, given the uncertainty in the flux estimates (see in this context the discussion in [Hardcastle et al. 2016](#), section 3.3 and Figure 8 therein). To highlight this point in quantitative, simple way, for our successive flux estimates $F_i \pm \sigma_i$ with $i = 1, \dots, 12$ (Table 3.1), we test for a constant signal by calculating

$$\chi^2 = \sum_{i=1}^{N=12} \frac{(F_i - F_m)^2}{\sigma_i^2} \simeq 20.8. \quad (3.1)$$

Here the model F_m is the mean flux given the Gaussian errors (for which we assumed average values in the case of asymmetric errors reported in Table 3.1),

$$F_m = \frac{\sum_{i=1}^{N=12} F_i / \sigma_i^2}{\sum_{i=1}^{N=12} 1 / \sigma_i^2} \simeq 5.72 \quad (3.2)$$

in units of $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. The probability that our model is correct, is therefore

$$P(\chi^2) = \frac{(\chi^2)^{(\nu-2)/2} \exp[-\chi^2/2]}{2^{\nu/2} \Gamma(\nu/2)} \simeq 0.011, \quad (3.3)$$

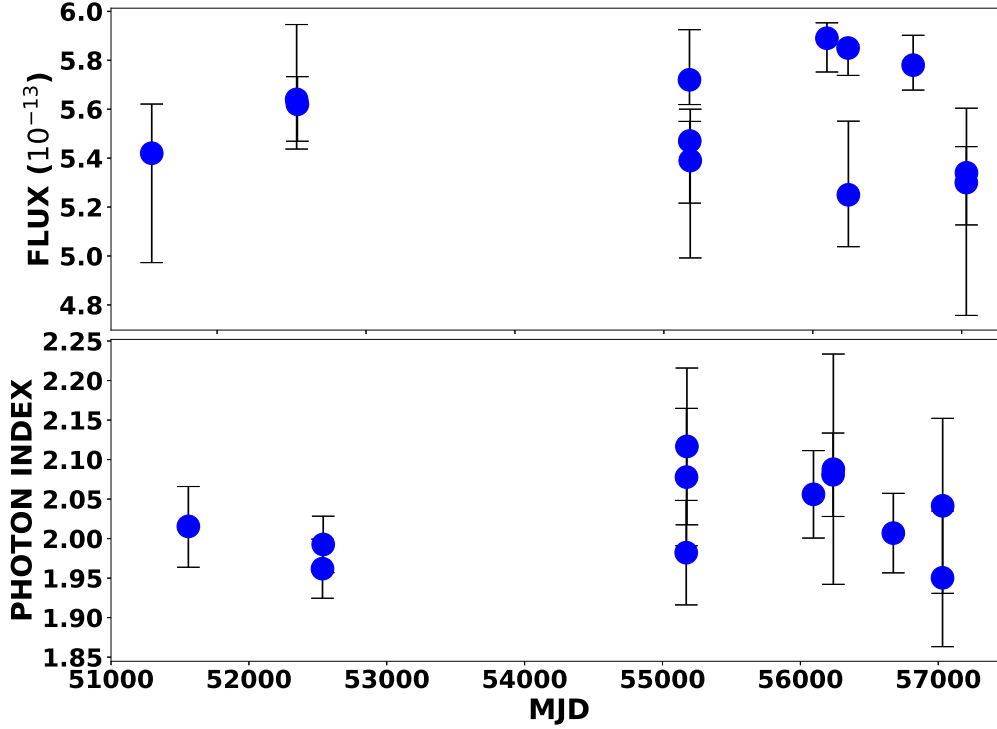


Figure 3.3: The 0.5 – 7.0 keV energy flux (upper panel) and the photon index (lower panel) for the W hotspot of Pictor A, determined from single absorbed power-law model (see Table 3.1). The energy flux is given in the units of 10^{-13} erg cm $^{-2}$ s $^{-1}$.

where $\Gamma(\nu/2)$ is the Gamma function, and the degrees of freedom $\nu = N - 1 = 11$. As follows, $\chi^2/\nu \simeq 1.89$, and the corresponding probability for a constant flux reads as $\sim 1\%$.

3.3.2 PSF modeling

For modeling of the *Chandra* PSF at the position of the W hotspot of Pictor A, we have used the Chandra Ray Tracer (ChaRT) online tool (Carter et al. 2003)¹ and MARX software (Davis et al. 2012)². The centroid coordinates of the selected source region were taken as the position of a point source. The source spectrum for the spectral specification in ChaRT was the background-subtracted 0.5 – 7.0 keV spectrum created separately for each observation and fitted with a single power-law model, as described in the previous sub-section. Next, a collection of event files were made using ChaRT by tracing rays through the Chandra X-ray optics. Then the rays were projected onto the detector through MARX simulation, taking into account all relevant detector issues. Through this process, an event file was obtained

¹<http://cxc.harvard.edu/ciao/PSFs/chart2/runchart.html>

²<https://space.mit.edu/cxc/marx>

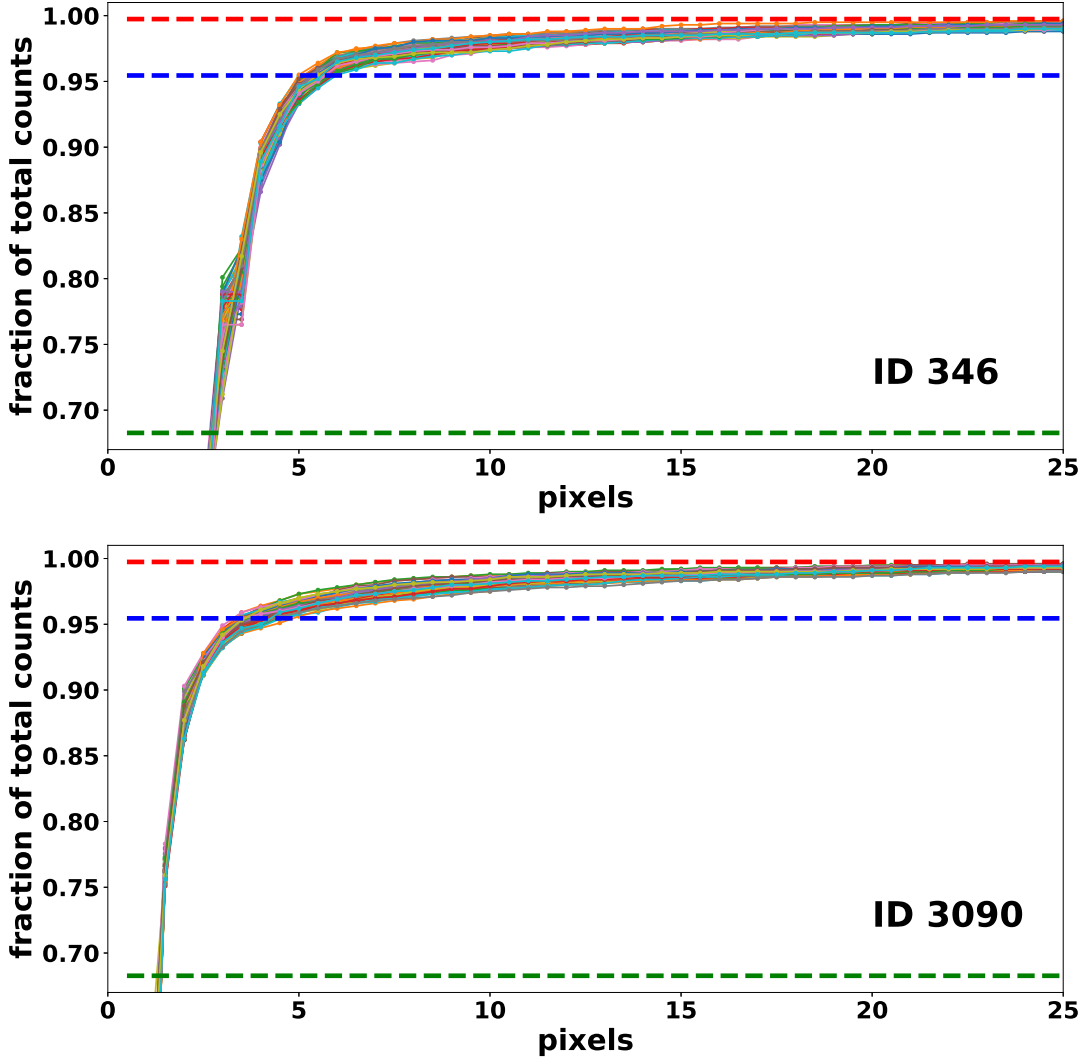


Figure 3.4: The enclosed count fraction as a function of the radius aperture for the simulated PSFs for ObsIDs 346 (upper panel) and 3090 (lower panel). For each ObsID we performed 100 PSF simulations, and each curve corresponds to one particular PSF realization. The horizontal green, blue, and red lines (from bottom to top), correspond to 1σ , 2σ , and 3σ count fractions, respectively.

from which an image of the PSF was created. We used one of the latest features in the last release of MARX, namely the option to use the energy-dependent sub-pixel event repositioning algorithm (EDSER) to adjust chip coordinates, and also to include the pileup effect. We reprocessed all the archival data, and used the aspect solution for each observation.

For every ObsID, we perform the PSF simulations, as described above, 100 times, as each particular realization of the PSF is different due to random photon fluctuations; an example of the simulated PSF for the ObsID 3090 is presented in Figure 3.1 (right panel).

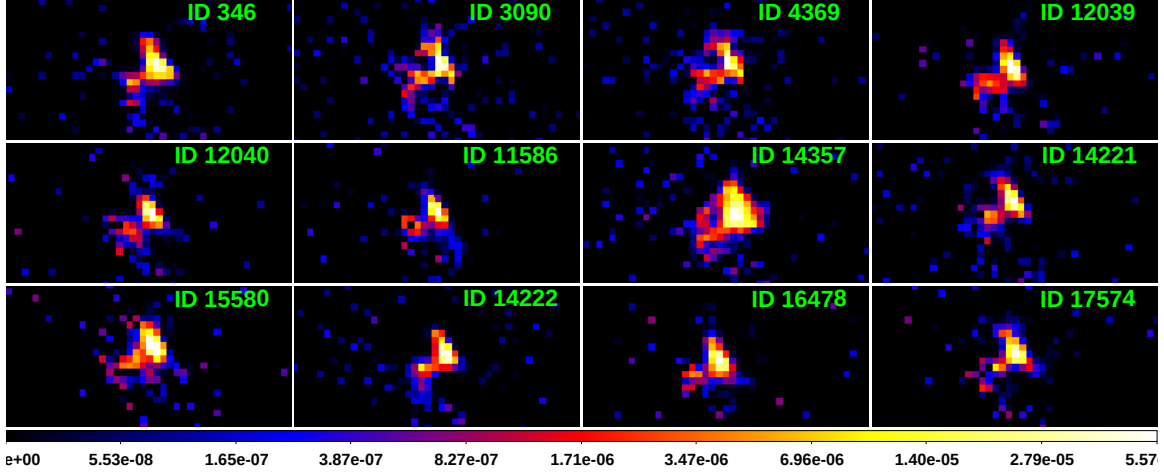


Figure 3.5: The deconvolved *Chandra* images of the W hotspot in Pictor A at 1 px resolution. Each image results from averaging over the restored images for 100 PSF realizations using the LRDA on the exposure-corrected maps. The color scale gives the count rate (cts s^{-1}).

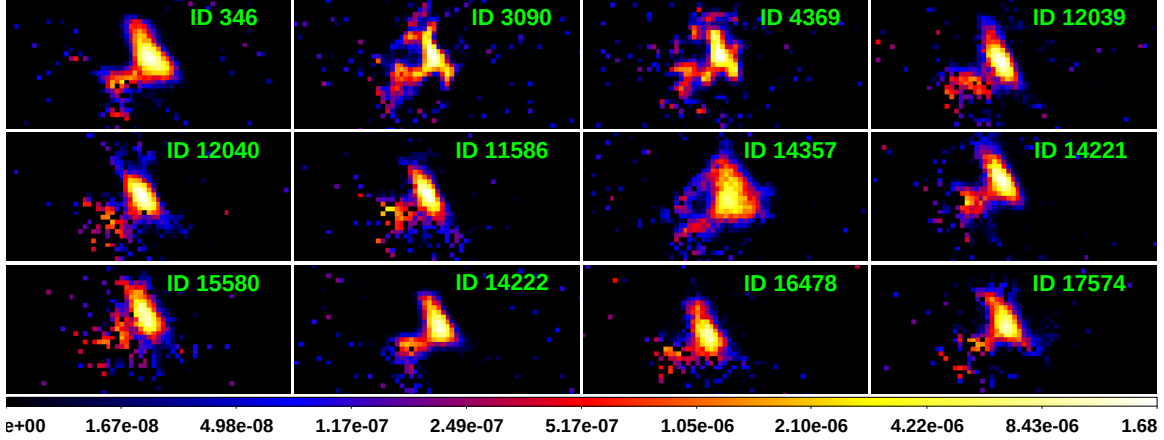


Figure 3.6: The deconvolved *Chandra* images of the W hotspot in Pictor A at 0.5 px resolution. Each image results from averaging over the restored images for 100 PSF realizations using the LRDA on the exposure-corrected maps. The color scale gives the count rate (cts s^{-1}).

With such, we first study the enclosed count fraction (ECF) in the simulated PSFs, i.e. the fraction of counts that have been detected within a circular radius aperture (noting that the *Chandra*'s PSF is in reality more and more elongated with increasing off-axis angle). For illustration, in Figure 3.4 we present the resulting ECF as a function of the radius aperture for the first two ObsIDs 346 and 3090, which differ in both exposure time and off-axis angle (see Table 3.1).

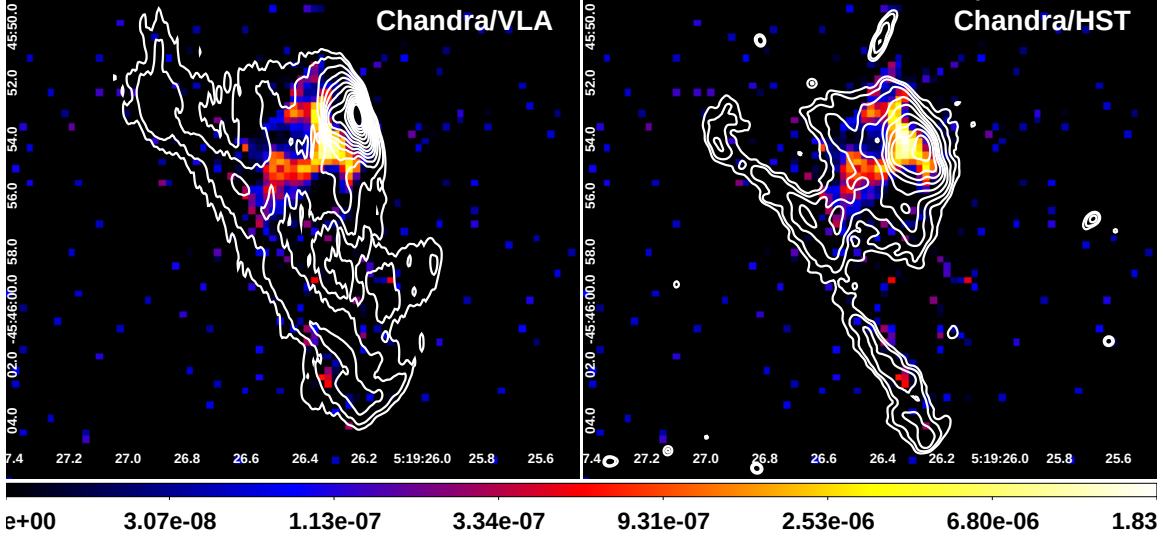


Figure 3.7: The deconvolved exposure-corrected *Chandra* image of the W hotspot in Pictor A at 0.5 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF, with the radio (3.6 cm wavelength, beam size $0.''77 \times 0.''17$, position angle -0.4 deg) VLA contours superimposed (left panel) and optical F606W filter ($5918\text{\AA}$, 90% encircled energy within radius $0.35''$) *Hubble* Space Telescope ACS/WFC contours superimposed (right panel). Radio contours are spaced with a factor of $\sqrt{2}$ between 0.552 and 70.71% of the peak intensity of $215 \text{ mJy beam}^{-1}$. Optical contours are spaced with a factor of $\sqrt{2}$ between 0.008 and 3 cts s^{-1} .

