

Fluorescent Iron Lines in Various Types of Radio-Loud Active Galactic Nuclei

A **Ph.D.** Dissertation

by

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Dedicated to

My Parents, Teachers, Family, and Friends.

Most importantly, in the memory of my Grandparents.

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Galactic Nuclei by mgr Karthik Balasubramaniam

Abstract

Active galactic nuclei (AGN) are systems powered by matter falling onto a super-massive black hole (SMBH). The X-ray radiation emitted by the accreting matter is particularly intriguing, since it may originate very close to the SMBH event horizon, and as such it is expected to bear the mark of the intense gravitational field. Typically, this X-ray radiation is composed of distinct spectral components. First, when optical/UV disc photons are inverse-Compton scattered by a corona of hot electrons around the SMBH, the main X-ray continuum emission takes on a power-law shape. Second, a fraction of this radiation is reflected and reprocessed by the absorbing gas and dust located further away from the center. The reprocessing of the X-ray continuum includes photoelectric absorption, followed by fluorescent line emission. Out of all fluorescence features, the iron feature is the most prominent; this is due to the combination of the high relative abundance of iron, and its high fluorescence yield. Moreover, when produced around the innermost orbits of the accretion disks, the iron features may be relativistically broadened and gravitationally redshifted, depending on the disk structure and the black hole spin.

In my research, summarized in this thesis, I have analyzed, in detail, the X-ray radiative output of three radio-loud AGN of various types, focusing, in particular, on their Fe fluorescence emission.

The first system I analyzed was the broad-line quasar 4C+74.26 with giant large-scale radio morphology. The analysis was done by means of modeling the relativistically broadened iron line; in this way, I have provided constraints on the structure of the innermost portions of the accretion disk. The analysis I have performed on the photon-rich *NuSTAR* spectrum of the source, relied in particular on a combination of the relativistic reflection model, with the warm ionized absorber model. The resulting best-fit model parameters implied a truncated disk in 4C+74.26, with the inner disk radius of the order of tens of gravitational radii (assuming a maximum spin of the black hole).

The second system I have analyzed, based on the ~ 100 ksec *Chandra* observations, was the LINER-type AGN CGCG 292-057, hosted by a post-merger disk galaxy, with a multi-component radio morphology reflecting intermittent jet activity of the central SMBH. The nuclear X-ray spectrum of the target revealed an ionized, Fe XXV $K\alpha$ line at ~ 6.7 keV, with the equivalent width of order 0.3 keV, which we explained in a scenario involving a Compton-thin gas located at the scale of the broad-lined region and photoionized by nuclear (disk and disk corona) illumination.

The third analyzed radio source, 1146+596 hosted by an elliptical galaxy NGC 3894 with a low-luminosity active nucleus, is one of the youngest radio galaxies known, which recently has also been confirmed as a high-energy γ -ray emitter. Based on the archival *Chandra* data, we have found that the X-ray spectrum of the target is best fitted by a combination of an ionized thermal plasma, and a moderately absorbed power-law component, with a prominent iron $K\alpha$ line at $\simeq 6.4$ keV. We argued that the line, with the estimated equivalent width of $EW \simeq 1$ keV, is indicative of the X-ray reflection from cold neutral gas in the central regions of NGC 3894, consistent with the “X-ray Baldwin effect”, given the mid-infrared luminosity of the AGN.

All in all, my research reveals a prevalent fluorescent iron line emission in various types of radio-loud AGN, including both low- and high-luminosity objects. There is a variety in the iron features in the population of jetted AGN, including relativistically broadened lines, ionized lines, and neutral lines with a larger range of equivalent widths. The research I have carried out during my PhD program highlights, in general, the importance of iron fluorescence studies for radio-loud AGN, for which the constraints regarding the innermost structure of AGN, enabled exclusively by the X-ray spectroscopy, can be uniquely complemented by the constraints on the energetics and duty cycle of the systems following from the analysis of their radio (jet) emission.

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Chapter 1

Introduction

Extreme gravity collapses all the matter into a singularity (a point of infinite density) at the very centre of a black hole. Due to severe curvature of space-time induced in this way, everything — including photons! — is unable to escape the radius around a singularity called the *event-horizon*. While no radiation escapes from within the event horizon, black holes are typically ringed by accretion disks, which collect surrounding matter and convert some fraction of its gravitational energy into electromagnetic radiation; Poynting flux can also be extracted from the ergospheres of rotating black holes, to form relativistic jets at the expense of the black hole rotational energy (e.g., [Meier 2012](#)).

Supermassive Black Holes (SMBHs) are objects with masses ranging from millions to tens of billions of solar masses, as opposed to smaller (stellar) black holes with masses on the order of tens of solar masses.

Active Galactic Nuclei (AGN) are SMBHs residing in the centers of massive galaxies, which are accreting at higher rates. While it is theorized and thus far observed that all galaxies contain SMBHs at their cores ([Lynden-Bell 1969](#); [Kormendy 2004](#)), only some fraction of them remain active at a given cosmological epoch (see, e.g., [Ho 2008](#)). These active SMBHs are among the Universe’s most luminous objects, emitting non-stellar radiation — via accretion disks, disk coronae, and relativistic jets in the case of “radio-loud” systems — at all wavelengths from radio to γ -rays (e.g. [Beckmann & Shrader 2013](#)). AGN are therefore essential to study because they emphasize some of the most spectacular and most extreme physical processes known, which are crucial for the fundamental research (physics of black holes and relativistic plasma), as well and for the study of the Cosmos (in particular, galaxy and structure formation in the Universe). In the latter context, one should emphasize complex but essential feedback processes between the SMBH activity and evolution, and the structure and evolution of their host galaxies (see, e.g., [Kormendy & Ho 2013](#); [Naab & Ostriker 2017](#), for reviews).

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Most astronomical observations have traditionally been in the optical (visible) band, but technical advancements in the previous 100 years have allowed for observations in other regions of the electromagnetic spectrum. The fact that black holes devouring matter are powerful “X-ray emitters”, makes them one of the most studied subjects in the X-ray astronomy (e.g., [Krolik 1999](#); [Kembhavi & Narlikar 1999](#)). In particular, accretion disk coronae in AGN (similarly as in Galactic black-hole binaries) can, in principle, generate X-ray photons with energies ranging from a few hundred keV to fractions of keV, due to extremely high temperatures and magnetization of the plasma. And because they are produced within the closest vicinity of the central SMBHs, and can easily pierce the absorbing material in the line of sight, high energy X-rays are the principal messenger for investigating the innermost structure of AGN.

During the course of my PhD program, I was learning how to use the modern space-borne X-ray telescopes such as XMM-Newton, Chandra, and NuSTAR, to investigate the physics of the three selected systems, representing the three distinct types of radio-loud — i.e., jetted — AGN, namely the Broad-Line Radio Quasar 4C +74.26, the LINER-type Radio Galaxy CGCG 292–057, and the Compact Symmetric Object NGC 3894. The results of my research are presented in this dissertation.

The thesis is organized in the following manner. In this Chapter 1, the introductory background material is given. This includes the most basic information about AGN (§ 1.1) and their X-ray emission (§ 1.2), as well as the software and methodologies utilized in my research. There is also a brief description of the on-going X-ray satellite missions and future X-ray telescopes that are/will be of particular interest for studying radio-loud AGN systems (§ 1.3). The modeling of the NuSTAR spectrum of the quasar 4C +74.26, along with the analysis of the multi-wavelength monitoring data for the target, is presented in Chapter 2. The studies of the low-luminosity systems observed with Chandra, CGCG 292–057 and NGC 3894, are presented in Chapters 3 and 4, respectively. Lastly, in Chapter 5 I present a summary and final remarks following from my research.

1.1 Radio-loud AGN

From the historical perspective, the scientific research on radio-loud AGN has started in the early 1960s, with the discovery of the radio source 3C 273. Based on the observations collected by the 210-foot antenna at the Parkes Station in Australia, [Hazard et al. \(1963\)](#) was able to get an exact location for the target; meanwhile, the hydrogen emission lines in the source optical spectrum were found by [Schmidt \(1963\)](#) to be redshifted by a large factor $z = 0.16$, indicating that the emitting gas was moving away from us at large speeds, i.e. that — in the expanding Universe — the source is cosmologically distant.

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This was later confirmed by Oke (1963), who found another redshifted emission line in the infrared range. Based on the above findings, Greenstein & Schmidt (1964) derived the radius for a spherical $H\beta$ emission region in 3C 273 as 1.2 pc, while Smith & Hoffleit (1963) calculated a mass of $10^9 M_\odot$ for the central source in the target by combining the size estimate with the observed optical variability timescale. Hoyle & Fowler (1963) proposed that the observed high luminosities from distant radio sources like 3C 273 might be supported by a relativistic collapse of a supermassive star with a mass of $\gtrsim 10^8 M_\odot$. The following theoretical work and observational effort have established the ever-growing field of AGN research and astrophysical jet studies (see, e.g., Shields 1999).

1.1.1 Supermassive Black Holes

Zel'dovich & Podurek (1964) were one of the first who discussed how the gas accretion onto massive objects — at the rate of roughly one solar mass per year — is, in general, capable of powering quasar sources such as 3C 273. The accretion process onto a massive ‘Schwarzschild throat’ (a black hole, in later nomenclature) in the shape of a disk, was subsequently described in more detail by Lynden-Bell (1969).

Although such a high (quasar-type) rate of accretion may slow down at some point of the cosmological evolution of the system, one of the consequences of the ‘accretion-powered quasar’ model is that SMBHs should be found at the centers of ordinary galaxies also without AGN, such as our own Galaxy, as pointed out by Lynden-Bell & Rees (1971). And indeed, Turriere (1970) used the Green Bank Interferometer to discover a compact radio source of a non-thermal emission at Sagittarius A* around the Milky Way’s center. Schödel et al. (2002), among the others, was later able to strengthen the evidence for the presence of a SMBH with three million solar masses in Sgr A*, by examining the trajectories of neighboring stars.

It is now a common knowledge that SMBHs with masses $\mathcal{M} \sim 10^6 - 10^{10} M_\odot$ can be found at the centers of virtually every larger galaxy (Kormendy & Richstone 1995). As summarized in the review by Ho (2008), ‘*The local census of nuclear activity supports the notion that most, perhaps all, bulges host a central SMBH.*’ The black hole mass was shown to scale with the brightness (or mass) of the galaxy’s bulge, and with the star (or gas) velocity dispersion within the central parts of the host (e.g., Ho 1999; Merritt & Ferrarese 2001). A comprehensive optical spectroscopic study of a large number of neighboring galaxies conducted by Ho et al. (1997), revealed moreover that between a third and half of their sample do possess AGN-like spectra (after the starlight is carefully removed/accounted for), although at low luminosity levels, suggesting that SMBHs in ordinary galaxies are not only extant, but also active (at least at some level).

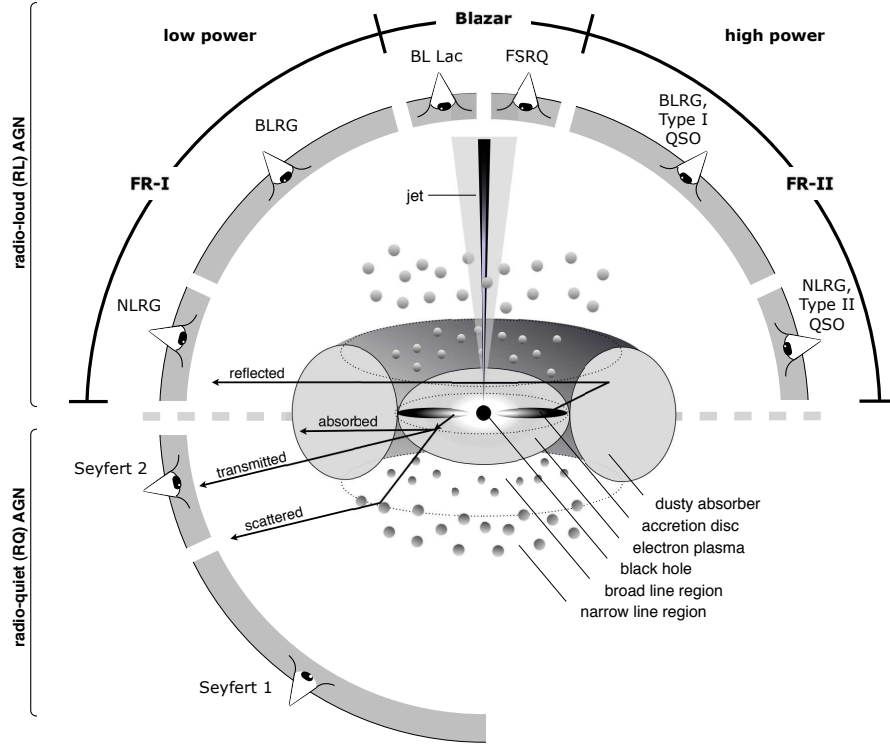


Figure 1.1: A schematic picture of an AGN in the orientation-based unified model. From [Beckmann & Shrader \(2012\)](#).

In fact, whether a galaxy is ‘*active*’ or ‘*non-active*’, is often rather difficult to assess with no high-quality multi-wavelength data, and the corresponding borderlines are often set quite arbitrarily. For example, one might consider *active galaxies* as those systems for which the nuclear radiative output, unrelated to normal stellar processes, is comparable to, or occasionally higher than, the sum of the luminosities of the host galaxy’s other regions (predominantly of the starlight). In general, the nuclear activity level is directly proportional to the nuclear mass accretion rate, which not only determines the bolometric luminosity of an AGN, but also shapes the very *structure* of the accretion disk, and of the entire circumnuclear environment.

The concept that, at comparable accretion rates, various AGN are fundamentally (intrinsically) identical, and only appears differently depending on the orientation (i.e., on the angle between the line of sight and the symmetry axis of the system), is the basic of the common ‘AGN unification scheme’ (e.g., [Urry & Padovani 1995](#), see also Figure 1.1). The primary elements of this model are as follows:

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- Accretion disk surrounding the SMBH at sub-pc scales; depending on the accretion rate, the disk may be either optically thin/geometrically thick, or optically thick/geometrically thin.
- High-density, dust-free gas clouds traveling at Keplerian speeds at a distance of 0.001–0.1 pc from the SMBH, constituting the ‘broad line region’.
- Axisymmetric dusty structure 0.1–10 pc away from the SMBH, often approximated by a toroidal geometry, and more recently described as a ‘clumpy torus’.
- A pair of relativistic (or at least mildly-relativistic) jets directed along the black hole/accretion disk rotational axis.
- Low-density gaseous clouds photo-ionized by the nuclear (disk) emission, and extending up to 10–1000 pc distances from the center, constituting the ‘narrow-line region’.

1.1.2 Accretion Disk

The friction between various relative velocities of gas layers/clouds in the SMBH environment, is expected to result in the formation of a revolving disk of matter known as a ‘*accretion disk*’. Through magneto-rotational instabilities, the accumulating matter transfers angular momentum and releases binding energy, allowing for the accretion to proceed, and creating a magnetically active corona above the disk surface (Shlosman et al. 1990). Accretion disk which is heated by magnetic and/or viscous processes, radiates throughout a large portion of the electromagnetic spectrum, from radio to soft X-rays.

The two main parameters determining the disk structure, are the accretion rate, $\dot{m}$ (in the dimensionless units, i.e. when normalized to the Eddington accretion rate), and the disk viscosity parameter, α , and only for some combinations of such parameters stable steady-state disk solutions exist (Chen et al. 1995). Those include optically-thin/geometrically thick disks at low accretion rates, commonly known as ‘*Radiatively Inefficient Accretion Flows*’ (RIAFs; see, e.g., Lasota 2016)¹. When $\alpha^2 < \dot{m} < 1$, the disk has the “standard” optically-thick/geometrically-thin structure; such ‘*Shakura-Sunyaev disks*’ are radiatively efficient, meaning about 10% of the available accretion power converted into electromagnetic radiation, predominantly within the UV/optical range in the case of SMBHs (Shakura & Sunyaev 1973).

¹in particular, ‘*Advection-Dominated Accretion Flow*’ (ADAF; Narayan et al. 1995), ‘*Advection-Dominated Inflows - Outflows solutions*’ (ADIOS; Blandford & Begelman 1999), and ‘*Convection-Dominated Accretion Flow*’ (CDAF; Narayan et al. 2000).

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1.1.3 Broad Line Region

Broad (FWHM $\sim$ few thousand km s^{-1}) permitted emission lines are visible in the IR, optical, and UV spectra of AGN, with a wide range of ionization; those include the Lyman, Balmer, Paschen, and Bracket series lines of atomic Hydrogen (i.e., Ly_α , H_α , H_β , Pa_α , Pa_β), Carbon (i.e., C[III] λ 1909 Å, C[IV] λ 1548 Å, 1551 Å), Silicon (i.e., Si[IV] λ 1394 Å, 1403 Å), Magnesium (Mg[II] λ 2796 Å, 2804 Å) and multiplets of Iron (FeII).

The gas producing the lines is believed to be photo-ionization by the nuclear (accretion disk) continuum, and distributed within compact thick clouds orbiting the central SMBH with velocities of the order of $\sim 3,000 - 10,000 \text{ km s}^{-1}$. The typical size of the ‘*Broad-Line (emission) Region*’ (BLR), can be estimated as $\sim 0.001 - 0.1 \text{ pc}$, from the broad line variability. Because SMBH gravity dominates the AGN radiation pressure force at such distances, the cloud system is bound to the gravitational potential of the nucleus. The lack of broad forbidden lines (the [OIII] doublet), and the presence of the semi-forbidden [CIII] line, indicate that the electron density in the BLR is $\sim 10^8 - 10^{10} \text{ cm}^{-3}$. The percentage of the direct disk emission reprocessed by BLR, typically ~ 0.1 , is about equal to the cloud covering factor (Osterbrock 1989; Netzer 1990; Krolik 1999). More recently, it was proposed that the BLR constitute some form of a “failed outflow”, from around where the accretion disk transitions to the dusty torus (Czerny & Hryniewicz 2011).

1.1.4 Dusty Torus

It was realized already early on, that the unified view on active galaxies — quasars, radio galaxies, and Seyfert galaxies — requires the presence of a circumnuclear dust surrounding the nuclei, and obscuring the direct disk and BLR emission in type 2 sources (including Narrow-line Radio Galaxies, and Seyferts type 2; Rowan-Robinson 1977; Antonucci & Miller 1985). The re-processed disk emission is re-emitted in the mid-IR range, consistently with the observed spectra of various types of AGN (Urry & Padovani 1995).

The circumnuclear dust in AGN has to be relatively hot, with temperatures of the order of 1,000 K, and located sufficiently far from the central engine to avoid the dust grain destruction by the UV/X-ray nuclear photons (Krolik & Begelman 1988). For the typical AGN luminosities, this sets the characteristic (inner) scale of the dust as $\sim 0.1 - 10 \text{ pc}$. With the expected density of $10^4 - 10^6 \text{ cm}^{-3}$, the corresponding equivalent hydrogen column density reads as $N_H \sim 10^{22} - 10^{25} \text{ cm}^{-2}$. The dust is therefore optically thick for optical, UV and soft X-rays. If N_H is equal to or larger than the inverse of the Thomson cross-section, $\sigma_T^{-1} \sim 1.5 \times 10^{24} \text{ cm}^{-2}$, the medium becomes “Compton thick” even for hard X-ray photons with energies up to several tens of keV (see, e.g., Comastri 2004).