3.3.3 Image Deconvolution

We use the Lucy-Richardson Deconvolution Algorithm (LRDA), which is implemented in the CIAO tool *arestore*, to remove the effect of the PSF and restore the intrinsic surface brightness distribution of the hot spot. The algorithm requires an image form of the PSF, which is provided by our *ChART* and *MARX* simulations as described in the previous subsection, and exposure-corrected maps of the source (see also in this context [Marchenko et al. 2017](#), for the *Chandra* image analysis of the large-scale jet in radio quasar 3C 273). As there are 100 iterations of PSF simulations for each given ObsID, we first produce 100 deconvolved images for each pointing, and next, average them. The collection of the resulting deconvolved images with 1 px resolution are presented in Figure 3.5, and with 0.5 px resolution in Figure 3.6.

We note that the deconvolved images corresponding to the ObsID 14357 look very different than the deconvolved images for the other ObsIDs, being in particular blurred and seemingly “unfocused”. Indeed, in this particular observation the hotspot was located on the S2 chip, while in the remaining observations analyzed here it was placed on the back illuminated S3 chip.

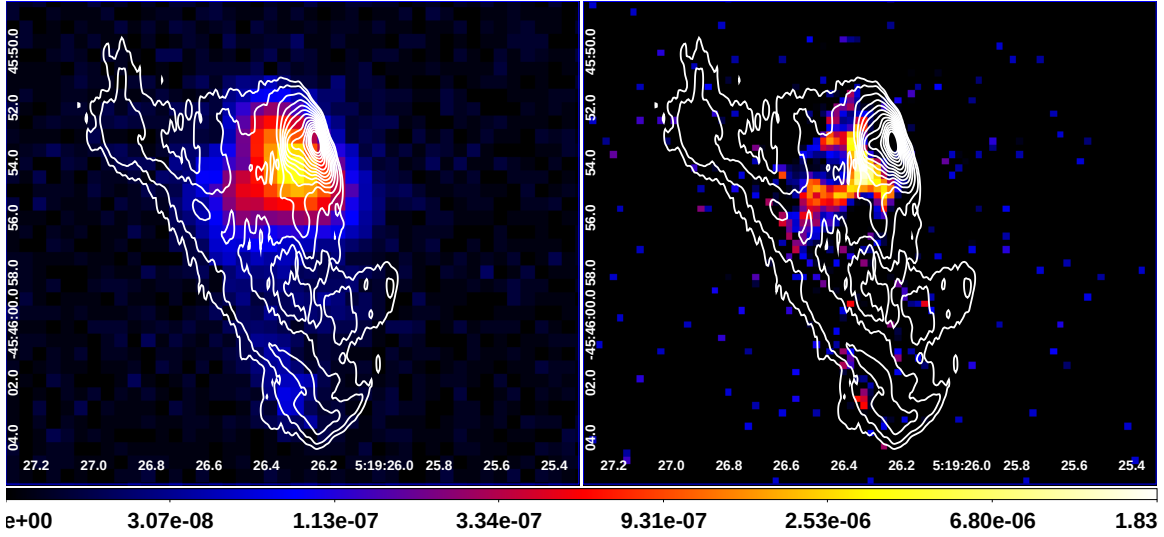


Figure 3.8: A comparison between the *Chandra* image of the W hotspot in Pictor A resulting from merging all the analyzed ObsIDs (left panel), and the deconvolved exposure-corrected image at 0.5 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF (right panel). In both panels, the VLA 3.6 cm radio contours are superimposed (see Figure 3.7).

3.4 Discussion: Results of the Analysis

In Figure 3.7 (upper panel), we present the deconvolved exposure-corrected *Chandra* image of the W hotspot in Pictor A at 0.5 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF, with the superimposed Very Large Array (VLA) radio contours (Perley et al. 1997), as well as *Hubble* Space Telescope optical contours from archival ACS/WFC F606W data obtained in May 2015 (1.35 hr exposure; program 13731). As shown, on the deconvolved *Chandra* image the X-ray structure of the hotspot is resolved into a seemingly linear feature oriented along the jet axis, and terminating into the perpendicular ($\sim 4''$ -long) disk-like segment located just upstream ($\sim 1''.5$ away) of the intensity peak of the radio hotspot. We identify this segment with the Mach disk of the hotspot as discussed in Meisenheimer et al. (1989), i.e. the very front of the reverse shock formed within the jet plasma due to the interaction of the jet head with the ambient medium; alternatively, we could be looking at the upstream conical shock formed at the head of the jet, as seen in some runs of the hydrodynamical simulations of a light, supersonic outflow by Saxton et al. (2002), depending on the choice of the main model parameters (jet/ambient medium density contrast, jet Mach number, and jet viewing angle). The radio continuum emission peaks further downstream of this shock, and extends up the distance which, again, *could* be identify with the contact discontinuity where the shocked jet plasma meets the shocked IGM. The position of the optical intensity peak of the hotspot agrees well with the position of the X-ray disk. On the other hand, the filament — a “bar” — perpendicular

to the jet axis, but located $\sim 10''$ upstream of the Mach disk, which is present in the radio image and particularly prominent in the optical image, possesses only a very weak X-ray counterpart on the deconvolved X-ray images.

In Figure 3.8, we show the X-ray image of the hotspot resulting from merging all the analyzed *Chandra* ObsIDs excluding ObsID 14357 (left panel), and the deconvolved exposure-corrected image at 0.5 px resolution for the ObsID 3090 (right panel). As shown, merging all the selected ObsIDs (aligned using the measured peak position of the hotspot) one significantly improves the photon statistics, but at the same time blurs the image due to different shapes of the PSFs superimposed. The offset between the X-ray and radio intensity peaks can, however, still be observed on the merged image (see [Hardcastle et al. 2016](#)), although the X-ray structure of the hotspot is no longer resolved into the jet and the perpendicular Mach disk/conical shock.

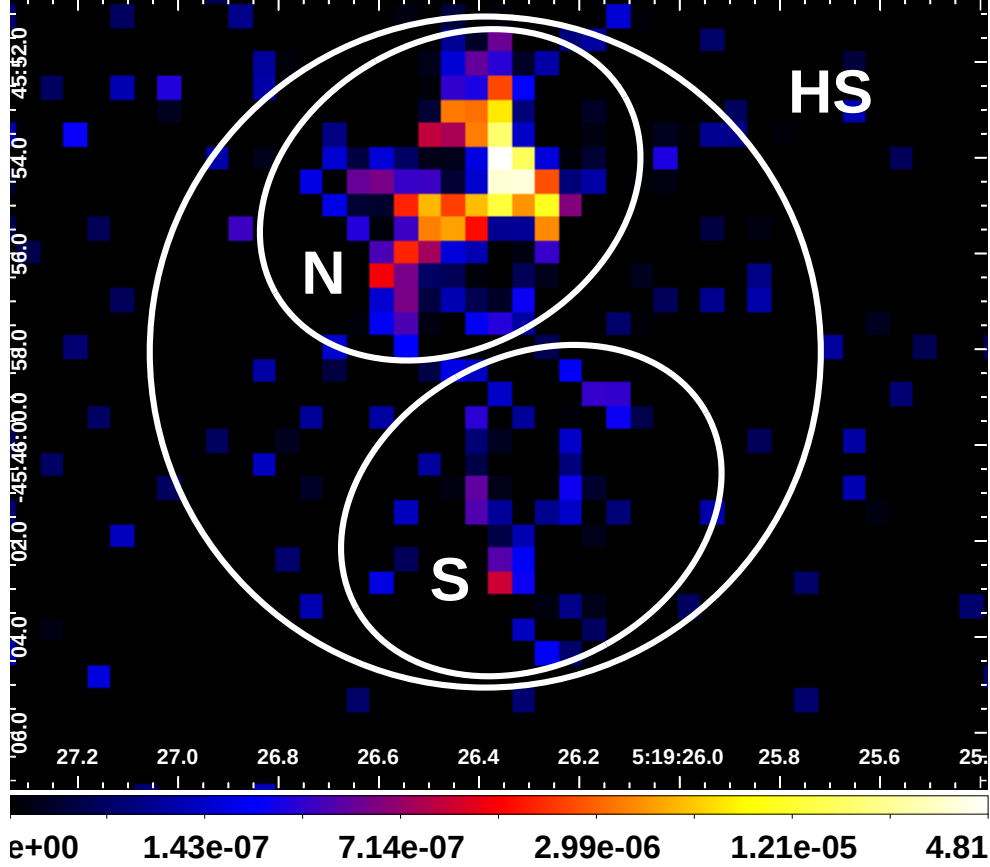


Figure 3.9: The deconvolved exposure-corrected *Chandra* image of the W hotspot in Pictor A at 1.0 px resolution for the ObsID 3090, averaged over 100 random realizations of the PSF. Source regions used for the extraction of the next counts — “hotspot total” (HS), “hotspot North” (N), and “hotspot South” (S) — are denoted by the circle and the two smaller ellipses.

CHAPTER 3. WESTERN HOTSPOT OF PICTOR A

As the image deconvolution procedure should not affect the number of counts on the image, but only their distribution, we have additionally attempted to investigate the variability of the W hotspot by means of measuring the count rates on the obtained deconvolved (1 px resolution) exposure-corrected maps of the target. In Figure 3.9 we show the flux extraction regions defined for this purpose, including the circular “hotspot total” (HS) region with the 14 px radius, the elliptical “hotspot North” (N) region with the major and minor axes of 8.5 px and 6.5 px, enclosing the main part of the hotspot, and finally the analogous elliptical “hotspot South” (S) region encompassing the Southern extension of the perpendicular filament (bar), which is pronounced clearly on the radio and optical maps, but only marginally on the *Chandra* images.

With such defined regions, we measure the net count rates (with the background chosen as adjacent to the hotspot but located outside of the radio lobe) individually on every image corresponding to particular random realizations of the PSF. As a result, for each given ObsID we obtained 100 independent net count rate measurements, for which the distribution is expected to be normal. Since the image deconvolution procedure does not provide any other way for propagating the errors, we consider the mean in those distributions μ as our final flux estimates, and the standard deviations, σ , as an estimate of the corresponding uncertainty in the performed flux measurements. Note in this context, that the PSF image is a simulated image based on a model, and there are uncertainties associated with the model adopted; by simulating 100 different realizations of the PSF we take into account the statistical uncertainties (so randomness of rays, detected rays, etc.), but not the systematic uncertainties in the model of the PSF simulator.

Table 3.2:: Net Count Rates of the W Hotspot in Pictor A and its Two Subregions, from the Deconvolved Images

ObsID	MJD	HS	N	S
	d	$[10^{-6} \text{ cts s}^{-1}]$	$[10^{-6} \text{ cts s}^{-1}]$	$[10^{-6} \text{ cts s}^{-1}]$
346	51561	291.3 $\pm$ 0.4	283.0 $\pm$ 0.5	7.0 $\pm$ 0.3
3090	52534	260.1 $\pm$ 0.2	251.8 $\pm$ 0.3	6.4 $\pm$ 0.1
4369	52539	260.4 $\pm$ 0.2	251.3 $\pm$ 0.4	6.8 $\pm$ 0.1
12039	55172	235.5 $\pm$ 0.5	228.7 $\pm$ 0.7	5.7 $\pm$ 0.3
12040	55174	248.0 $\pm$ 0.4	241.0 $\pm$ 0.6	6.1 $\pm$ 0.3
11586	55177	243.9 $\pm$ 0.4	238.0 $\pm$ 1.0	2.6 $\pm$ 0.5
14357	56095	216.1 $\pm$ 0.2	210.3 $\pm$ 0.4	4.7 $\pm$ 0.2
14221	56237	223.5 $\pm$ 0.4	217.1 $\pm$ 0.5	5.2 $\pm$ 0.2
15580	56239	233.1 $\pm$ 0.4	228.8 $\pm$ 0.7	2.2 $\pm$ 0.4
14222	56674	210.8 $\pm$ 0.3	203.7 $\pm$ 0.4	6.0 $\pm$ 0.2
16478	57031	182.2 $\pm$ 0.3	176.2 $\pm$ 0.5	4.4 $\pm$ 0.3
17574	57032	189.3 $\pm$ 0.3	183.4 $\pm$ 0.4	4.6 $\pm$ 0.3

Figure 3.10 presents the distributions of the net count rates for the ObsID 3090, along with the values of μ and σ emerging from fitting Gaussians to the distributions. The flux estimates for all the analyzed ObsIDs, obtained in the analogous way by fitting Gaussians to the net count rate distributions, are summarized in Table 3.2; the corresponding