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Except of the inner scale estimated based on the dust sublimation temperature argument, the other parameters of the circumnuclear dust are rather poorly restricted. The AGN unification scheme requires the dust to be distributed within a toroidal structure around the nucleus (see Figure 1.1). More recently, it was widely accepted that such AGN dusty tori have to be “clumpy”, i.e. must consist of high density gaseous condensations/clouds with a range of scales and masses (e.g., [Nenkova et al. 2008](#)). By collision friction, such condensations may lose sufficient angular momentum to fall on the SMBH through the creation of the disk ([Shlosman et al. 1990](#)).

1.1.5 Relativistic Jets

Jets in AGN are launched from the closest vicinity of SMBHs, and transfer the black hole/accretion disk energy, momentum, and angular momentum, over long distances up to the scales of hundreds of kpc and even a few Mpc in several cases ([Begelman et al. 1984](#); [Blandford et al. 2019](#)). AGN jets range from sub-relativistic, low-power, and weakly-collimated outflows observed in Seyfert galaxies, to ultra-relativistic (bulk Lorentz factors up to $\Gamma_j \sim 100$), powerful (kinetic luminosities up to $L_j \sim 10^{47} \text{ erg s}^{-1}$), and extremely well-collimated (opening angles below a few degrees) structures seen in blazars, radio quasars, and high-power radio galaxies ([Urry & Padovani 1995](#)).

AGN jets emit non-thermal broad-band radiation from radio wavelengths to very high-energy γ -rays (photon energies 0.1-100 TeV), and the jet emission at radio, optical, and X-ray frequencies can be spatially resolved and imaged on the scales from a few up to tens of, or even hundreds of, kpc away from galactic centers (see, e.g., [Harris & Krawczynski 2006](#)). This emission is strongly Doppler-boosted in the observer frame, due to relativistic bulk velocities of the emitting plasma.

The radio-to-optical continuum emission of AGN jets is, in general, synchrotron in origin, as confirmed by the observed polarization signatures. The high- and very-high energy γ -ray emission of the jets is, on the other hand, best explained as due to inverse-Compton scattering of the surrounding photon fields by the synchrotron-emitting jet electrons; in the X-ray range we are possibly witnessing a superposition of the two aforementioned dominant radiative processes (e.g., [Stawarz 2003](#); [Sikora et al. 2009](#)).

AGN jets are widely considered to be launched from the ergospheres of rotating SMBHs, whenever accreting matter entering the ergospheres is sufficiently magnetized so that a large amount of the accumulated poloidal magnetic field can drive the Poynting flux outwards along the black hole/accretion disk rotational axis ([Blandford & Znajek 1977](#)); such electromagnetic outflows are subsequently collimated by the disk winds, and accelerated to ultra-relativistic velocities by a gradual conversion of the Poynting flux to

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the bulk kinetic power (Blandford & Payne 1982). AGN jets are therefore produced at the expense of the the SMBH rotational energy, as confirmed recently by extensive 3D GRMHD simulations (see Komissarov & Porth 2021, and references therein).

1.1.6 Narrow Line Region

Low density ($\sim 10^3 - 10^6 \text{ cm}^{-3}$) gas clouds located at larger (0.01–1 kpc) distances from the central engines, are the source of narrow emission lines (FWHM $\sim$ few hundred km s^{-1}) visible in the optical spectra of various types of active galaxies, including AGN type 1 and 2, as well as low-luminosity AGN of the “Low-ionization nuclear emission-line region” (LINER) type (Osterbrock 1989; Netzer 1990; Krolik 1999). This includes permitted emission lines, such as H I, H β , and H γ , as well as narrow forbidden emission lines, such as [O III] λ 4959 Å, 5007 Å, [O II] λ 3727 Å, [N II] λ 6548 Å, 6583 Å. Except for $\text{Ly}\alpha$, the line [O III] λ 5007 Å is generally the strongest narrow line in AGN.

The narrow line emission is believed to be predominantly due to photo-ionization by the direct disk emission (e.g., Ferland & Netzer 1983; Stasinska 1984), although a contribution from the high-velocity photoionizing radiative shocks cannot be excluded in this context as well (see Dopita & Sutherland 1995). The ‘*Narrow-Line (emission) Region*’ (NLR) has been spatially resolved in several nearby AGN (e.g., Pogge 1989); its elongated or even biconical morphology, along the axis perpendicular to the hypothesized torus, and often along the radio jet axis, provides a strong support to the orientation-based unification scheme of AGN.

1.2 AGN in X-rays

Why are X-rays so useful for studying AGN? X-rays offer a clean diagnostic of a nuclear activity in galaxies. That is because (i) X-rays are naturally produced in great numbers by the matter accreting onto SMBHs, due to extremely high temperatures and magnetization of the plasma within coronal regions of AGN accretion disks, (ii) X-rays are less affected by the absorption effects due to circumnuclear dust than optical and UV photons, and (iii) the X-ray band is less contaminated by non-AGN (starlight and starformation-related) radiative output of the host than the IR or optical bands. As a result, X-rays provide a more representative view on accretion processes in galaxies across cosmic time, serving as messengers of the formation and subsequent growth of SMBHs in the Universe (see, e.g., [Barger et al. 2005](#); [Brandt & Alexander 2015](#)).

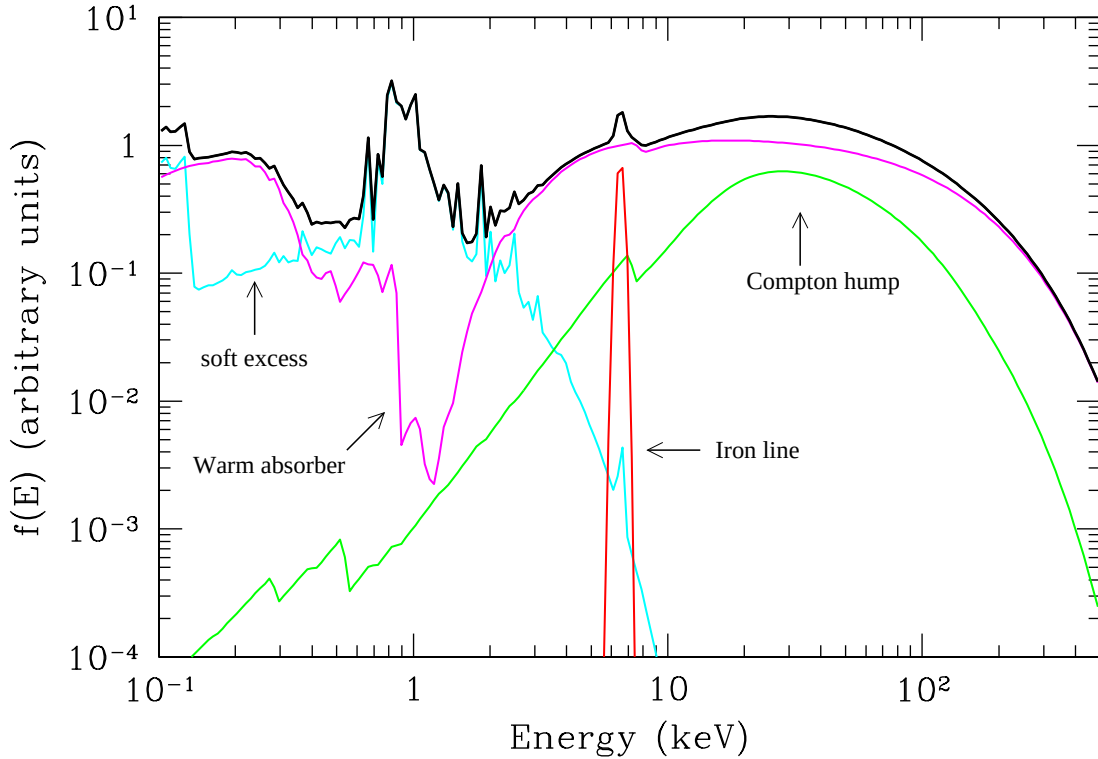


Figure 1.2: From [Risaliti & Elvis \(2004\)](#): “Average X-ray spectrum of a type 1 AGN. The main primary continuum component is a power law with an high energy cut-off at $\sim 100 - 300$ keV, absorbed at soft energies by warm gas with a column density $\sim 10^{21} - 10^{23} \text{ cm}^{-2}$. A cold reflection component is also shown. The most relevant narrow feature is the iron $K\alpha$ emission line at 6.4 keV. A “soft excess” is also shown, due to thermal emission of a Compton thin plasma with temperature $\lesssim 1$ keV.”

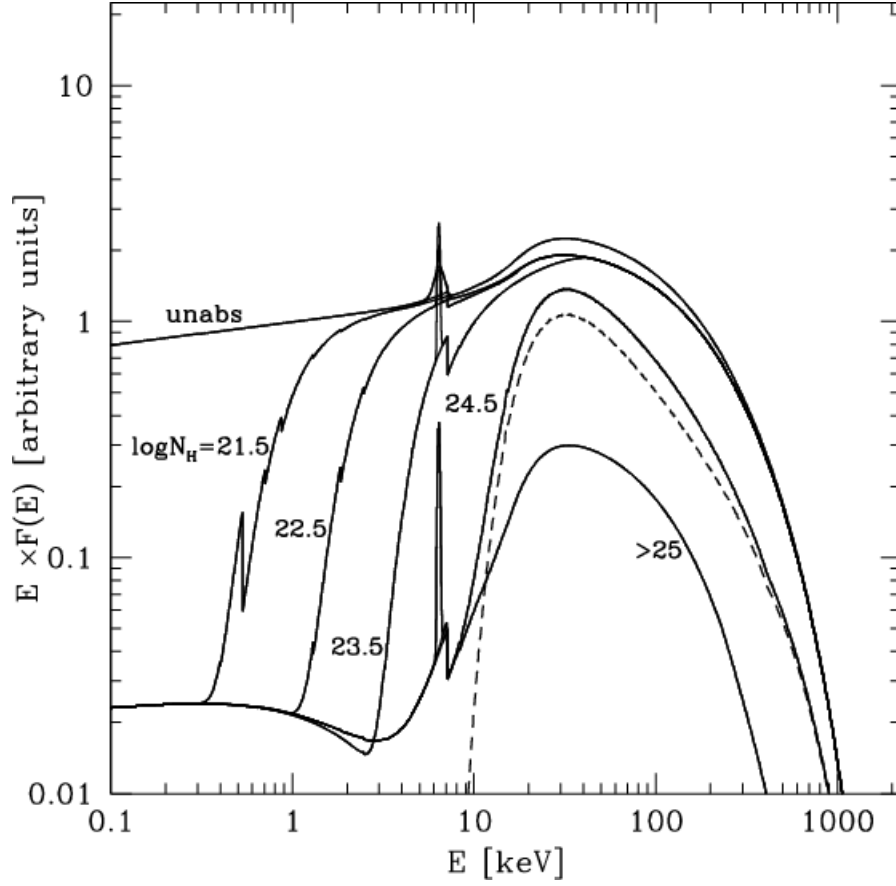


Figure 1.3: X-ray spectra of AGN absorbed by a cold gas with the equivalent hydrogen column densities N_{H} between $< 10^{21} \text{ cm}^{-2}$ (“unabs” case) and $> 10^{25} \text{ cm}^{-2}$, as indicated near each model curve. From [Gilli et al. \(2007\)](#).

The nuclear X-ray emission, which typically accounts for as much as $\sim 10\%$ of the bolometric luminosity of an AGN, is composed of several distinct spectral components. First, when optical/UV disc photons are inverse-Compton scattered by a corona of hot electrons around the SMBH, the main X-ray continuum emission takes on a power-law shape. Depending on the temperature and optical depth of the hot electron plasma that makes up the corona, the power-law continuum displays a high energy rollover at a few hundreds keV. Second, a fraction of this radiation is reflected and reprocessed by the accretion flow itself, and next by the absorbing gas and dust located further away from the center (within ionized disk outflows and circumnuclear dusty tori). And third, X-ray emission spectra of AGN are often contributed by a thermal emission of a hot gas (collisionally ionized and/or photoionized plasma), as well as — in the case of radio-loud (jetted) systems — by a non-thermal emission of relativistic jets.

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In Figure 1.2, we present the template X-ray spectrum of a luminous type 1 AGN. Note that, in the framework of the AGN unification scheme, “type 1” sources are expected to be viewed at inclinations (with respect to the symmetry axis of the central engine) smaller than the dusty torus opening angle, and as such are expected to be basically free from cold gas absorption. Nonetheless, their X-ray spectra may still be absorbed by warm gas corresponding to ionized disk winds and outflows, with column densities $\sim 10^{21} - 10^{23} \text{ cm}^{-2}$. On the other hand, “type 2” AGN are expected to be observed as larger inclinations, i.e. through the absorbing cold gas constituting the dusty torus. In Figure 1.3 we present the model X-ray spectra of such sources, for different equivalent hydrogen column densities N_{H} from $< 10^{21} \text{ cm}^{-2}$ up to $> 10^{25} \text{ cm}^{-2}$.

The exact structure and geometry of the hot corona in AGN is hardly known, and many different scenarios have been proposed and discussed in the literature, as illustrated in Figure 1.4. One of the most popular model in this respect, is the “lamp post model”, in the framework of which the corona is a very compact, basically a point-like region hovering above the SMBH along its spin axis, which is sometimes identified with the base of a jet (but see the discussion in [Niedźwiecki et al. 2016](#)).

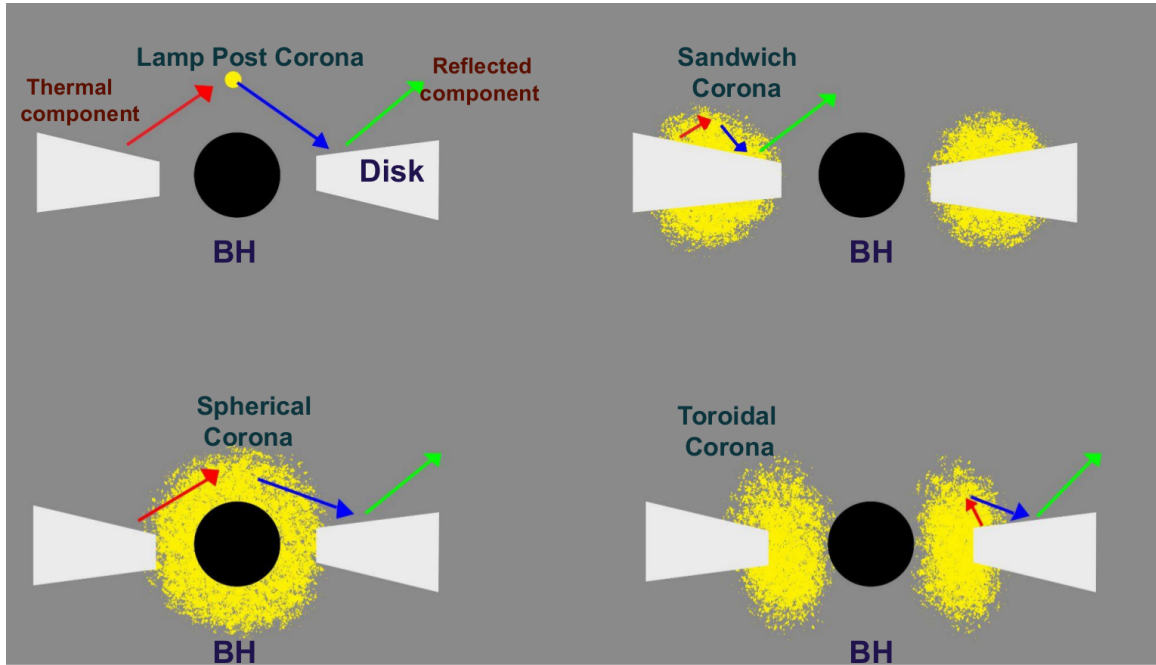


Figure 1.4: Examples of possible disk corona geometries in AGN, discussed in the literature: lamp post geometry (top left panel), sandwich geometry (top right panel), spherical geometry (bottom left panel), and toroidal geometry (bottom right panel). Reproduced from [Bambi \(2017\)](#).

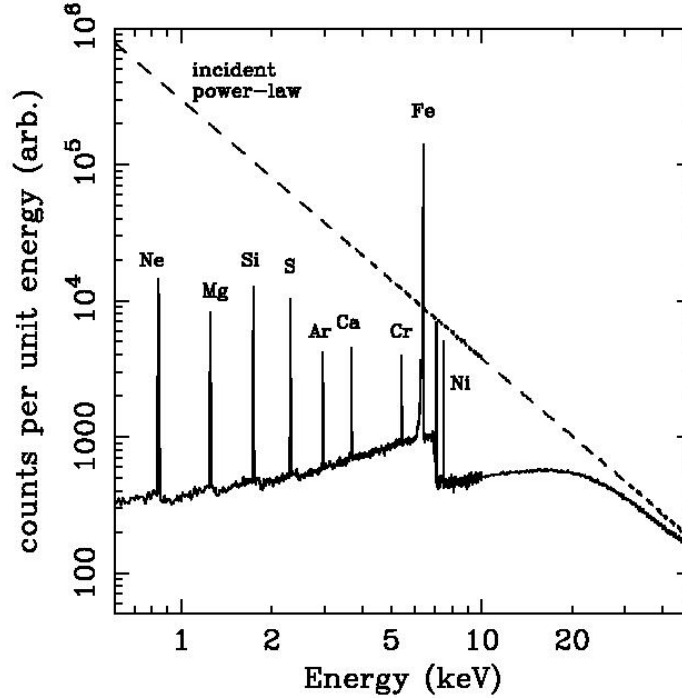


Figure 1.5: From Reynolds (1999): “X-ray reflection from an illuminated slab. Dashed line shows the incident continuum and solid line the reflected spectrum.”

1.2.1 X-ray Reflection

The reprocessing of the X-ray (disk corona) continuum by the surrounding gas and dust, includes photoelectric absorption, followed by fluorescent line emission (or by Auger de-excitation). The other contributor to the reflection component is Compton scattering, producing a “Compton hump” that peaks around 20 – 30 keV (Lightman & White 1988; Pounds et al. 1990; George & Fabian 1991). Note that only when the material around the SMBH is Compton-thick ($N_H > 10^{24} \text{ cm}^{-2}$) can the Compton hump appear in the composite spectrum of the source, but the Fe $K\alpha$ line can be present even in the Compton-thin ($N_H < 10^{24} \text{ cm}^{-2}$) case (Matt 2002; Guainazzi et al. 2005; Fabian et al. 2006).