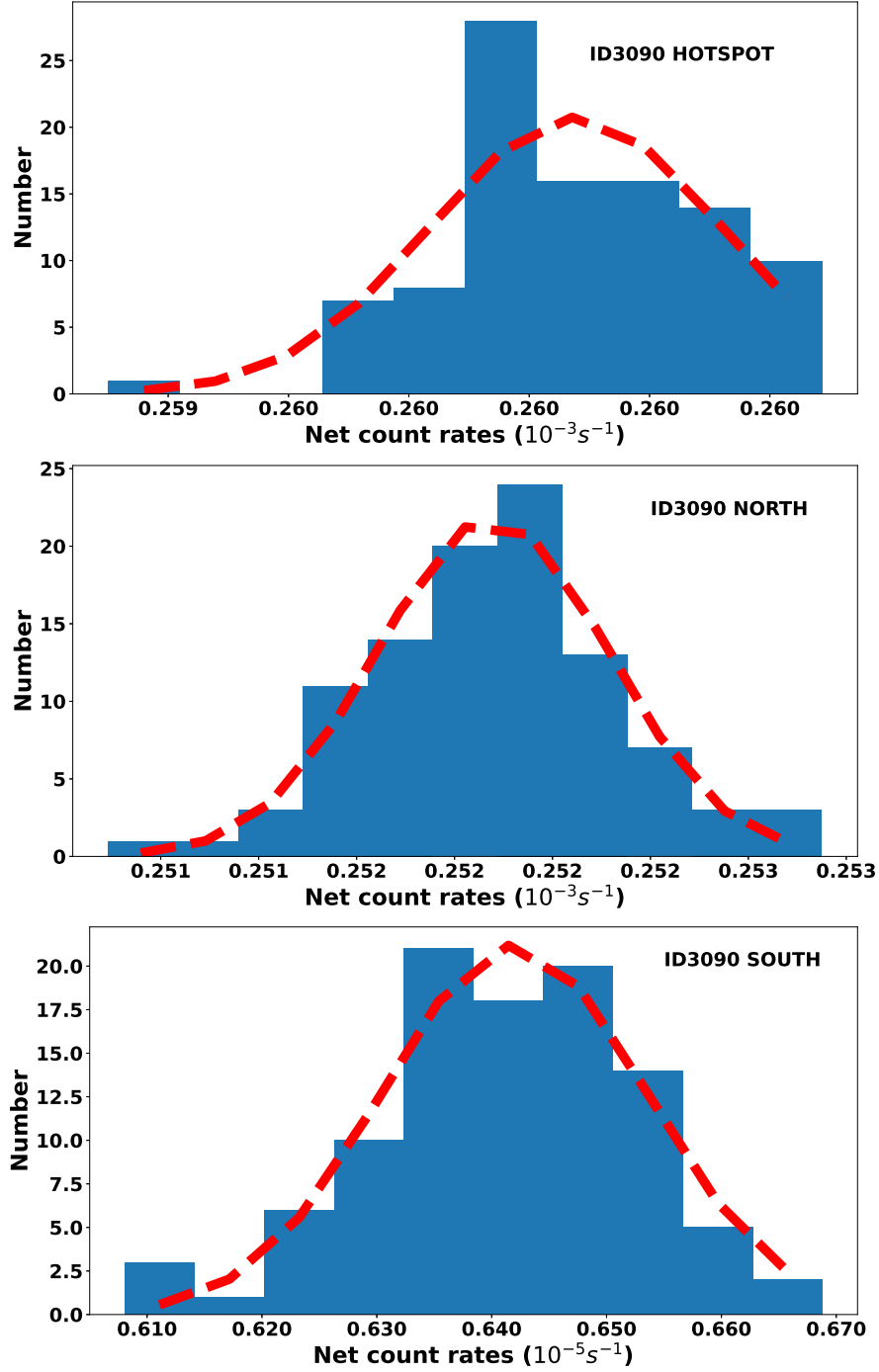


Figure 3.10: Histograms of the net count rates calculated for the selected regions HS (top panel), N (middle panel), and S (lower panel) within the W hotspot in Pictor A, on the deconvolved exposure-corrected *Chandra* images for the ObsID 3090, for 100 random realizations of the PSF.

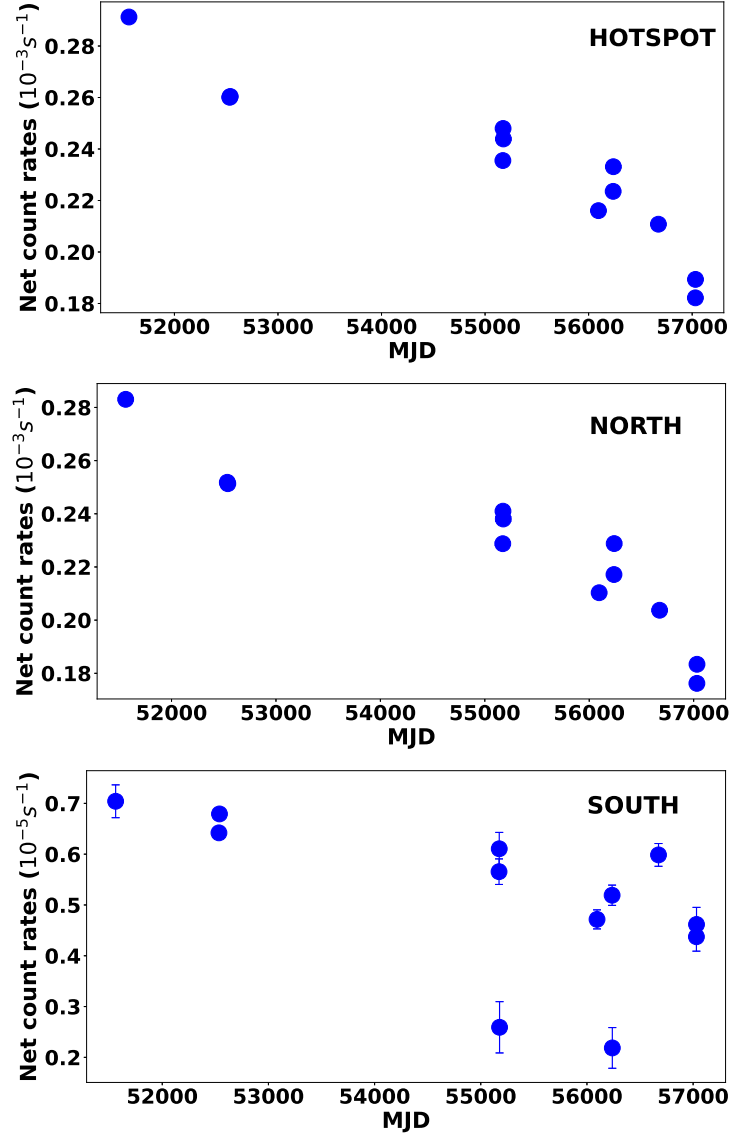


Figure 3.11: The net count rate measured for the selected regions HS (top panel), N (middle panel), and S (lower panel) within the W hotspot in Pictor A on the deconvolved exposure-corrected *Chandra* images (see Table 3.2), as a function of the observing time.

histograms (HS regions only) are shown in the Appendix 3.5. Figure 3.11 presents the resulting lightcurves of the hotspot. The HS region is dominated by the N region, and in both, we observe a monotonic and statistically significant decrease of the net count rate by about 30% between 2000 and 2015.

As the deconvolution procedure was performed on the exposure-corrected images, we do not believe that this decrease could be due to the known degradation of the ACIS CCDs (see [Plucinsky et al. 2018](#)), at least not entirely — some of the flux changes have to be

intrinsic to the hotspot, especially after 2010 when the observed net count rate decrease seemingly sped up. Interestingly, in the S region we also see the overall net count rate decrease between 2000 and 2015, and this could be considered as evidence for the observed flux changes being rather due to the CCDs’ degradation. On the other hand, for the S region the lightcurve seems much more erratic, and the overall net count rate is at the level of a few percent of the net count rate for the N region, and so it is possible that what we observe here is rather a photon leakage from the N region to the adjacent S region.

If the observed X-ray flux changes, at the level of 30%, are indeed intrinsic to the hotspot, they have to originate within the brightest part of the source, i.e. within the Mach disk/conical shock. This feature is clearly extended for about $4''$ in the longitudinal direction (i.e., perpendicularly to the jet axis), meaning a physical scale of about 3 kpc; the question is if it can also be resolved transversely. In order to investigate this issue, we use the `dmregrid2` tool implemented in the CIAO to rotate the deconvolved *Chandra* images of the hotspot, and we extract the integrated counts along the major axis of the N region displayed on Figure 3.9. We perform this exercise separately for each realization of the PSF for a given ObsID. As a result, we obtain 100 surface brightness profiles for each ObsID. These are shown for comparison for the ObsIDs 346 and 3090 on Figure 3.12 (left and right panels, respectively), at either 1 px or 0.5 px resolution (upper and lower panels, respectively). The profiles for all the analyzed ObsIDs (only sub-px resolution) are displayed in the Appendix 3.5 below. As follows, on the 0.5 px-resolution de-convolved images the brightest segment of the hotspot appears narrower than on the 1 px-resolution de-convolved images. The intensity profiles of this segment are in all the cases (except of ObsID 14357 commented above in § 3.3.3) symmetric and centrally-peaked; this indicates that the shock structure is transversely unresolved even at the sub-px *Chandra* resolution, with the corresponding scale upper limit of $\sim 0.''25 < 200$ pc.

3.5 Conclusions

The Western hotspot in the radio galaxy Pictor A is known for its complex multi-wavelength morphology, and also for its broad-band emission spectrum defying simple modeling. In the context of the former, one may reiterate on the presence of the extended radio/optical filament perpendicular to the jet axis and located several kpc upstream of the termination shock (Perley et al. 1997; Thomson et al. 1995; Saxton et al. 2002), as well as of the high-brightness temperature compact (pc-scale) radio knots within/around the termination shock (Tingay et al. 2008). Regarding the latter, one may note the mid-infrared excess over the integrated radio-to-optical continuum of the entire structure (Isobe et al. 2017), as well as the intense power-law X-ray emission, for which both the observed flux and the best-fit slope challenge all simple “one-zone” emission scenarios, ascribing the production of the observed keV-energy photons to either synchrotron or inverse-Compton processes (e.g., Wilson et al. 2001).

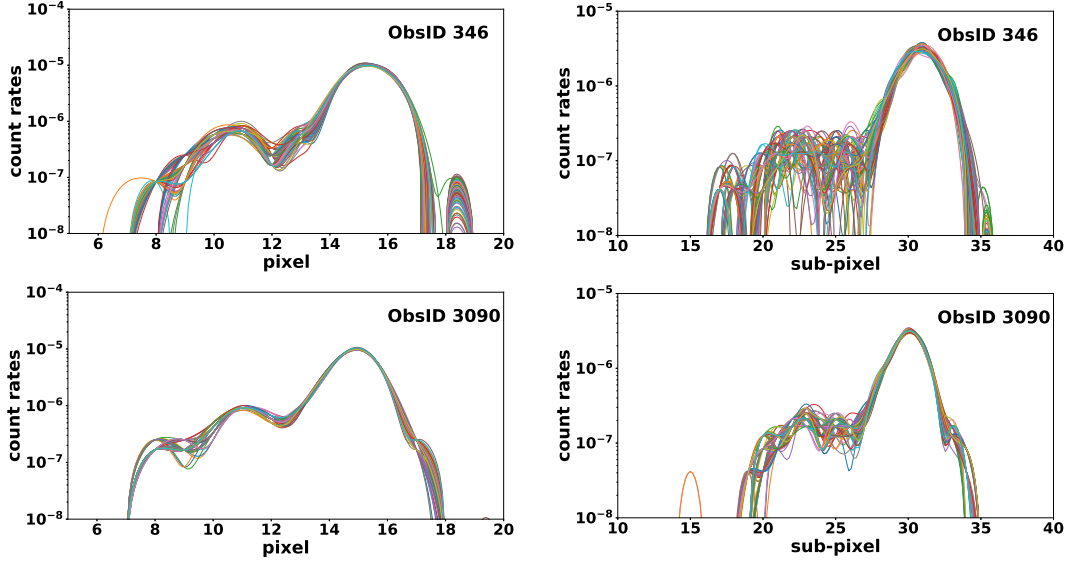


Figure 3.12: Integrated intensity profiles along the major axis of the N region displayed on Figure 3.9, for the ObsID 346 and 3090 (upper and lower panels, respectively), at either 1 px or 0.5 px resolution (left and right panels, respectively). Each curve on the panels corresponds to a single realization of the PSF for a given ObsID.

Multiple *Chandra* observations of the source, summarized and re-analyzed in (Hardcastle et al. 2016), enriched the overall picture by a tentative detection of the X-ray flux variability within the hotspot, on the relatively short timescale of years. The novelty of the analysis of the *Chandra* data presented here, is that by means of detailed PSF simulations and image deconvolution, we were able to resolve the X-ray structure of the hotspot into (i) the jet-like feature located in between the radio/optical filament and the termination shock, and (ii) the disk-like or conical feature perpendicular to the jet axis, and located $\sim 1.''5 \simeq 1$ kpc upstream the intensity peak of the radio hotspot. We believe that this later feature — resolved in its longitudinal direction to be $\sim 4'' \sim 3$ kpc long, while remaining basically unresolved in its transverse direction, with the corresponding scale upper limit of $\sim 0.''25 < 200$ pc — marks the position of the reverse shock front in the system, where efficient particle acceleration takes place. Note in this context, that in the case of the reverse shock, one is dealing with mildly-relativistic plasma bulk velocities (Meisenheimer et al. 1989; Kino & Takahara 2004), and a quasi-perpendicular magnetic configuration as evidenced by the radio polarimetry of the hotspot (Perley et al. 1997).

We also noted the monotonically decreasing count rate on the deconvolved *Chandra* images, amounting to about $\sim 30\%$ drop over the 15 years covered by the *Chandra* monitoring (January 2000 – January 2015). We believe that this decrease cannot be explained as (solely) due to the degradation of the ACIS CCDs.

The finding that the transverse size of the shock front at X-ray frequencies turns out to be less than 200 pc, should not be surprising, however, once the X-ray production mechanism

is identified as a synchrotron process. Indeed, the observed propagation length of ultra-relativistic electrons emitting synchrotron photons at a given (observed) frequency ν_{syn} , is $\ell_{\text{rad}} \simeq \beta c \Gamma \times \tau'_{\text{rad}}(\nu_{\text{syn}})$, where β , Γ , and δ are the bulk velocity, the bulk Lorentz factor, and the bulk Doppler of the emitting plasma, respectively, while $\tau'_{\text{rad}}(\nu_{\text{syn}})$ is the radiative cooling timescale, as measured in the plasma rest frame for the electrons with Lorentz factors corresponding to the frequency of the synchrotron photons $\gamma \propto \sqrt{\nu_{\text{syn}}/\delta B}$; in particular

$$\left(\frac{\ell_{\text{rad}}}{\text{pc}}\right) \sim \frac{10 \beta \Gamma \delta^{1/2} B_{100 \mu\text{G}}^{-3/2}}{1 + 10^{-3} \Gamma^2 B_{100 \mu\text{G}}^{-2}} \times \left(\frac{\nu_{\text{syn}}}{10^{18} \text{ Hz}}\right)^{-1/2} \quad (3.4)$$

where $B_{100 \mu\text{G}}$ is the magnetic field intensity within the emission region in the units of $100 \mu\text{G}$, and we also included the inevitable radiative losses related to the inverse-Compton up-scattering of the Cosmic Microwave Background photons (at the source redshift of $z \simeq 0.035$; see [Stawarz et al. 2004](#), equation 7 therein). The above equation, with the expected $\beta \sim 0.3$ characterizing the downstream of the reverse shock (e.g., [Meisenheimer et al. 1989](#); [Kino & Takahara 2004](#)), and so $\Gamma \sim \delta \sim 1$, as well as $B_{100 \mu\text{G}} \gtrsim 1$ (see [Meisenheimer et al. 1989, 1997](#); [Isobe et al. 2017](#)), gives $\ell_{\text{rad}} \lesssim 3 \text{ pc}$ for keV energies of the observed synchrotron photons. Interestingly, such a small spatial scale would be in rough agreement with the observed variability timescale as well, since the corresponding light-crossing timescale $\ell_{\text{rad}}/c \lesssim 10 \text{ yr}$.