X-ray reflection in AGN is often modelled assuming that the hard power-law X-ray continuum illuminates a semi-finite slab of “cold” gas (i.e., the surrounding accretion flow, where metal atoms are generally neutral, while H and He are mostly ionized; e.g., Reynolds 1999). Due to the energy dependence of photoelectric absorption, incident soft X-rays are generally absorbed, but hard X-rays are Compton dispersed and escape the slab, until Compton recoil reduces the backscattered photon flux. As a result, the reflection hump-like continuum is σ_T/σ_{pe} weaker than the incident spectrum, where σ_T is the Thompson cross-section and σ_{pe} denotes the photoelectric cross-section (Fabian et al. 2000).

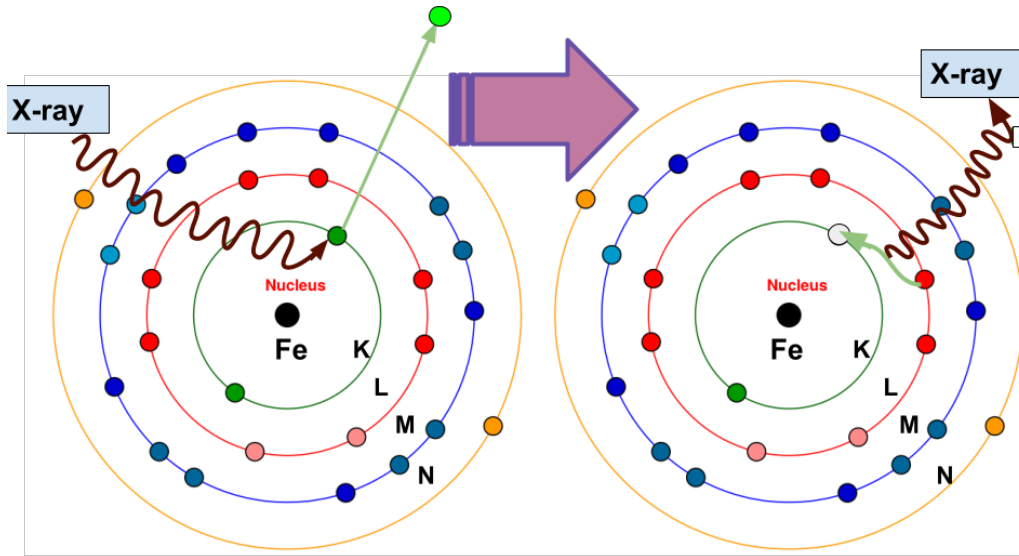


Figure 1.6: When the X-ray photon ejects an electron from the Fe K-shell, the $K\alpha$ transition occurs. When the electron from the L-shell fills the hole created by the K-shell electron, a 6.4 keV photon is released.

1.2.2 Iron Fluorescence

Out of all fluorescence features, the iron feature is the most prominent (see Figure 1.5), and this is due to the combination of the high relative abundance of iron, and its high fluorescence yield (i.e., the probability that a photoelectric absorption event is followed by fluorescent line emission rather than the Auger effect)².

When an X-ray photon collides with a K-shell electron of an iron atom and ejects it from its orbital, the fluorescence Fe $K\alpha$ line is produced. The hole created by the K-shell electron will be filled by an L-shell electron, producing a 6.4 keV photon or, in certain instances, transferring energy to another (Auger) electron and ejecting it from the atom (see Figure 1.6). Lyman α is the hydrogen equivalent of the Fe $K\alpha$, however because of a much smaller charge of a hydrogen, this line lies in the UV rather than the X-ray region.

²For neutral matter, the fluorescence yield scales with the atomic number as $\propto Z^4$ (Matt et al. 1997; Fabian et al. 2000).

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The Fe $K\alpha$ line is really a doublet, with the spin-orbit interaction energy between the electron spin and the 2p orbital momentum determining the small energy difference between $K\alpha 1$ at 6.391 keV and $K\alpha 2$ at 6.404 keV (Roseberry & Bearden 1936). However, because contemporary X-ray satellites lack the spectral resolution to resolve the doublet, the Fe $K\alpha$ feature is typically referred to as a single line. The sole exception in this respect was the Hitomi X-ray Telescope, which unfortunately suffered a catastrophic failure in March 2016 after only one month of the initial operation (Aharonian et al. 2016). The situation may improve in the future with the launching of X-ray satellite XRISM and Athena (see the next section 1.3).

For ionized iron, the energy of both the photoelectric threshold and the $K\alpha$ line are increased, even though the latter one is significantly above 6.4 keV only when the M-shell is lost, i.e. for Fe XVII and higher states. In general, the iron fluorescent yield depends on the ionization state: the dependence is rather weak from neutral iron Fe I up to Fe XXIII; for Lithium-like iron Fe XXIV and above, the Auger effect cannot occur due to the lack of at least two electrons in the L-shell; for He-like Fe XXV and H-like Fe XXVI, the line is produced by the capture of free electrons, i.e. recombination (Matt et al. 1997).

The intrinsic width of the Fe $K\alpha$, < 10 eV, is much below the energy resolution of the currently operating X-ray satellites (see § 1.3 below). The exact position, width, and shape of the line, may however be significantly deformed depending on the exact disk structure, including velocity profile of the accreting matter, its ionization state, position of the disk's innermost stable circular orbit (ISCO) with respect to the black hole's event horizon, inclination with respect to the line-of-sight, the coronal geometry, etc. Especially all the accompanying relativistic effects may be relevant in this context, as illustrated in Figure 1.7, and commented on below. As a result, the iron line may appear broad, and as such potentially “resolvable” by the X-ray instruments with the energy resolution of the order of 100 eV, such as Chandra and XMM-Newton (e.g., Fabian et al. 1989; Laor 1991; Martocchia et al. 2000; Ballantyne & Fabian 2003; Brenneman & Reynolds 2006; Dauser et al. 2010; Niedźwiecki & Życki 2008; Niedźwiecki et al. 2019).

First, there is the Doppler shift of the radiation released by the approaching and receiving ends of the accretion disc. In the case of non-relativistic orbital velocities, this would result in the Fe $K\alpha$ line having a completely symmetrical double-horned profile. Second, when orbital velocities approach the speed of light, the blue-shifted line component is strongly beamed in the observer's frame, while the red-shifted line component is strongly de-beamed, so that the double-horned profile becomes highly asymmetrical. And third, if the innermost segments of the disk are located close to the SMBH's event horizon, gravitational redshift of the light becomes relevant, shifting the line toward longer wavelengths, and blurring the entire double-horned profile into a single broad feature with the extended red wing.

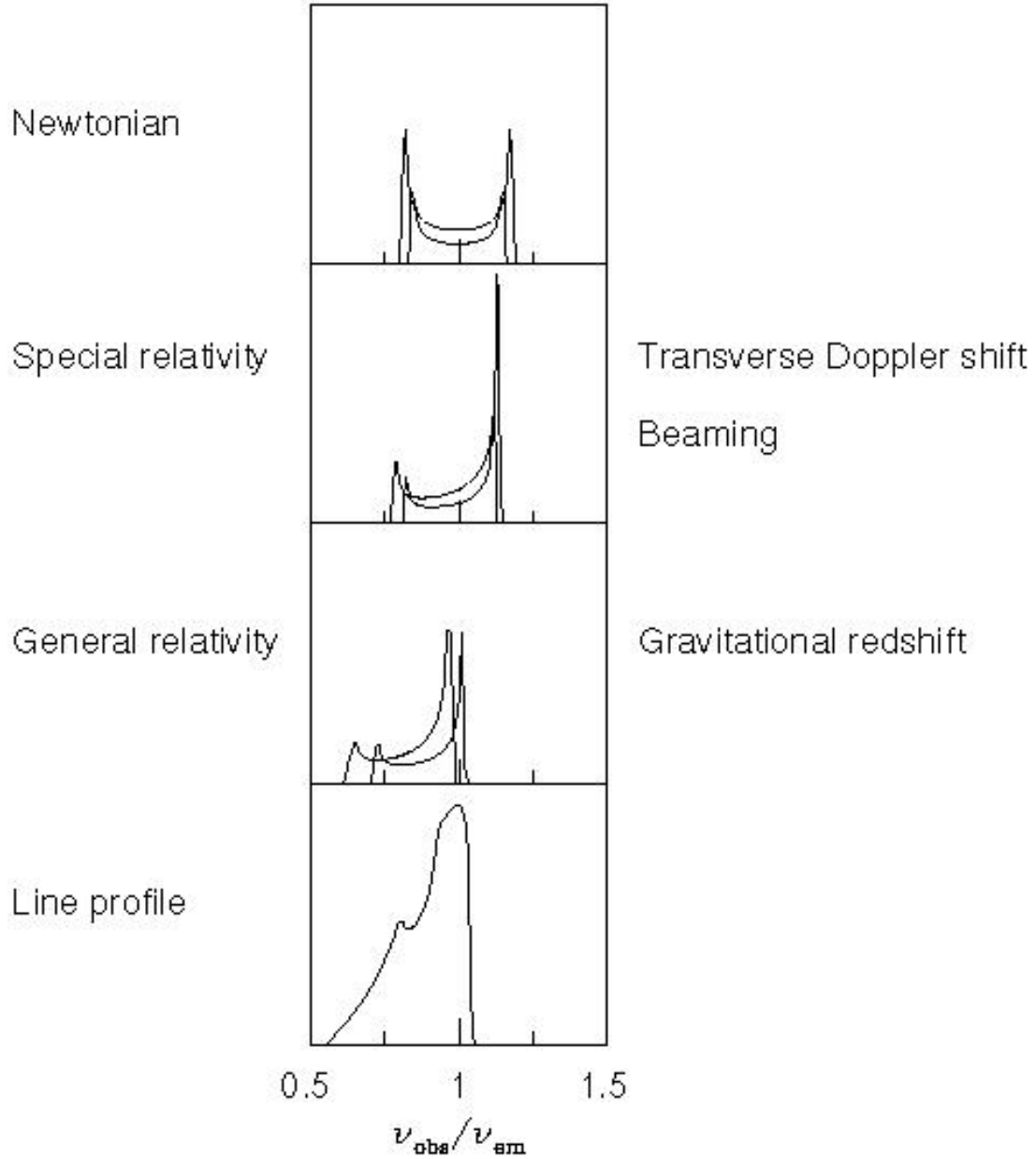


Figure 1.7: From [Fabian et al. \(2000\)](#): “The profile of the broad iron line is caused by the interplay of Doppler and transverse-Doppler shifts, relativistic beaming and gravitational redshifting. The upper panel shows the symmetric double peaked profiles from two narrow annuli on a non-relativistic disk. In the second panel the effects of transverse Doppler shifting and relativistic beaming have been included, and in the third panel gravitational redshifting has been included. These give rise to a broad, skewed line profile, such as that show in the lower panel.”

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The main consequence from the above-described effects, is that the exact profile of the broad iron $K\alpha$ line in AGN carries the information regarding not only the structure of the innermost segments of the accretion disks, but also of the SMBH spin. That is because the ISCO position for the standard Shakura-Sunyaev disks — and hence the amount of relativistic beaming and gravitational redshift shaping the line — depends on the black hole spin, in particular ranging from 6 gravitational radii for a non-rotating (Schwarzschild) black hole, down to about one gravitational radius for a maximally rotating (Kerr) black hole (Reynolds 2019). In other words, by means of precise observational studies of the iron fluorescence in AGN which display broad Fe $K\alpha$ line, one can put observational constraints on the spin of the central SMBH, the parameter which is hardly accessible observationally otherwise.

Fluorescence iron lines, either neutral or ionized, are now being routinely found in the X-ray spectra of various types of AGN (e.g., Terashima et al. 1998; Page et al. 2004; Nandra et al. 2007; González-Martín et al. 2009a, 2011; Fukazawa et al. 2011a; Patrick et al. 2012a; Ricci et al. 2014), although typically radio-quiet ones, and in addition with the number of systems displaying undoubtedly the relativistically broadened feature, remaining relatively small (amounting to about 20 sources; see Reynolds 2014, and references therein). The relevant question is therefore, why not *all* AGN (at least of the type 1) display relativistically broadened Fe $K\alpha$ line, keeping in mind that all such systems are expected to have comparable accretion disks and disk coronae (see in this context the discussion in, e.g., Nandra et al. 2007; Guainazzi et al. 2006; Mantovani et al. 2014).

1.3 X-ray Instruments

X-ray telescopes must, in general, be installed on high-altitude rockets, balloons, or satellites, because the Earth's atmosphere is opaque to photons with energies of the order tenths of keV and above. And even though Edward Hulburt devised the technology to send detectors via rockets already in 1929, and Herbert Friedman used it to detect solar X-rays in 1949, the true birth of the X-ray astronomy can be traced back only to 1962, when Riccardo Giacconi has imaged the first extra-solar X-ray source Scorpius (Sco) X-1, with a rocket-borne detector (see in this context Figure 1.8 and [Elvis 2020](#)). Sco X-1 was eventually recognized to be a neutron star orbiting a low-mass star in a binary system.

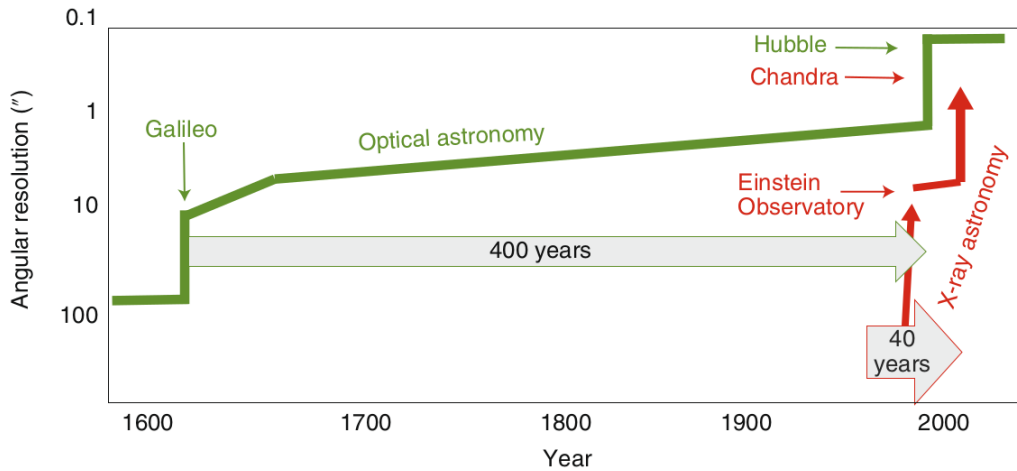


Figure 1.8: Optical telescopes (shown in green) have gradually improved their angular resolution over the last 400 years, whereas X-ray telescopes (shown in red) have only improved by 40 years. From [Elvis \(2020\)](#).

The problems in concentrating X-ray photons hinder the advancement of the X-ray astronomy and the equipment necessary for it: X-ray photons have a 1000-fold higher energy level than optical photons, so that the energy of an X-ray photon exceeds typically the binding energy of electrons in most atoms, resulting in a refractive index of less than unity. Therefore, for X-rays with incidence angles near the normal, single surface reflectivity is minimal, and X-ray telescopes must be substantially different from optical telescopes. In other words, if the X-ray equipment had the same structure as optical instruments, X-ray photons “*would pierce mirrors as a bullet would*”. To be focused, X-ray photons must strike the mirror at a grazing angle, similar to “*how bullets bounce when they strike a grazing angle wall*”. For energies up to 10 keV, the grazing angle is roughly a degree, but it decreases as the energy increases. As a result, the X-ray telescope’s point spread function (PSF) is, in general, energy-dependent.

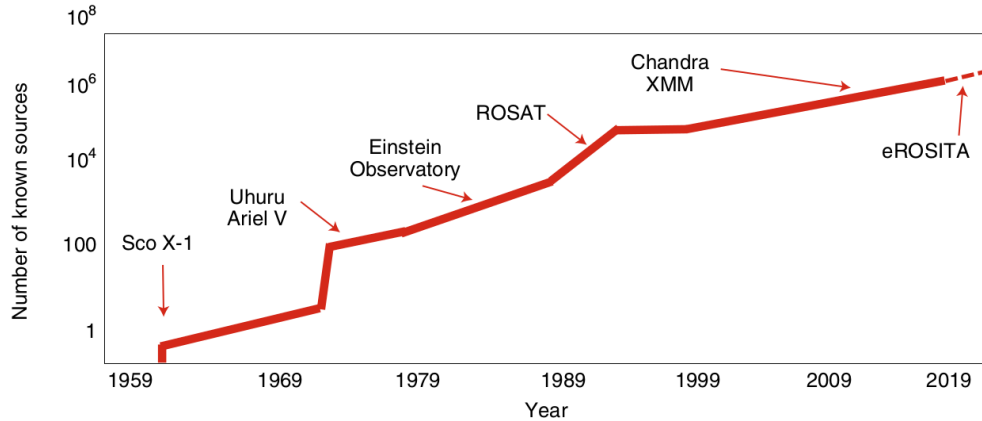


Figure 1.9: Since 1962, the number of astronomical X-ray sources has increased exponentially with each space mission. From [Elvis \(2020\)](#).

It was Hans Wolter who invented the X-ray focusing device in 1952, that used mirrors shaped like rotating conic arcs ([Wolter 1952](#)); there are three different imaging configurations described by Wolter, nowadays called the Wolter Type I, II, and III Telescopes.

At this moment, there are over six X-ray astronomy satellites circling Earth, with thirteen having completed their missions; the resulting number of known astronomical X-ray sources has increased to about 1.25 million (see Figure 1.9). Below, I'll go through some of the X-ray observatories which are currently in operation, before introducing some of the planned X-ray missions that will revolutionize the field in the near future.

1.3.1 XMM-Newton

The XMM-Newton, formerly known as the “X-ray Multi-mirror Mission”, is the X-ray space observatory launched by the European Space Agency on December 10, 1999 (see Figure 1.10). XMM-Newton is equipped with three Wolter Type I telescopes, which have a total collecting area of over 120 m², the largest among the X-ray observatories to date.³

Each mirror module is made up of 58 stacked golden plated nickel mirrors that are separated by barely a few millimeters. The telescopes' focal length is 7.5 m, and the mirrors have a diameter of 70 cm. There are three instruments on board the spacecraft. The European Photon Imaging Camera (EPIC), which is positioned at the focal point of the three telescopes, is the principal instrument. EPIC is made up of three cameras that record incoming X-ray photons while also providing imaging and spectroscopy.