The simple estimates presented above seem, therefore, to suggest that an efficient acceleration of ultra-relativistic electrons, up to energies enabling the production of synchrotron X-ray photons ($\gamma \sim 10^7$), takes place exclusively within a rather thin layer of the very front of the termination shock in the radio galaxy Pictor A. In this framework, the fact that the radio intensity peak position is located further downstream, could be explained as solely due to the increasing volume of the emitting plasma around the position of the contact discontinuity, where the flow (i.e., shocked jet material) diverges. Interestingly, for the radio-emitting electrons (say, $\nu_{\text{syn}} \simeq 10 \text{ GHz}$), the above equation 3.4 returns $\ell_{\text{rad}} \sim 30 B_{100 \mu\text{G}}^{-3/2} \text{ kpc}$, which would be consistent with the observed X-ray/radio offset of the order of $\sim 1 \text{ kpc}$, if only the magnetic field intensity within the hotspot (downstream of the reverse shock) is $B \sim 1 \text{ mG}$, i.e. a factor of a few above the equipartition value. Moreover, for electrons emitting optical synchrotron photons in $\sim 1 \text{ mG}$ magnetic field, the observed propagation length reads as $\ell_{\text{rad}} \sim 10 \text{ pc}$, in agreement with no pronounced offset observed between the positions of the X-ray and optical intensity peaks. Still, in such a case, the presence of the upstream X-ray enhancement (i.e., the jet-like feature located in between the radio/optical filament and the termination shock), would remain unexplained. Hydrodynamical simulations of light, supersonic jets propagating within hot gaseous atmospheres, such as those presented by, e.g., [Saxton et al. \(2002\)](#) or [Mizuta et al. \(2004\)](#), hint however a rather complex morphology around the jet termination regions, consisting of a network of various shocks, backflows, and vortex structures, and so any robust identification of the features revealed by our image deconvolution awaits a more careful comparison with the numerical data.

Appendix A: Net count rates and integrated intensity profiles for all the Chandra pointings

Here we provide histograms of the net count rates for the HS region (Figure 3.13), as well as the integrated intensity profiles along the major axis of the N region (Figure 3.14), calculated based on the deconvolved exposure-corrected Chandra images of the W hotspot in Pictor A, at 1 px resolution, for all of the analyzed ObsIDs.

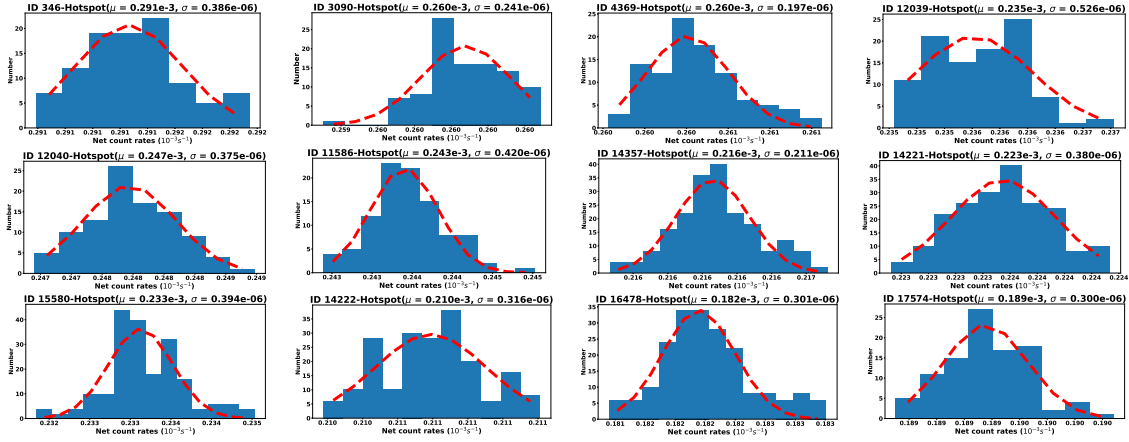


Figure 3.13: Histograms of the net count rates calculated for the HS region on the deconvolved exposure-corrected *Chandra* images of the W hotspot in Pictor A, at 1 px resolution, for all the analyzed ObsIDs. Each panel corresponds to 100 random realizations of the PSF for a given ObsID.

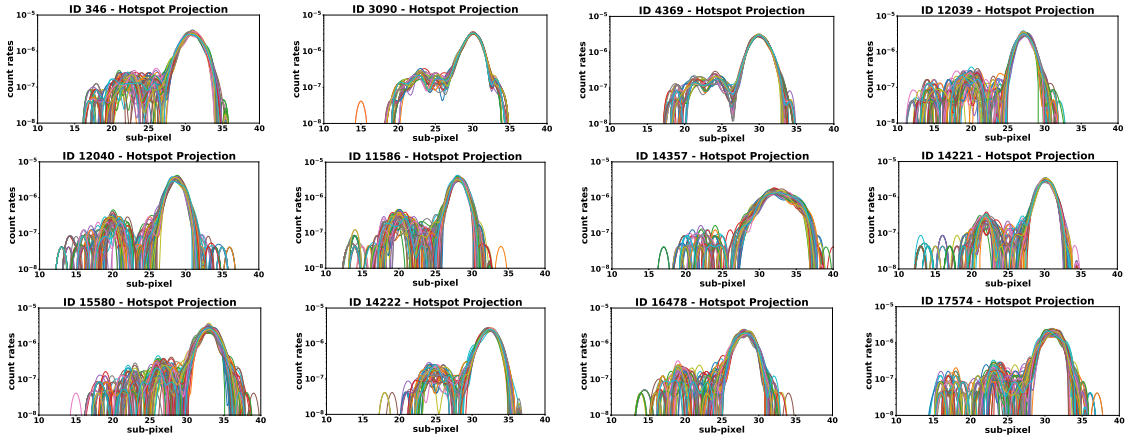


Figure 3.14: Integrated intensity profiles along the major axis of the N region displayed on Figure 3.9, for all the analyzed ObsIDs, at 0.5 px resolution. Each curve on the panels corresponds to one single realization of the PSF for a given ObsID.

Chapter 4

Eastern Lobe of Pictor A: Spectral Analysis and X-ray/Radio Correlations

This chapter will appeared as ‘Complex Structure of the Eastern Lobe of the Pictor A Radio Galaxy: Spectral Analysis and X-ray/Radio Correlations’ by R. Thimmappa, Ł. Stawarz, U. Pajdosz-Śmierciak, K. Balasubramaniam, & V. Marchenko; 2021, The Astrophysical Journal, submitted

4.1 Introduction

Pictor A, classified as a Broad-Line Radio Galaxy (BLRG) with the “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, that has become the prime target for detailed multiwavelength investigations in the recent decades, from radio to the X-ray ranges. More recently, it has been also confirmed as a source of high-energy γ -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 nucleus, and extends up to hundreds of kiloparsecs beyond the host galaxy to the West (Perley et al. 1997); the counter-jet 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 counter-jet (to the East); the bright Western hotspot is clearly detected and even, in some cases, resolved at radio, infrared, optical, and X-ray frequencies (Röser & Meisenheimer 1987; Thomson et al. 1995; Perley et al. 1997; Wilson et al. 2001; Werner

CHAPTER 4. EASTERN LOBE OF PICTOR A

Table 4.1:: *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	51561	25.8	ACIS-23678
12039	2009-12-07	55172	23.7	ACIS-235678
12040	2009-12-09	55174	17.3	ACIS-235678
11586	2009-12-12	55177	14.3	ACIS-235678
14357	2012-06-17	56095	49.3	ACIS-235678
14222	2014-01-17	56674	45.4	ACIS-235678
16478	2015-01-09	57031	26.8	ACIS-235678
17574	2015-01-10	57032	18.6	ACIS-235678

et al. 2012; Isobe et al. 2017; Thimmappa et al. 2020b). 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 ultra-relativistic electrons. Detailed radio studies of the lobes with the 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 *Chandra* or *XMM-Newton*, allowed to resolve the lobes and to detect the emission consistent with a non-thermal power-law continuum; if due to the inverse-Comptonization of the Cosmic Microwave Background (CMB) radiation by the lobes’ electrons, as typically assumed, this gives the volume-averaged lobes’ magnetic field intensities at the level of the equipartition values, namely $B \sim 1 - 10 \mu\text{G}$ (see Kataoka & Stawarz 2005; Croston et al. 2005). Some of the most prominent and extended lobes in nearby radio galaxies have been also resolved in high-energy γ -rays by the *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 ultra-relativistic electrons and magnetic field, with the total internal energy equal to that of the jet bulk kinetic energy (e.g., Begelman & Cioffi 1989). However, several observational findings have recently been reported on 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 (Stawarz et al. 2013; O’Sullivan et al. 2013; Seta et al. 2013; Wykes et al. 2013).

CHAPTER 4. EASTERN LOBE OF PICTOR A

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 ksec exposure (see [Hardcastle et al. 2016](#), for a summary of all the available *Chandra* data for Pictor A galaxy). The X-ray maps of the target are compared in detail with various radio maps obtained by [Perley et al. \(1997\)](#) with the NRAO¹ Very Large Array (VLA).²

Throughout the paper we assume the Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, for which the luminosity distance to the source is 154 Mpc, and the conversion angular scale is $0.697 \text{ kpc arcsec}^{-1}$. The X-ray spectral fits all take into account Galactic absorption, with the corresponding hydrogen column density $4.12 \times 10^{20} \text{ cm}^{-2}$. The photon index Γ is defined as $F_\epsilon \propto \epsilon^{-\Gamma}$ for the photon flux spectral density F_ϵ .

4.2 X-ray and Radio Data

4.2.1 Chandra Observations and Data Processing

Pictor A was observed by the *Chandra* X-ray Observatory ([Weisskopf et al. 2002](#)) using the Advanced CCD Imaging Spectrometer (ACIS) ([Garmire et al. 2003](#)) on 14 different occasions from January 2000 till January 2015, with the total exposure of about 464 ksec. Various pointings were optimized for different regions in the extended system, including the nucleus, the Western (W) hotspot, the jet, and the Eastern (E) lobe ([Wilson et al. 2001](#); [Hardcastle & Croston 2005](#); [Hardcastle et al. 2016](#)). For our study, we selected a subset of the eight *Chandra* pointings, for which the edge of the E lobe — in particular the E hotspot — is located away from the chip gap on the detector. In Table 4.1, we list the corresponding ObsIDs, observation dates, and exposure times, noting that from those, only in the case of the ObsID 14357 is the E lobe placed on the back illuminated ACIS-S3 chip, which is characterized by a higher sensitivity at low energies, and a more spatially-uniform, significantly better energy resolution than the front-illuminated chips.

The selected *Chandra* observations listed in Table 4.1, were reprocessed according to the standard procedure with the CIAO-4.10 package (using the `chandra_repro` script) and the Calibration database CALDB-4.7.8 ([Fruscione et al. 2006](#)), recommended by the CIAO analysis threads. Pixel randomization was removed during the reprocessing, and the readout streaks were removed for each observational data. The `merge_obs` script was used to create merged event files for the eight selected pointings; because of the miss-alignments of the source regions in the ACIS-S chip, during the merging process the ObsID 14357

¹The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

²The authors thank R. Perley for kindly providing all the radio maps which are presented and analyzed in this paper.

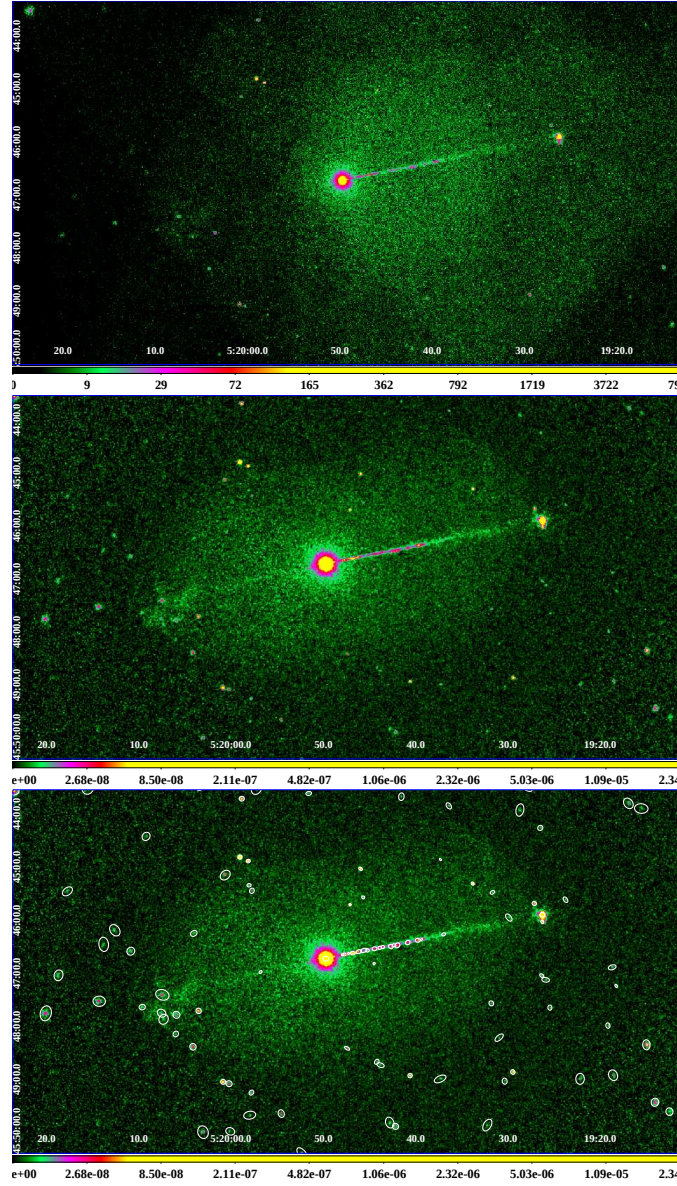


Figure 4.1: **Top:** Merged counts image of the Pictor A radio galaxy, for the selected eight *Chandra* observations listed in Table 4.1, in the energy range 0.5–7.0 keV, with native $0.492''$ pixels. Note a much reduced exposure toward the E lobe when compared to the W lobe. **Middle:** Exposure-corrected merged *Chandra* image, smoothed with 3σ Gaussian radius, revealing the bright core, the jet extending to the North-West from the core, the W hotspot, the weak counterjet to the South-East, 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.