³https://www.esa.int/Science_Exploration/Space_Science/XMM-Newton_factsheet

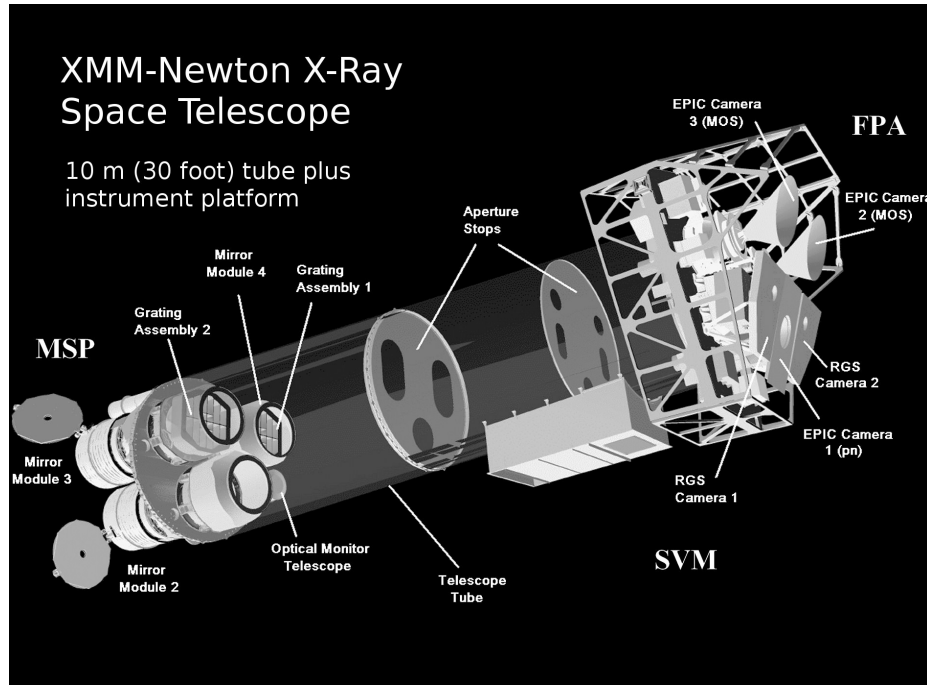


Figure 1.10: Labeled diagram of the XMM-Newton X-Ray Telescope. (Courtesy: XMM-Newton/ESA)

The EPIC cameras provide sensitive imaging with a field of view (FOV) of 30 arcmins and a spectral resolution of $E/\Delta E \simeq 20-50$ and an angular resolution of 6 arcsec FWHM throughout the energy range 0.15–15 keV. Two of the cameras utilize MOS CCDs, while the third uses a novel form of CCD detector called “PN”. The MOS detectors are at the focal point of the two telescopes, whereas the PN EPIC CCDs get an unimpeded stream of photons.

Reflection Grating Spectrometer (RGS) is the second instrument onboard the satellite, made of a grating structure on the two telescopes, with its own CCD camera. The optical monitor (OM), which is installed on the mirror platform alongside the mirror modules, is the third instrument on XMM-Newton. The center 17 arcmin^2 area of the X-ray field of vision is covered by OM’s UV/optical wavelength coverage. The devices can detect wavelengths ranging from 170 nm to 650 nm. The Digital Electronics Modules and a Telescope Module make up the XMM-OM.

The Instrument Control Unit, which is in charge of communication with the spacecraft, and the Processing Unit, which pre-processes data before sending it to the ground, are both found in the Digital Electronic Modules, which are made up of two identical units for redundancy. The telescope optics and detectors, as well as the detector processor and power supply, are all housed in the Telescope Modules.

1.3.2 Chandra

NASA launched the Chandra X-ray Observatory (CXO), formerly known as the “Advanced X-ray Astrophysics Facility” (AXAF), aboard the Space Shuttle Columbia on July 23, 1999. Despite being assigned a 5-year life expectancy, Chandra has been monitoring the Universe since then for more than 20 years.⁴

The mirrors, the scientific equipment, and the spacecraft are the three primary components of Chandra (see Figure 1.11). Chandra’s focusing mirrors are the world’s biggest, smoothest, and most precisely manufactured and aligned X-ray mirrors: *“The highest mountain on Earth would be barely two meters tall if the surface were as smooth as the Chandra mirrors!”* This allowed to achieve an angular resolution of 0.5" (on-axis).

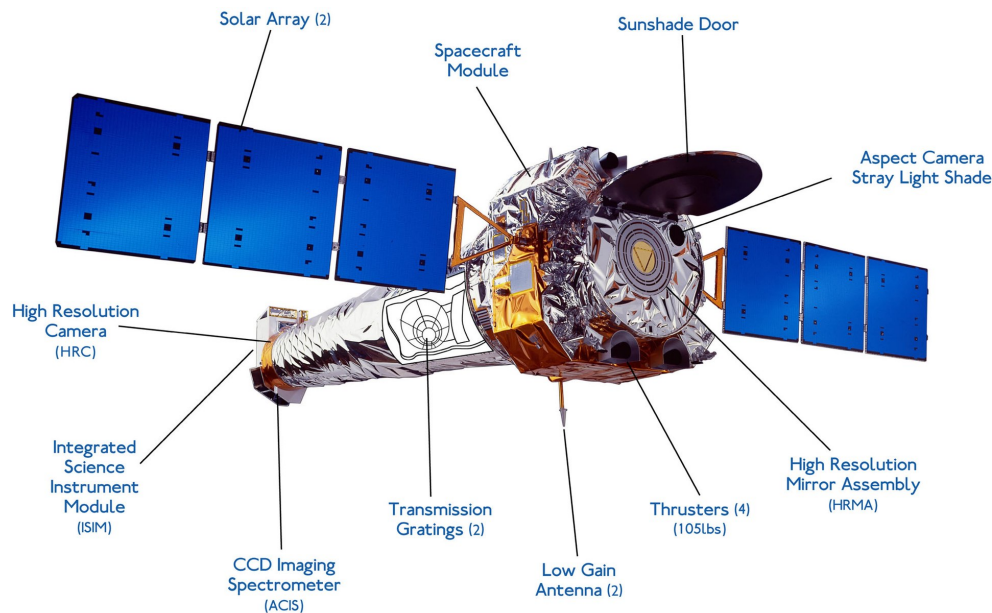


Figure 1.11: Labeled diagram of the Chandra X-ray Observatory. (Courtesy: CXC/NASA)

For the reflecting surface, the mirrors feature a 2 cm thick substrate covered with a 33 nm thick iridium layer. The thick substrate is made of Zerodur, a material chosen for its low coefficient of thermal expansion and ability to produce extremely smooth polished surfaces. The mirror must be this thick to be more stable and to avoid deformations after the launch or due to temperature fluctuations. At the same time, the substrate thickness restricts the number of stacked mirrors that can be used, resulting in a lower collecting area (when compared to XMM-Newton).

⁴<https://chandra.si.edu/about/>

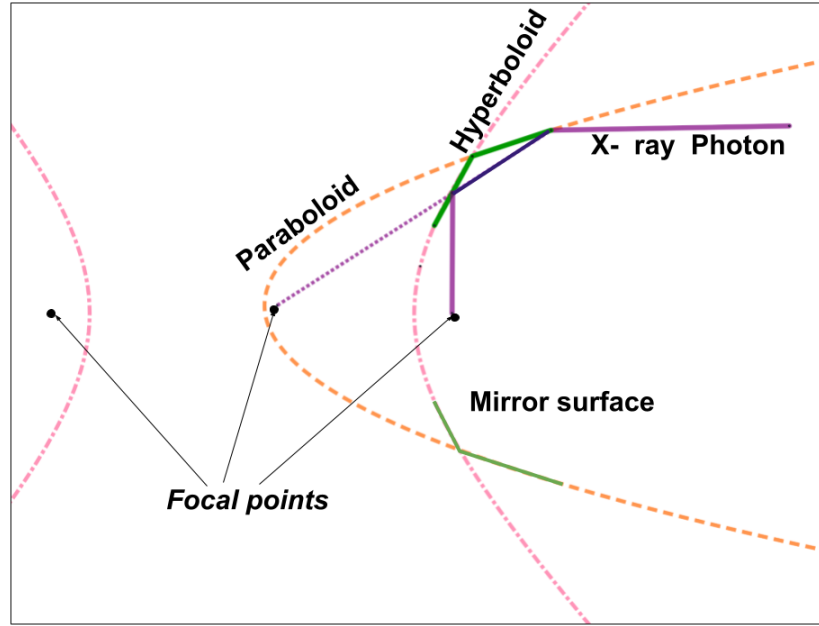


Figure 1.12: Scheme of the Wolter Type I optics.

Chandra is a Wolter Type I Telescope, in which X-ray photons are reflected by the mirrors at grazing angles (as otherwise they would either be absorbed by the matter they interact with, or pass through unreflected, instead of being focused). Although it is technically feasible to concentrate X-ray photons using solely paraboloidal mirror shells, the focal length would be too long to be practical. Four pairs of nested cylindrical paraboloids and hyperboloids with a common focal length of 10 m make up the Chandra's mirrors (see Figure 1.12). The mirror system and its supporting framework are referred to as the High-Resolution Mirror Assembly (HRMA).

The Advanced CCD Imaging Spectrometer (ACIS) and the High-Resolution Camera (HRC) are the two focal plane cameras in the Chandra scientific instrument module. ACIS is equipped with two CCD arrays that provide data on the energy and location of each detected X-ray photon. The imaging array (ACIS-I), which is designed for surveys, is made up of four CCDs (I0-I3), each with 1024×1024 pixels and placed in a 2×2 arrangement. The spectroscopic array (ACIS-S) is made up of six CCDs (S0-S5) that are placed in a 1×6 configuration and may be utilized for imaging or moderate-resolution spectroscopy with a resolving power of about $E/\Delta E \simeq 15 - 50$ over the 0.4–8 keV range.

The High-Resolution Camera (HRC) is a microchannel plate (MCP) device with two detectors, one for imaging (HRC-I) and the other (HRC-S) for reading the Low Energy Transmission Grating (LETG). On Chandra, the HRC detector has the best spatial and temporal resolution.