CHAPTER 4. EASTERN LOBE OF PICTOR A

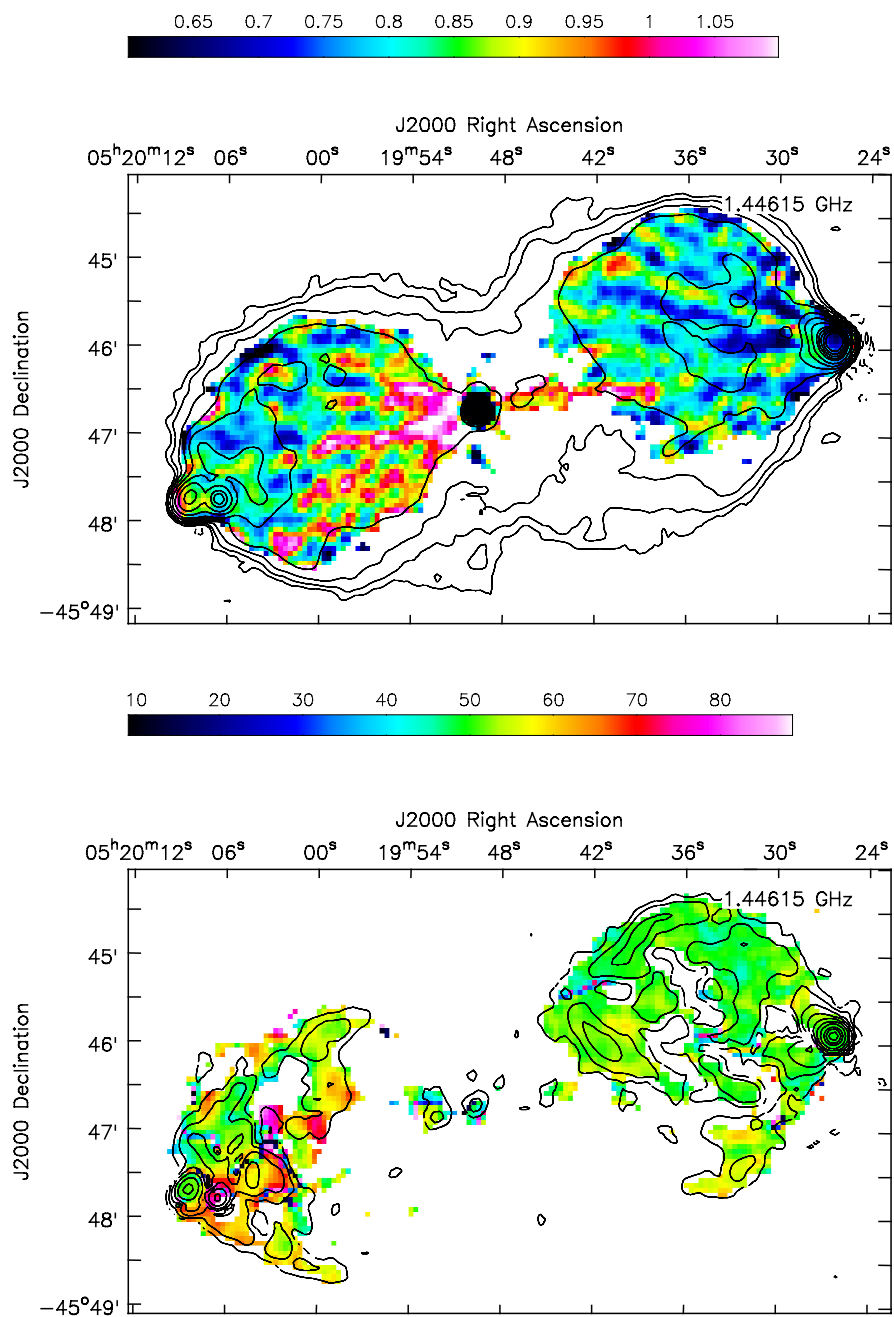


Figure 4.2: **Top:** The VLA spectral index map of Pictor A radio galaxy, between L and C bands, with the *total intensity* L-band (1.45 GHz) contours superimposed, at 10'' resolution. **Bottom:** The VLA rotation measure (RM) map between L and C bands, with the *polarized intensity* L band contours superimposed, at 10'' resolution.

CHAPTER 4. EASTERN LOBE OF PICTOR A

was taken as the reference observation, due to its high count rates. After merging, the total effective exposure corresponds to 221 ks. The exposure-corrected images were next generated within the energy band 0.5–7.0 keV.

The merged counts image and the corresponding exposure-corrected image for the entire Pictor A radio galaxy, are shown in Figure 4.1. On the exposure-corrected map, we searched for point and compact sources with the `wavdetect` tool implemented in CIAO package, that uses Poisson statistics as appropriate in a low-count regime. The results are shown in the bottom panel of the Figure. Note that, with the applied “minimum PSF” method, as recommended when dealing with merged pointings with different off-axis angles, the `wavdetect` size should match closely the size of sources being detected; for a point source, the corresponding size should therefore reflect the effective Point Spread Function (PSF) at a given position, which may vary across the field. As follows, the algorithm detects the core, a series of knots along the jet, the W hotspot, a net of sources in the E hotspot region, and multiple unrelated background sources (located mostly outside of the lobes).

For the spectral analysis, we have selected various segments of the E lobe around the counter-jet termination region, based on their enhanced X-ray surface brightness, including five sources that appear point-like, as well as three extended regions, one characterised by a filamentary morphology (see Section 4.3 below). Only one ObsID 14357 was utilised for the extraction of the source spectra, and for the following spectral modelling. The source spectra were extracted using the `specextract` script separately for each region in the 0.5–7.0 keV range, and fitted with the `SHERPA` package (Freeman et al. 2001).

4.2.2 VLA Observations and Radio Maps

Detailed VLA studies of Pictor A have been presented and discussed extensively in Perley et al. (1997). For the E lobe, the authors noted a higher rms scatter in the derived rotation measure (RM) when compared with the W lobe, though with a similar mean RM value $\sim 45 \text{ rad m}^{-2}$. The polarization degree 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 4.2, we show the VLA total intensity contours of Pictor A at 1.45 GHz, superimposed on the spectral index map between 330 MHz and 1.45 GHz, with $10''$ resolution. In the lower panel of the Figure, we present the polarized intensity contours of the source at 1.45 GHz, superimposed on the distribution of RM. As shown, the structure of the E lobe around the jet termination region, and in particular upstream of the E hotspot, appear 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.

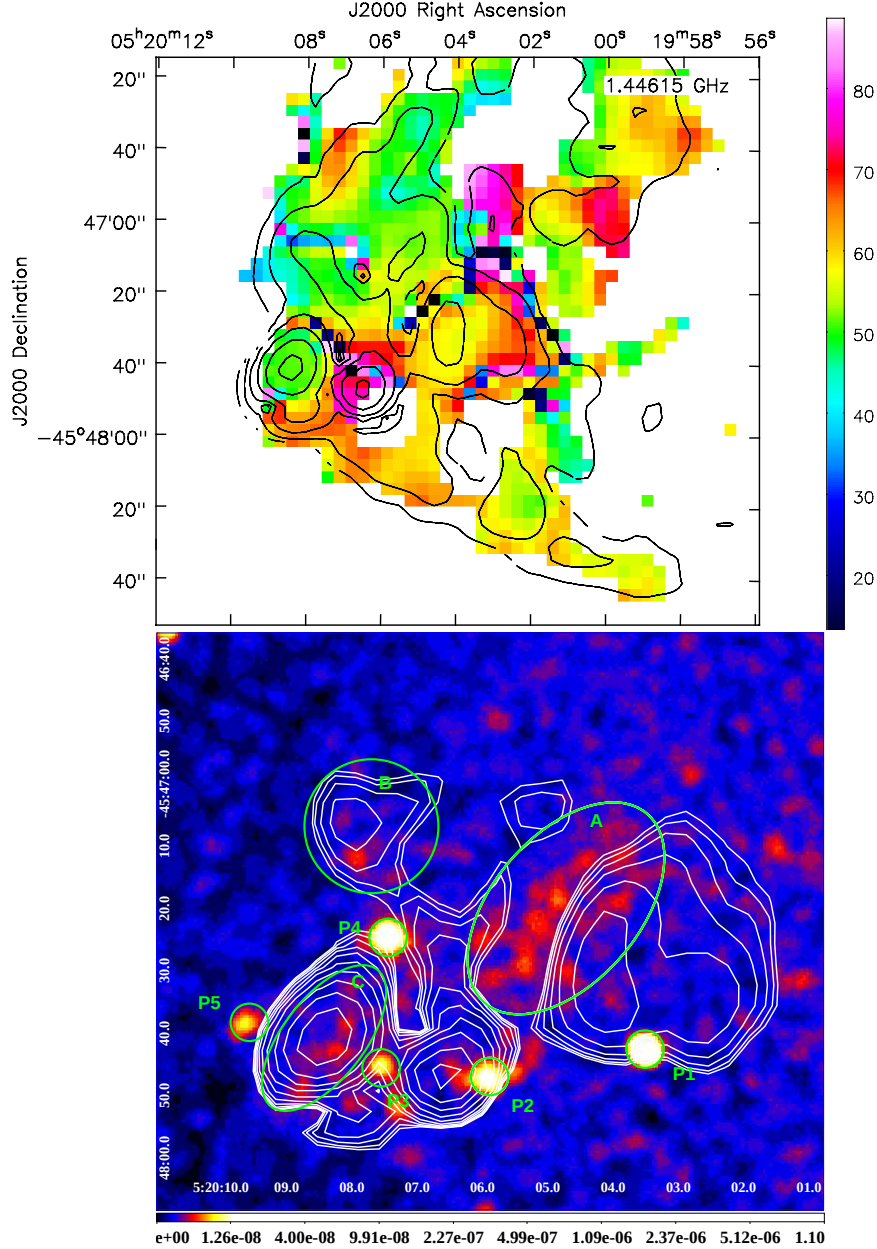


Figure 4.3: Top: A zoomed view of the RM distribution within the E hotspot region in Pictor A, with the polarized intensity L band contours superimposed, at $10''$ resolution. **Bottom:** A zoomed view of the 0.5–7.0 keV emission of the E hotspot region in Pictor A, with the 1.45 GHz polarized intensity contours (white) superimposed. The 0.5–7.0 keV *Chandra* image is smoothed with 3σ Gaussian radius. Radio contours start from 3σ confidence level. Regions selected for the *Chandra* data analysis are labeled and indicated by green contours.

Table 4.2:: Power-law fitting results for the selected regions within the E lobe

Region	Region size [†] [px]	Photon index Γ	Energy flux $F_{0.5-7.0\text{keV}}$ [$10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$]	Counts [‡]
src A	40/24	$1.70^{+0.23}_{-0.21}$	$21.19^{+3.25}_{-5.33}$	219
src B	22	$1.89^{+0.55}_{-0.46}$	$4.86^{+2.84}_{-1.34}$	68
src C	28/13	$2.17^{+0.62}_{-0.53}$	$5.59^{+1.94}_{-2.22}$	66
src P1	6	$2.27^{+0.37}_{-0.34}$	$5.07^{+1.94}_{-0.13}$	41
src P2	6	$2.15^{+0.42}_{-0.39}$	$3.56^{+0.19}_{-1.70}$	27
src P3	6	$0.43^{+0.71}_{-0.74}$	$4.55^{+0.06}_{-2.99}$	12
src P4	6	$1.13^{+0.31}_{-0.30}$	$7.85^{+1.11}_{-1.41}$	38
src P5	6	$1.02^{+0.58}_{-0.57}$	$3.11^{+0.17}_{-1.53}$	12
Background	—	$0.27^{+0.03}_{-0.03}$	—	—

Note. — [†] Radius in the case of a circle, and major/minor semi-axes in the case of an ellipse; note the conversion scale $0.492''/\text{px}$; [‡] total number of counts within the $0.5 - 7.0 \text{ keV}$ range.

4.3 Analysis Results

In Figure 4.3, we present a zoomed 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 $0.5-7.0 \text{ keV}$ *Chandra* image, with the 1.45 GHz polarized intensity contours superimposed (note that in the bottom panel, radio contours start for clarity only from 3σ confidence level). The images reveal several interesting features we emphasize below:

- 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 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”. We do not analyze the spectrum of the ‘primary’ hotspot, i.e. of the more compact radio feature located upstream (to West) from the secondary. Note different values of the RM for both features, namely $\sim 50 \text{ rad m}^{-2}$ and $\sim 80 \text{ rad m}^{-2}$ for the secondary and primary, respectively.
- There are several bright point/compact X-ray sources in the closest vicinity of the double E hotspot (cf. the bottom panel in Figure 4.1), none of which coincides however

with the peaks of either total or polarized radio intensity. For our spectral analysis, we select four such distinct regions, labelled as “P2–P5”. 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 3σ confidence level contours).

- High-polarized intensity feature extends to the North from the hotspot, terminating in the moderately prominent spot with some enhanced level of the diffuse X-ray emission; this spot is selected for our analysis as the extended region “B”.
- Upstream of the entire double structure of the E hotspot, an another prominent and extended feature can easily be seen on the polarized intensity map, which in addition seems surrounded by an arc of a sharp RM gradient ($\Delta\text{RM} \sim 50 \text{ rad m}^{-2}$). 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 Northern-Eastern 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 ($\sim 20 \text{ rad m}^{-2}$). The radio continuum at the position of the filament appear marginally steeper when compared with its surroundings (spectral index ~ 0.9 versus ~ 0.8 , see the top panel in Figure 4.2).

4.3.1 Chandra Spectral Analysis

Due to the limited or even very-limited photon statistics, the ObsID 14357-extracted, unbinned spectra of all the selected regions 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 power-law 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 any bright point sources. The results of the fitting are summarized in Table 4.2.

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 ($\Gamma \simeq 1.7 \pm 0.2$ versus $\simeq 2.2_{-0.5}^{+0.6}$) is not significant statistically. The point/compact sources P1 and P2 are characterized by relatively steep X-ray continua ($\Gamma > 1.8$ within the errors), while the remaining source P3–P5 appear very hard ($\Gamma < 1.5$ within the errors), especially P3, although here the photon statistics is particularly poor.

The total number of 219 counts detected from the A region, allows us to attempt a more detailed spectral modelling, and in particular to confront the most basic thermal and non-thermal emission models. With this goal in mind, we fit exclusively the ObsID 14357 spectrum for region A together with the background (same as before), assuming either the

Table 4.3:: Spectral fitting results for the source region A.

Model [†]	Parameter	Value with 1σ errors	C-stat./DOF
Power-law	Photon index Γ	$1.71^{+0.24}_{-0.22}$	1077.31/888
	PL normalization	$4.37^{+0.56}_{-0.52} \times 10^{-6}$	
	Background photon index Γ_{bck}	$0.25^{+0.08}_{-0.08}$	
	Background normalization	$6.44^{+0.56}_{-0.53} \times 10^{-6}$	
APEC	Temperature kT	$8.22^{+12.18}_{-3.20}$	1079.54/888
	APEC normalization	$1.78^{+0.29}_{-0.20} \times 10^{-5}$	
	Background photon index Γ_{bck}	$0.26^{+0.08}_{-0.08}$	
	Background normalization	$6.46^{+0.57}_{-0.53} \times 10^{-6}$	
Power-law +APEC	Photon index Γ	$1.27^{+0.27}_{-0.41}$	1074.3/886
	PL normalization	$3.12^{+0.78}_{-0.92} \times 10^{-6}$	
	Temperature kT	$0.27^{+0.14}_{-0.07}$	
	APEC normalization	$5.04^{+4.54}_{-2.63} \times 10^{-6}$	
	Background photon index Γ_{bck}	$0.27^{+0.08}_{-0.08}$	
	Background normalization	$6.52^{+0.61}_{-0.56} \times 10^{-6}$	

Note. — [†] all the models include the Galactic hydrogen column density $N_{\text{H,Gal}} = 4.12 \times 10^{20} \text{ cm}^{-2}$; thermal model assumes one-third solar abundance.

power-law emission model, the APEC model, or a combination of the two; in the APEC model, we freeze the abundance at the 0.3 solar value. The resulting best-fit parameters are summarized in Table 4.3, and the corresponding background-subtracted modelled spectra are shown in Figure 4.4.

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, $kT > 5.0 \text{ keV}$; 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 $kT \simeq 0.3 \pm 0.1 \text{ keV}$, though implies at the same time a rather flat non-thermal continuum, although with larger errors, $\Gamma \simeq 1.3^{+0.3}_{-0.4}$. The confidence contours for the model parameters kT and Γ for this two-component model fit, are presented in Figure 4.5. 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 non-thermal population of electrons emitting inverse-Compton X-rays – is allowed by the data, it is not, strictly speaking, required or even favoured by the spectral modelling.

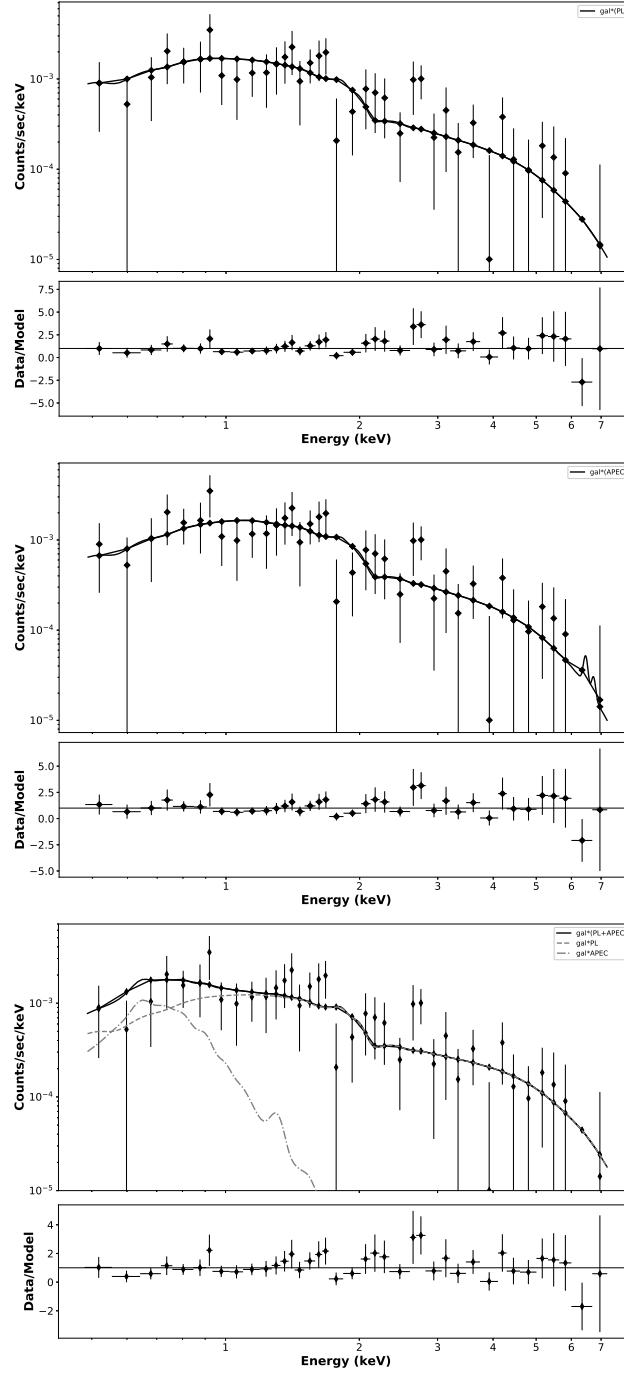


Figure 4.4: The background-subtracted *Chandra* 0.5–7.0 keV spectrum for the selected source region A, binned with $S/N = 3$ and fitted with a power-law model (top panel), APEC model (middle panel), and a two-component power-law+APEC model (bottom panel). See Table 4.3 for the corresponding best-fit model parameters.

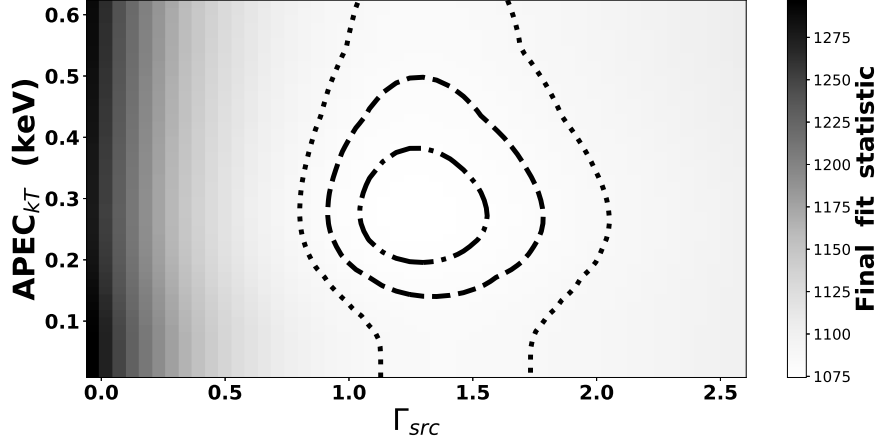


Figure 4.5: The confidence contours for the model parameters kT and Γ for the two-component power-law+APEC model applied to the selected source region A.

4.3.2 The Surface Brightness Profile

In Figure 4.6, 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 total and polarized intensity (3σ) contours superimposed. The two elongated yellow 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 `dmregrid2`, is divided into 16 vertical boxes, as indicated in the upper panel of Figure 4.7. 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.³ The total and polarized radio flux spectral densities for the corresponding segments of the lobe, were calculated based on the 1.45 GHz VLA maps. The resulting profiles are presented in the middle and bottom panels of Figure 4.7. In an analogous way, we calculated the X-ray and radio profiles also for the Profile 2 rectangular region, divided into eight vertical boxes, and rotated by $\theta = 360^\circ$, see Figure 4.8.

Figure 4.7 reinforces our main observational finding stated above: the prominent X-ray filament A runs in between high-polarization radio domains. And while there is a general correlation between the integrated X-ray surface brightness and the total radio flux — in a sense that the X-ray flux maximum coincides exactly with the total radio intensity peak (~ 0.2 Jy; see bottom panel of the Figure), there is at the same time a significant anti-correlation between the integrated X-ray surface brightness and the polarized radio flux. In

³https://cxc.cfa.harvard.edu/ciao/threads/radial_profile/

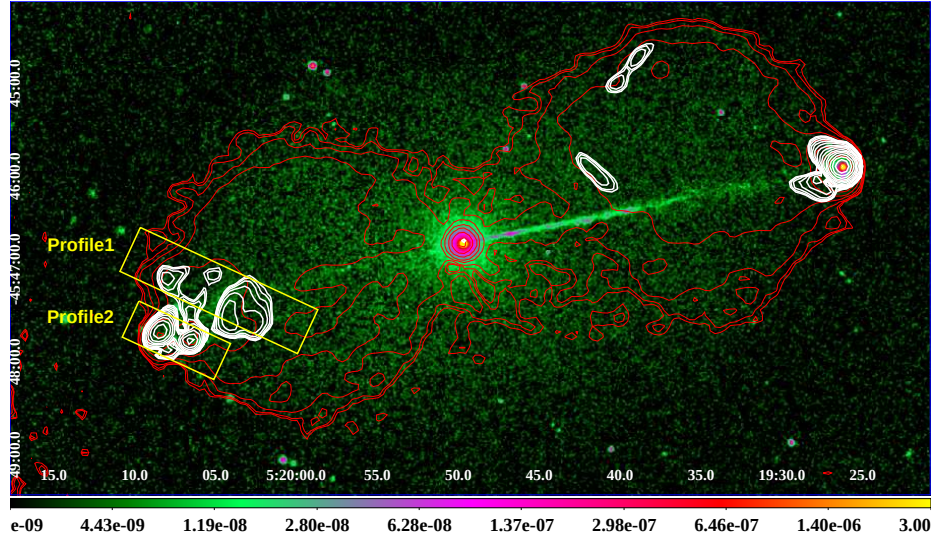


Figure 4.6: The exposure-corrected 0.5–7.0 keV merged *Chandra* image of the entire structure of Pictor A, smoothed with 3σ Gaussian radius, with the 1.45 GHz VLA total and polarized intensity (3σ) contours superimposed (red and white, respectively). The two elongated yellow rectangles, denote the areas across the high-polarization regions of the E lobe, for which we extracted the surface brightness profiles at X-ray and radio frequencies.

particular, going sideways from the position of the X-ray peak, we see the X-ray photon flux dropping by a factor of about three, while the polarized radio flux increasing by a factor of about two; in other words, 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 4.7 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, this time one can see a general correlation between the X-ray photon fluxes and either total and polarized radio fluxes, with both primary and secondary hotspots coinciding with the local X-ray intensity peaks, and both features displaying a high degree of radio polarization ($\sim 45\%$ and $\sim 37\%$, respectively).

4.4 Discussion and Conclusions

A relation of point-like/compact X-ray features with no optical counterparts, to the radio lobes and especially hotspot regions of radio galaxies and radio quasars, is often unclear and subjected to speculations (see the discussion in, e.g., [Hardcastle et al. 2007](#)). Such features may simply be unrelated background AGN, but may also result from various energy dissipation processes taking place within the lobes with complex magnetic field structure. For example, [Stawarz et al. \(2013\)](#) speculated that, if the lobes’ radio filaments represent indeed tangled magnetic field tubes ([O’Neill & Jones 2010](#)), then at the places of the

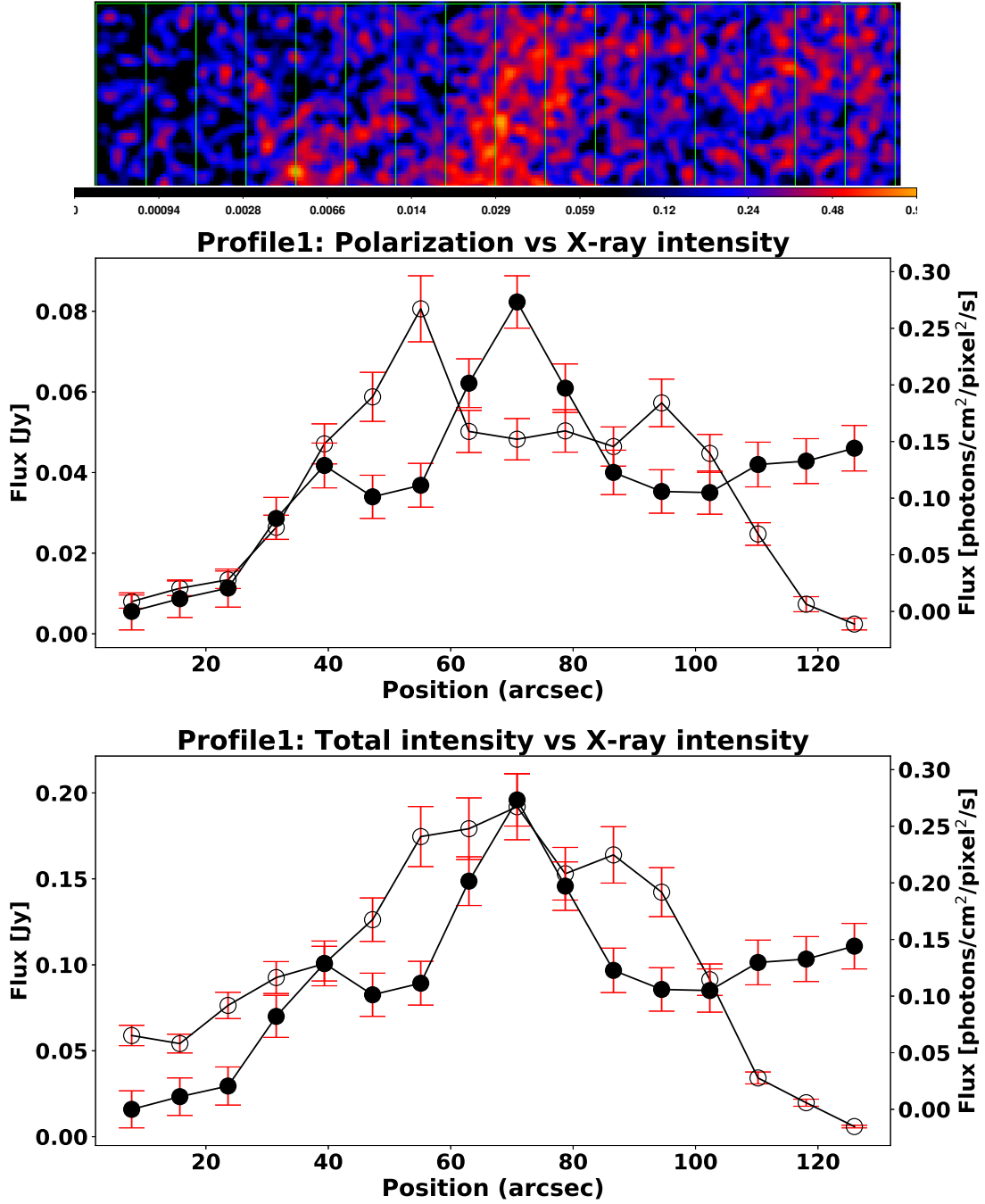


Figure 4.7: Top: The Profile 1 rectangular region, rotated by $\theta = 335^\circ$, and divided into 16 vertical boxes. **Middle:** The X-ray photon fluxes per unit area (filled circles), and the polarized radio flux spectral densities (empty circles), integrated over each box. **Bottom:** The X-ray photon fluxes per unit area (filled circles), and the total radio flux spectral densities (empty circles), integrated over each box.

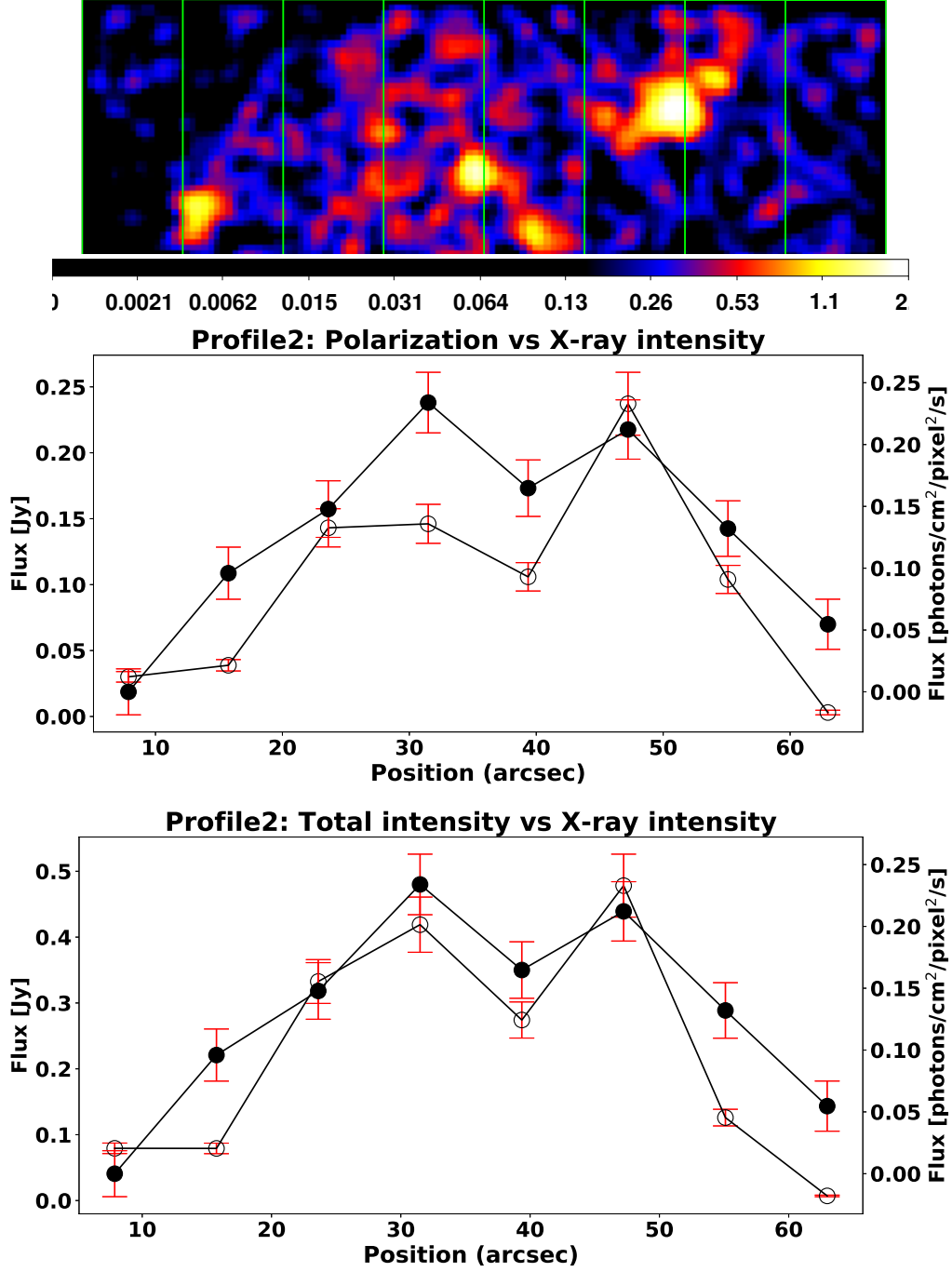


Figure 4.8: **Top:** The Profile2 rectangular region, rotated by $\theta = 360^\circ$, and divided into eight vertical boxes. **Middle:** The X-ray photon fluxes per unit area (filled circles), and the polarized radio flux spectral densities (empty circles), integrated over each box. **Bottom:** The X-ray photon fluxes per unit area (filled circles), and the total radio flux spectral densities (empty circles), integrated over each box.

CHAPTER 4. EASTERN LOBE OF PICTOR A

filaments’ interactions with density or magnetic enhancements in the surrounding plasma, localized multiple and 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 possesses any obvious optical counterpart. However, the steep-spectrum P1 spot coincides exactly with the mid-infrared (MIR) source listed in the CatWISE2020 Catalog (Marocco et al. 2020), which includes objects selected from WISE (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 to 2018. In fact, in the same catalog, possible MIR counterparts to P4 and P4 may also be noted (each with the 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 the lobe-related compact X-ray structures. We note in this context, that the two spots are located just upstream of the primary hotspot and the secondary hotspot, respectively. In addition, P3 seems extremely hard in X-rays, as revealed by our spectral modelling despite a very low photon statistics (photon index $\Gamma < 1.2$ within the errors; see Table 4.2), while P2 seems partly resolved by *Chandra* (see Hardcastle et al. 2016).

The main findings following from the analysis presented in this paper, regard however the elongated X-ray filament A, located upstream of the jet termination region, extending for at least three tens of kiloparsecs (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 the photon index $\Gamma \simeq 1.7 \pm 0.2$, or alternatively a combination of a flat power-law component with $\Gamma \simeq 1.3^{+0.3}_{-0.4}$ and a thermal $kT \simeq 0.3 \pm 0.1$ 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 accord 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 model 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 a thermal matter distributed within thin shells or filaments. Possibly, 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 internal depolarization related to the thermal (X-ray emitting) gas present within the filament. But at the same time the filament coincides also 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, since $\text{RM} \propto \int n_e \vec{B} \cdot d\vec{\ell}$ where n_e stands for the gas electron number density, $\vec{B}$ is the magnetic field intensity vector, and the integration $d\vec{\ell}$ is over the path length through the plasma.

Chapter 5

Summary and Main Conclusions

As mentioned at the very beginning of this thesis, in my analysis of the *Chandra* X-ray Observatory data for the active galaxy Pictor A, I have focused on the following three main research problems: **Chapter 2:** an approach to the X-ray spectroscopy of the active nucleus in the Pictor A system, carried out in a regime of a severe instrumental pile-up; **Chapter 3:** investigating the X-ray structure of the termination shocks of relativistic jets in Pictor A, the so-called “hotspots”, by means of detailed image deconvolution and timing analyses; and **Chapter 4:** investigating correlations between the X-ray and radio emission features within the extended lobes of the source.

Our approach to the analysis of the *Chandra* data for the active nucleus in Pictor A radio galaxy, presented in Chapter 2, and in particular to the spectral analysis in a regime of a strong instrumental pile-up, is alternative to the approach presented in the literature so far. In particular, instead of analyzing the extended wings of the central PSF as typically performed in such cases, we have utilized the updated pile-up model implemented in the modeling and fitting software *Sherpa*. And while in the framework of our approach we were not able to completely remove/fully account for the instrumental pile-up effect, we nonetheless outlined the two main novel conclusions emerging from our analysis: (i) the contribution of the hot gaseous atmosphere of the host to the radiative output of the Pictor A nucleus, is very significant, and even dominates at distances of only several pixels from the center (up to ~ 30 px); as a result, one should be careful when analyzing the extended wings of the central PSF in search of the AGN emission component free from the instrumental pile-up; (ii) the available *Chandra* data allow, formally, for the presence of the very broad fluorescent iron line in the nuclear spectrum of Pictor A; we however deem this exciting possibility as rather unlikely, due to the fact that the “grade migration” in the piled-up detector is a more probable cause of the observed hard X-ray excess in the 0.5–7.0 keV *Chandra* spectra of the system.

CHAPTER 5. SUMMARY AND MAIN CONCLUSIONS

In the Chapter 3 of the Dissertation, I presented the analysis of the X-ray morphology and flux variability of the particularly bright and extended Western hotspot in Pictor A, based on data obtained with *Chandra*. The hotspot marks the position where the relativistic jet, that originates in the active nucleus of the system, interacts with the intergalactic medium, at hundreds-of-kiloparsec distances from the host galaxy, forming a termination shock that converts jet bulk kinetic energy to internal energy of the plasma. The hotspot is bright in X-rays due to the synchrotron emission of electrons accelerated to ultra-relativistic energies at the shock front. In our analysis, we make use of several *Chandra* observations targeting the hotspot over the last decades with various exposures and off-axis angles. For each pointing, we study in detail the PSF, which allows us to perform the image deconvolution, and to resolve the hotspot structure. In particular, the brightest segment of the X-ray hotspot is observed to be extended in the direction perpendicular to the jet, forming a thin, ~ 3 kpc-long, feature that we identify with the front of the reverse shock. The position of this feature agrees well with the position of the optical intensity peak of the hotspot, but is clearly off-set from the position of the radio intensity peak, located ~ 1 kpc further downstream. In addition, we measure the net count rate on the deconvolved images, finding a gradual flux decrease by about 30% over the 15-year timescale of the monitoring.

In the Chapter 4 of the Dissertation, I presented 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, utilising the data obtained from *Chandra*. Various emission features have been selected for the study based on their enhanced X-ray surface brightness when compared with the surroundings, including five sources that appear point-like, as well as three extended regions, one characterised 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 non-thermal radio emission, utilising the high-resolution radio maps from the VLA at GHz frequencies. The main novel findings following from our analysis, regard the newly recognized bright X-ray filament located upstream of the jet termination region, extending for at least three tens of kiloparsecs (projected), and inclined with respect to the jet axis, for which we observe a clear anti-correlation 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 thermal gas, only partly mixed with the non-thermal radio/X-ray emitting electrons within the lobe, combined with the reversals in the lobe’s net magnetic field.

All in all, my research summarized in this Dissertation, demonstrates an extraordinary richness of the *Chandra* X-ray Observatory archive, and at the same time an astonishing complexity of the physics behind the phenomenon of active galaxies. Together with my supervisor dr hab. Łukasz Stawarz, we sincerely hope that my effort directed into mastering the astronomical X-ray data analysis techniques, and in this way understanding better the X-ray emission of a particular active galaxy Pictor A, does provide a notable contribution to the modern high-energy astrophysics in general.

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Facility: *Chandra* (ACIS)

Software: CIAO ([Fruscione et al. 2006](#)), **Sherpa** ([Freeman et al. 2001](#)), **ChaRT** ([Carter et al. 2003](#)), and **MARX** ([Davis et al. 2012](#))

CHAPTER 5. SUMMARY AND MAIN CONCLUSIONS

References

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, *Science*, 328, 725
- Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, *ApJ*, 810, 14
- Ackermann, M., Ajello, M., Baldini, L., et al. 2016, *ApJ*, 826, 1
- Alfvén, H., & Herlofson, N. 1950, *Physical Review*, 78, 616
- Allington-Smith, J., Murray, G., Content, R., et al. 2002, *PASP*, 114, 892
- Anderson, C. S., Gaensler, B. M., Heald, G. H., et al. 2018, *ApJ*, 855, 41
- Angioni, R., Ros, E., Kadler, M., et al. 2019, *A&A*, 627, A148
- Antonucci, R. 1993, *ARA&A*, 31, 473
- Araudo, A. T., Bell, A. R., Crilly, A., & Blundell, K. M. 2016, *MNRAS*, 460, 3554
- Arnaud, K., Smith, R., & Siemiginowska, A. 2011, *Handbook of X-ray Astronomy*
- Baade, W., & Minkowski, R. 1954, *ApJ*, 119, 206
- Balmaverde, B., & Capetti, A. 2006, *A&A*, 447, 97
- Bambi, C. 2020, *Tutorial Guide to X-ray and Gamma-ray Astronomy; Data Reduction and Analysis*, doi:10.1007/978-981-15-6337-9
- Beckmann, V., & Shrader, C. R. 2012, *Active Galactic Nuclei*
- Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, *Reviews of Modern Physics*, 56, 255
- Begelman, M. C., & Cioffi, D. F. 1989, *ApJ*, 345, L21
- Belsole, E., Worrall, D. M., Hardcastle, M. J., & Croston, J. H. 2007, *MNRAS*, 381, 1109
- Best, P. N., Kauffmann, G., Heckman, T. M., et al. 2005, *MNRAS*, 362, 25
- Bianchi, S., Guainazzi, M., Matt, G., Fonseca Bonilla, N., & Ponti, G. 2009, *A&A*, 495, 421

REFERENCES

- Blandford, R., Meier, D., & Readhead, A. 2019, *ARA&A*, 57, 467
- Blandford, R. D. 1990, in *Active Galactic Nuclei*, ed. R. D. Blandford, H. Netzer, L. Woltjer, T. J. L. Courvoisier, & M. Mayor, 161–275
- Blandford, R. D., & Rees, M. J. 1974, *MNRAS*, 169, 395
- Blumenthal, G. R., & Gould, R. J. 1970, *Reviews of Modern Physics*, 42, 237
- Bolton, J. G., Stanley, G. J., & Slee, O. B. 1954, *Australian Journal of Physics*, 7, 110
- Bowyer, S., Byram, E. T., Chubb, T. A., & Friedman, H. 1964, *Nature*, 201, 1307
- Bradt, H. 2004, *Astronomy Methods: A Physical Approach to Astronomical Observations*
- Bridle, A. H., & Perley, R. A. 1984, *ARA&A*, 22, 319
- Brown, A. M., & Adams, J. 2012, *MNRAS*, 421, 2303
- Brunetti, G., Mack, K. H., Prieto, M. A., & Varano, S. 2003, *MNRAS*, 345, L40
- Burke, B. E., Gregory, J. A., Bautz, M. W., et al. 1997, *IEEE Transactions on Electron Devices*, 44, 1633
- Burke, B. F., & Graham-Smith, F. 2009, *An Introduction to Radio Astronomy*
- Burke-Spolaor, S., Ekers, R. D., Massardi, M., et al. 2009, *MNRAS*, 395, 504
- Capetti, A., & Balmaverde, B. 2006, *A&A*, 453, 27
- Carilli, C. L., & Barthel, P. D. 1996, *A&A Rev.*, 7, 1
- Carroll, B. W., & Ostlie, D. A. 1996, *An Introduction to Modern Astrophysics*
- . 2006, *An Introduction to Modern Astrophysics and Cosmology*
- Carswell, R. F., Baldwin, J. A., Atwood, B., & Phillips, M. M. 1984, *ApJ*, 286, 464
- Carter, C., Karovska, M., Jerius, D., Glotfelty, K., & Beikman, S. 2003, in *Astronomical Society of the Pacific Conference Series*, Vol. 295, *Astronomical Data Analysis Software and Systems XII*, ed. H. E. Payne, R. I. Jedrzejewski, & R. N. Hook, 477
- Chen, X., Rachen, J. P., López-Caniego, M., et al. 2013, *A&A*, 553, A107
- Chiaberge, M., Capetti, A., & Macchetto, F. D. 2005, *ApJ*, 625, 716
- Christiansen, W. N., Frater, R. H., Watkinson, A., et al. 1977, *MNRAS*, 181, 183
- Contopoulos, I., Gabuzda, D., & Kylafis, N. 2015, *The Formation and Disruption of Black Hole Jets*, Vol. 414, doi:10.1007/978-3-319-10356-3
- Couto, G. S., Storchi-Bergmann, T., Robinson, A., et al. 2016, *MNRAS*, 458, 855

REFERENCES

- Croston, J. H., Hardcastle, M. J., Harris, D. E., et al. 2005, *ApJ*, 626, 733
- Dabbech, A., Onose, A., Abdulaziz, A., et al. 2018, *MNRAS*, 476, 2853
- Davis, J. E. 2001, *ApJ*, 562, 575
- Davis, J. E., Bautz, M. W., Dewey, D., et al. 2012, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 8443, *Proc. SPIE*, 84431A
- Dermer, C. D., & Giebels, B. 2016, *Comptes Rendus Physique*, 17, 594, gamma-ray astronomy / Astronomie des rayons gamma - Volume 2
- Drake, J. J., Ratzlaff, P., Kashyap, V., et al. 2006, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 6270, *Proc. SPIE*, 62701I
- Eracleous, M., & Halpern, J. P. 1998, *ApJ*, 505, 577
- . 2004, *VizieR Online Data Catalog*, J/ApJS/150/181
- Eracleous, M., Sambruna, R., & Mushotzky, R. F. 2000, *ApJ*, 537, 654
- Erlund, M. C., Fabian, A. C., Blundell, K. M., Crawford, C. S., & Hirst, P. 2010, *MNRAS*, 404, 629
- Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., et al. 2019a, *ApJ*, 875, L1
- . 2019b, *ApJ*, 875, L4
- Fabian, A. C. 2012, *ARA&A*, 50, 455
- Fabian, A. C., & Miniutti, G. 2005, *arXiv e-prints*, astro
- Fanaroff, B. L., & Riley, J. M. 1974, *MNRAS*, 167, 31P
- Fath, E. A. 1909, *Popular Astronomy*, 17, 504
- Feain, I. J., Cornwell, T. J., Ekers, R. D., et al. 2011, *ApJ*, 740, 17
- Feigelson, E. D., Laurent-Muehleisen, S. A., Kollgaard, R. I., & Fomalont, E. B. 1995, *ApJ*, 449, L149
- Ferrarese, L. 2002, *ApJ*, 578, 90
- Ferrarese, L., & Merritt, D. 2000, *ApJ*, 539, L9
- Filho, M. E., Barthel, P. D., & Ho, L. C. 2006, *A&A*, 451, 71
- Filippenko, A. V. 1985, *ApJ*, 289, 475
- Fomalont, E. B., & Sramek, R. A. 1976, *Phys. Rev. Lett.*, 36, 1475

REFERENCES

- Freeman, P., Doe, S., & Siemiginowska, A. 2001, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4477, Proc. SPIE, ed. J.-L. Starck & F. D. Murtagh, 76–87
- Friedman, H., Lichtman, S. W., & Byram, E. T. 1951, *Physical Review*, 83, 1025
- Fruscione, A., McDowell, J. C., Allen, G. E., et al. 2006, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 6270, Proc. SPIE, 62701V
- Gallo, E., Treu, T., Jacob, J., et al. 2008, *ApJ*, 680, 154
- Garmire, G. P. 1997, in American Astronomical Society Meeting Abstracts, Vol. 190, American Astronomical Society Meeting Abstracts #190, 34.04
- Garmire, G. P., Bautz, M. W., Ford, P. G., Nousek, J. A., & Ricker, George R., J. 2003, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4851, X-Ray and Gamma-Ray Telescopes and Instruments for Astronomy., ed. J. E. Truemper & H. D. Tananbaum, 28–44
- Gentry, E. S., Marshall, H. L., Hardcastle, M. J., et al. 2015, *ApJ*, 808, 92
- Georganopoulos, M., & Kazanas, D. 2003, *ApJ*, 589, L5
- George, I. M., & Fabian, A. C. 1991, *MNRAS*, 249, 352
- George, I. M., Nandra, K., & Fabian, A. C. 1990, *MNRAS*, 242, 28P
- Ghisellini, G. 2013, *Radiative Processes in High Energy Astrophysics*, Vol. 873, doi:10.1007/978-3-319-00612-3
- Giacconi, R., & Gursky, H. 1974, *X-ray Astronomy*, doi:10.1007/978-94-010-2105-0
- Giacconi, R., Gursky, H., Paolini, F. R., & Rossi, B. B. 1962, *Phys. Rev. Lett.*, 9, 439
- Giacconi, R., Kellogg, E., Gorenstein, P., Gursky, H., & Tananbaum, H. 1971, *ApJ*, 165, L27
- Giacconi, R., & Rosati, P. 2008, *Scholarpedia*, 3, 4391
- Giacconi, R., & Tananbaum, H. 1980, *Science*, 209, 865
- Giacconi, R., Branduardi, G., Briel, U., et al. 1979, *ApJ*, 230, 540
- Ginzburg, V. L., & Syrovatskii, S. I. 1969, *The origin of cosmic rays*
- Glass, I. S. 1981, *MNRAS*, 197, 1067
- Golombek, D., Miley, G. K., & Neugebauer, G. 1988, *AJ*, 95, 26
- Gould, R. J. 2005, *Electromagnetic Processes*

REFERENCES

- Grandi, P., Guainazzi, M., Maraschi, L., et al. 2003, *ApJ*, 586, 123
- Guilbert, P. W., & Rees, M. J. 1988, *MNRAS*, 233, 475
- Gursky, H., Solinger, A., Kellogg, E. M., et al. 1972, *ApJ*, 173, L99
- Halpern, J. P., & Eracleous, M. 1994, Emergence of Double-peaked Emission Lines in the Broad-Line Radio Galaxy Pictor A, doi:10.1086/187537
- Hardcastle, M. J., & Croston, J. H. 2005, *MNRAS*, 363, 649
- . 2020, *New Astronomy Reviews*, 88, 101539
- Hardcastle, M. J., Croston, J. H., & Kraft, R. P. 2007, *ApJ*, 669, 893
- Hardcastle, M. J., Harris, D. E., Worrall, D. M., & Birkinshaw, M. 2004, *ApJ*, 612, 729
- Hardcastle, M. J., Lenc, E., Birkinshaw, M., et al. 2016, *MNRAS*, 455, 3526
- Hargrave, P. J., & Ryle, M. 1974, *MNRAS*, 166, 305
- Harris, D. E., Carilli, C. L., & Perley, R. A. 1994, *Nature*, 367, 713
- Harris, D. E., & Grindlay, J. E. 1979, *MNRAS*, 188, 25
- Harris, D. E., & Krawczynski, H. 2006, *ARA&A*, 44, 463
- Harwit, M. 2006, *Astrophysical Concepts*, doi:10.1007/978-0-387-33228-4
- Heckman, T. M. 1980, *A&A*, 500, 187
- Hey, J. S., Parsons, S. J., & Phillips, J. W. 1946, *Nature*, 158, 234
- Hickox, R. C., & Alexander, D. M. 2018, *ARA&A*, 56, 625
- Ho, L. C. 2008, *ARA&A*, 46, 475
- Isobe, N., Koyama, S., Kino, M., et al. 2017, *ApJ*, 850, 193
- Isobe, N., Sunada, Y., Kino, M., et al. 2020, arXiv e-prints, arXiv:2006.10737
- Jackson, J. D. 1975, *Classical electrodynamics*
- Jansky, K. G. 1933, *Nature*, 132, 66
- Jansky, K. G. 1935, *A Note on the Source of Interstellar Interference* (Dordrecht: Springer Netherlands), 36–41
- Jennison, R. C., & Das Gupta, M. K. 1953, *Nature*, 172, 996
- Jones, M. H., & Lambourne, R. J. A. 2004, *An Introduction to Galaxies and Cosmology*

REFERENCES

- Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, *A&A*, 440, 775
- Kaneda, H., Tashiro, M., Ikebe, Y., et al. 1995, *ApJ*, 453, L13
- Kataoka, J., & Stawarz, L. 2005, *ApJ*, 622, 797
- Kataoka, J., Stawarz, L., Takahashi, Y., et al. 2011, *ApJ*, 740, 29
- Katsuta, J., Tanaka, Y. T., Stawarz, L., et al. 2013, *A&A*, 550, A66
- Kino, M., & Takahara, F. 2004, *MNRAS*, 349, 336
- Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, *ApJS*, 182, 216
- Kormendy, J., & Gebhardt, K. 2001, in *American Institute of Physics Conference Series*, Vol. 586, 20th Texas Symposium on relativistic astrophysics, ed. J. C. Wheeler & H. Martel, 363–381
- Landau, L. D., & Lifshitz, E. M. 1975, *The classical theory of fields*
- Lee, H., Kashyap, V. L., van Dyk, D. A., et al. 2011, *ApJ*, 731, 126
- Lewis, K. T., & Eracleous, M. 2006, *ApJ*, 642, 711
- Longair, M. S. 2011, *High Energy Astrophysics*
- Mainzer, A., Bauer, J., Cutri, R. M., et al. 2014, *ApJ*, 792, 30
- Maltby, P., & Moffet, A. T. 1962, *ApJS*, 7, 141
- Marchenko, V., Harris, D. E., Ostrowski, M., et al. 2017, *ApJ*, 844, 11
- Marocco, F., Eisenhardt, P. R. M., Fowler, J. W., et al. 2020, *arXiv e-prints*, arXiv:2012.13084
- Marshall, F. E., Boldt, E. A., Holt, S. S., et al. 1979, *ApJS*, 40, 657
- Marshall, F. E., Mushotzky, R. F., Boldt, E. A., et al. 1978, *Nature*, 275, 624
- Marshall, H. L., Hardcastle, M. J., Birkinshaw, M., et al. 2010, *ApJ*, 714, L213
- Matt, G., Perola, G. C., & Piro, L. 1991, *A&A*, 247, 25
- Meisenheimer, K., Roser, H. J., Hiltner, P. R., et al. 1989, *A&A*, 219, 63
- Meisenheimer, K., Yates, M. G., & Röser, H. J. 1997, *A&A*, 325, 57
- Meléndez, M., Mushotzky, R. F., Shimizu, T. T., Barger, A. J., & Cowie, L. L. 2014, *ApJ*, 794, 152
- Migliori, G., Grandi, P., Palumbo, G. G. C., Brunetti, G., & Stanghellini, C. 2007, *ApJ*, 668, 203

REFERENCES

- Mills, B. Y. 1952, *Australian Journal of Scientific Research A Physical Sciences*, 5, 266
- Mills, B. Y., Slee, O. B., & Hill, E. R. 1960, *Australian Journal of Physics*, 13, 676
- Mizuta, A., Yamada, S., & Takabe, H. 2004, *ApJ*, 606, 804
- Morris, D., Radhakrishnan, V., & Seielstad, G. A. 1964, *ApJ*, 139, 560
- Murray, S. S., Chappell, J. H., Kenter, A. T., et al. 1997, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 3114, EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VIII, ed. O. H. Siegmund & M. A. Gummin, 11–25
- Mushotzky, R. F., Done, C., & Pounds, K. A. 1993, *ARA&A*, 31, 717
- Nagar, N. M., Falcke, H., & Wilson, A. S. 2005, *A&A*, 435, 521
- Nandra, K., & George, I. M. 1994, *MNRAS*, 267, 974
- Nandra, K., & Pounds, K. A. 1994, *MNRAS*, 268, 405
- O’Neill, S. M., & Jones, T. W. 2010, *ApJ*, 710, 180
- Orienti, M., Brunetti, G., Nagai, H., et al. 2017, *MNRAS*, 469, L123
- Orienti, M., Prieto, M. A., Brunetti, G., et al. 2012, *MNRAS*, 419, 2338
- O’Sullivan, S. P., Feain, I. J., McClure-Griffiths, N. M., et al. 2013, *ApJ*, 764, 162
- Padovani, P. 2016, *A&A Rev.*, 24, 13
- Padovani, P., Morganti, R., Siebert, J., Vagnetti, F., & Cimatti, A. 1999, *MNRAS*, 304, 829
- Perley, R. A., Roser, H.-J., & Meisenheimer, K. 1997, *A&A*, 328, 12
- Peterson, J. R., & Fabian, A. C. 2006, *Phys. Rep.*, 427, 1
- Piconcelli, E., Jimenez-Bailón, E., Guainazzi, M., et al. 2005, *A&A*, 432, 15
- Plucinsky, P. P., Bogdan, A., Marshall, H. L., & Tice, N. W. 2018, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 10699, Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, ed. J.-W. A. den Herder, S. Nikzad, & K. Nakazawa, 106996B
- Prieto, M. A., Brunetti, G., & Mack, K.-H. 2002, *Science*, 298, 193
- Pyrzas, S., Steenbrugge, K. C., & Blundell, K. M. 2015, *A&A*, 574, A30
- Reber, G. 1940, *ApJ*, 91, 621
- . 1944, *ApJ*, 100, 279

REFERENCES

- Rees, M. J. 1984, *ARA&A*, 22, 471
- Reynolds, C. S., & Nowak, M. A. 2003, *Phys. Rep.*, 377, 389
- Richstone, D. 1998, in *The Central Regions of the Galaxy and Galaxies*, ed. Y. Sofue, Vol. 184, 451
- Robertson, J. G. 1973, *Australian Journal of Physics*, 26, 403
- Röser, H.-J., & Meisenheimer, K. 1987, *apj*, 314, 70
- Rybicki, G. B., & Lightman, A. P. 1986, *Radiative Processes in Astrophysics*
- Saxton, C. J., Sutherland, R. S., Bicknell, G. V., Blanchet, G. F., & Wagner, S. J. 2002, *A&A*, 393, 765
- Scheuer, P. A. G. 1974, *MNRAS*, 166, 513
- Schilizzi, R. T. 1976, *AJ*, 81, 946
- Schlegel, E. M. 2002, *The Restless Universe - Understanding X-Ray Astronomy in the Age of Chandra and Newton*
- Schreier, E., Levinson, R., Gursky, H., et al. 1972, *ApJ*, 172, L79
- Schwarz, U. J., Whiteoak, J. B., & Cole, D. J. 1974, *Australian Journal of Physics*, 27, 563
- Schwinger, J. 1949, *Physical Review*, 75, 1912
- Seielstad, G. A. 1966, *AJ*, 71, 180
- . 1967, *ApJ*, 147, 24
- Seta, H., Tashiro, M. S., & Inoue, S. 2013, *PASJ*, 65, 106
- Seyfert, C. K. 1943, *ApJ*, 97, 28
- Shi, Y., Rieke, G. H., Hines, D. C., et al. 2005, *ApJ*, 629, 88
- Shklovskii, I. S. 1960, *Soviet Ast.*, 4, 243
- Simkin, S. M., Sadler, E. M., Sault, R., Tingay, S. J., & Callcut, J. 1999, *ApJS*, 123, 447
- Singh, K. P., Rao, A. R., & Vahia, M. N. 1990, *MNRAS*, 246, 706
- Stanley, G. J., & Slee, O. B. 1950, *Australian Journal of Scientific Research A Physical Sciences*, 3, 234
- Stawarz, L., Cheung, C. C., Harris, D. E., & Ostrowski, M. 2007, *ApJ*, 662, 213
- Stawarz, L., Sikora, M., Ostrowski, M., & Begelman, M. C. 2004, *ApJ*, 608, 95

REFERENCES

- Stawarz, L., Tanaka, Y. T., Madejski, G., et al. 2013, *ApJ*, 766, 48
- Sulentic, J. W., Marziani, P., Zwitter, T., & Calvani, M. 1995, *ApJ*, 438, L1
- Tadhunter, C. 2016, *A&A Rev.*, 24, 10
- Tashiro, M., Kaneda, H., Makishima, K., et al. 1998, *ApJ*, 499, 713
- Tavecchio, F., Cerutti, R., Maraschi, L., et al. 2005, *ApJ*, 630, 721
- Thimmappa, R., Stawarz, L., Balasubramaniam, K., & Marchenko, V. 2020a, in *Perseus in Sicily: From Black Hole to Cluster Outskirts*, ed. K. Asada, E. de Gouveia Dal Pino, M. Giroletti, H. Nagai, & R. Nemmen, Vol. 342, 224–226
- Thimmappa, R., Stawarz, L., Marchenko, V., et al. 2020b, *ApJ*, 903, 109
- Thomson, R. C., Crane, P., & Mackay, C. D. 1995, *ApJ*, 446, L93
- Tingay, S. J., Lenc, E., Brunetti, G., & Bondi, M. 2008, *AJ*, 136, 2473
- Tingay, S. J., Jauncey, D. L., Reynolds, J. E., et al. 2000, *AJ*, 119, 1695
- Tucker, W. 1975, *Radiation processes in astrophysics*
- Tucker, W., & Giacconi, R. 1985, *The x-ray universe*
- Ward, M., Allen, D. A., Wilson, A. S., Smith, M. G., & Wright, A. E. 1982, *MNRAS*, 199, 953
- Weisskopf, M. C., Brinkman, B., Canizares, C., et al. 2002, *PASP*, 114, 1
- Werner, M. W., Murphy, D. W., Livingston, J. H., et al. 2012, *ApJ*, 759, 86
- Wilkes, B., & Tucker, W. 2019, *The Chandra X-ray Observatory; Exploring the high energy universe*, doi:10.1088/2514-3433/ab43dc
- Wilson, A. S., Young, A. J., & Shopbell, P. L. 2000, *ApJ*, 544, L27
- . 2001, *ApJ*, 547, 740
- Worrall, D. M. 2009, *A&A Rev.*, 17, 1
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, 140, 1868
- Wykes, S., Croston, J. H., Hardcastle, M. J., et al. 2013, *A&A*, 558, A19