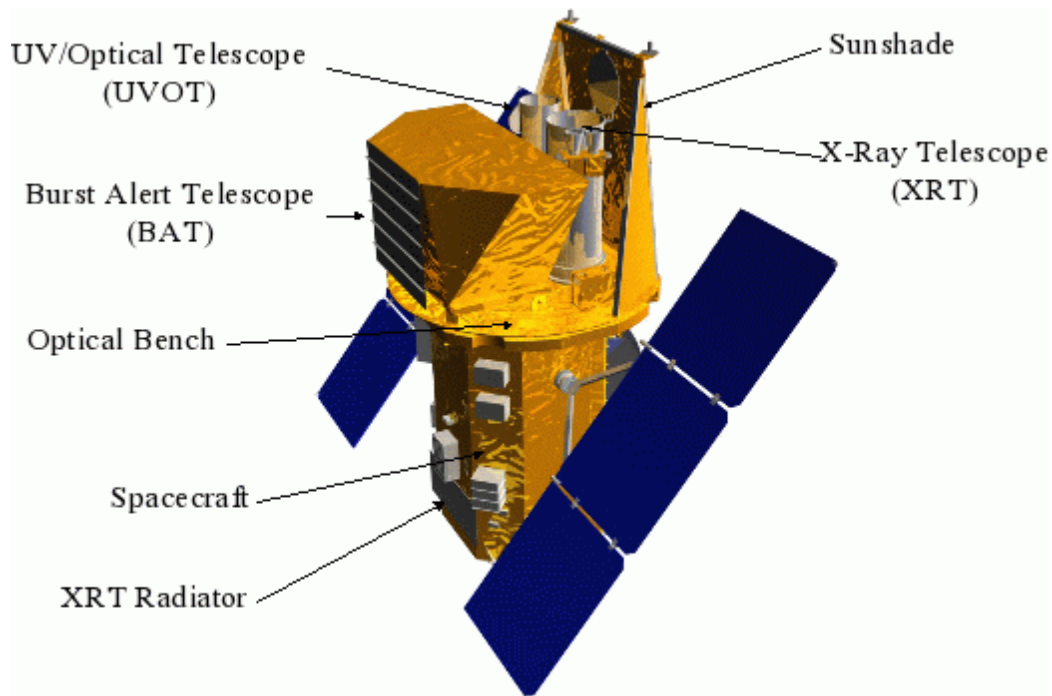


Figure 1.13: Labeled image of the Neil Gehrels Swift Observatory. (Courtesy: UK Swift Science Data Centre)

1.3.3 Swift

The Neil Gehrels Swift Observatory, formerly known as the Swift Gamma-Ray Burst Mission, is a NASA space observatory primarily designed to detect gamma-ray bursts (GRBs). It was launched by a Delta II rocket on November 20, 2004. The project was designed in a cooperative collaboration between NASA Goddard Space Flight Center and Italian Space Agency.⁵

Swift contains the following instruments onboard (see Figure 1.13):

- The Burst Alert Telescope (BAT), covering a significant portion of the 15–150 keV sky (over one steradian fully coded, three steradians partially coded; the whole sky solid angle is 4π or about 12.6 steradians). Within 15 seconds after detecting the burst, the instrument pinpoints the location of the event with an accuracy of 1–4 arcminutes. The BAT is purpose-built for Swift and employs a coded-aperture mask of 52,000 randomly arranged 5 mm lead tiles, 1 meter above a detector plane of 32,768 four mm CdZnTe hard X-ray detector tiles.

⁵https://swift.gsfc.nasa.gov/about_swift/

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- The X-ray Telescope (XRT), imaging and measuring the spectra of the targets within 0.2–10 keV photon energy range. With a typical error circle of around 2 arcseconds radius, this allows for a more exact localization of the transients. Depending on the strength of the afterglow, the XRT is also utilized to undertake long-term monitoring of GRB afterglow light-curves for days to weeks after the event. The XRT houses a Wolter Type I X-ray telescope with 12 nested mirrors that are focused on a single MOS charge-coupled device (CCD) comparable to the XMM-Newton EPIC MOS cameras.
- After Swift has slewed towards a transient, the UVOT is used to detect an optical afterglow. The UVOT provides a sub-arcsecond position and provides optical and ultra-violet photometry through lenticular filters and low resolution spectra (170–650 nm) through the use of its optical and UV grisms. The UVOT is also used to provide long-term follow-ups of GRB afterglow lightcurves. The UVOT is based on the XMM-Newton mission’s Optical Monitor (OM) instrument, with improved optics and upgraded onboard processing computers.

1.3.4 NuSTAR

NuSTAR (Nuclear Spectroscopic Telescope Array Mission) is the X-ray mission with the first *hard* X-ray focusing optics, operating in the energy range 3 – 79 keV. Launched by NASA into low-inclination low-Earth orbit on June 13, 2012, it was originally planned for a two-year mission, but it is still collecting data (see Figure 1.14).⁶

X-ray photons are focused onto two Focal Plane Module Detectors by two co-aligned Conical Wolter-I mirrors (FPMA and FPMB). 133 concentric conical multi-layer mirror shells make up the mirrors. Pt/SiC and W/Si multilayers are coated on top of thin sheets of flexible glass, with graphite spacers between nested layers. They are installed on a space-extended pole with a focal length of 10 m. Two lasers on the optics end of the telescope are aimed at three light-sensing detectors to create a metrology system. Its FoV (50% resp.) is 10° at 10 keV, and 6° at 68 keV, while the angular resolution is 58'' (HPD), and 18'' (FWHM).

The FPM detectors are rectangular Cadmium-Zinc-Telluride (CdZnTe) crystals with a dimension of 20 × 20 × 2 mm and pixels split into 32 × 32 gridded arrays. The energy Resolution (FWHM) of the detector is 400 eV at 10 keV and 900 eV at 68 keV. Cesium Iodide (CsI) crystals surround the detectors as active anti-coincidence detectors, registering and rejecting background from high-energy photons and cosmic rays arriving from off-axis.

⁶<https://www.nustar.caltech.edu/page/about>

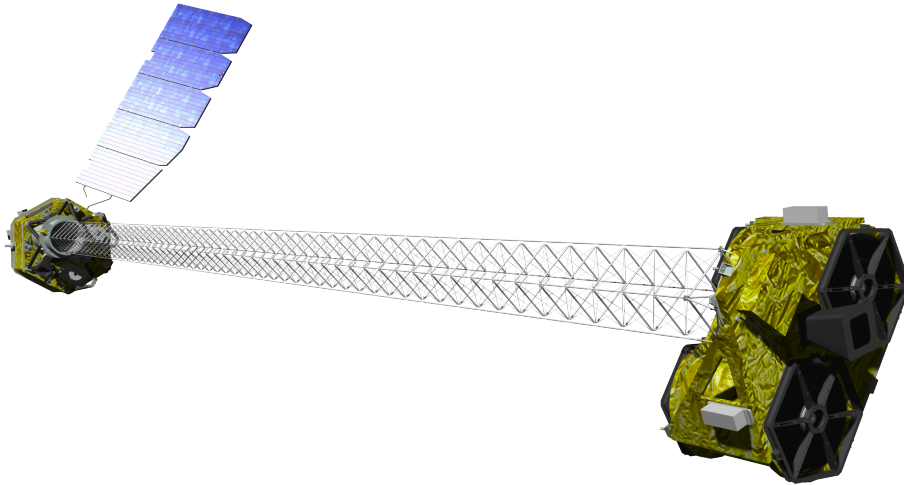


Figure 1.14: Artistic image of NuSTAR. (Courtesy: NASA)

1.3.5 AstroSat

The AstroSat project is India's first dedicated space mission. It has equipment that can view a wide range of wavelengths in the electromagnetic spectrum, including visible, near and far ultraviolet, and X-ray wavelengths. The Satish Dhawan Space Centre in Sriharikota, India, launched the satellite on September 28, 2015, into a 650 km orbit with a 6 degree equatorial inclination from the International Space Station. Early in October of 2015, the first light appeared. The initial mission plan calls for a five-year mission, but that will almost certainly be expanded.⁷

AstroSat contains a variety of astrophysical instrumentation (see Figure 1.15):

- UVIT is a pair of twin telescopes that span wavelengths between 350 and 600 nm (near UV and optical) and 130 to 300 nm (far UV).
- Large Area Xenon Proportional Counter (LAXPC) is a set of three proportional counters for hard X-rays with energies ranging from 3 to 100 keV. At a voltage of 10 keV, the combined counters have an effective area of 8000 cm².
- Soft X-ray Telescope (SXT) detects soft X-rays with energies ranging from 0.3 to 10 keV. SXT has a CCD detector with an effective area of 120 cm² at 1 keV and a set of conical foil mirrors. The CCD array is cooled to a temperature of -80°C via thermal-electric cooling.

⁷<https://www.isro.gov.in/astrosat-0>

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- Cadmium-Zinc-Telluride Imager (CZTI) for hard X-rays with energies between 10 and 100 keV. Below 100 keV, CZTI has a field of view of 6° and an effective area of 490 cm^2 . A Tantalum plate with a coded aperture mask covers the instrument's top, allowing picture reconstruction from the shading pattern. The detector is divided into four quadrants, each with 16 pixels with a cross-section of $2.5 \text{ mm} \times 2.5 \text{ mm}$ with a timing precision of 20 microseconds. CdZnTe detector elements provide a spectral precision of 0.5 keV (5%) at 10 keV.
- Scanning Sky Monitor (SSM) for sky surveys in the 2 – 10 keV energy range. Three one-dimensional position-sensitive proportional counters with coded masks are used in the SSM instrument. SSM is housed on a single platform that can be rotated to offer various angles.
- The Charge Particle Monitor (CPM) detects high-energy particles and places equipment on temporary hold in the case of severe radiation. Although AstroSat's low inclination orbit avoids the most severe regions of the South Atlantic Anomaly (SAA), it does come into contact with the SAA: CPM monitors must ramp down high voltage systems to minimize sensor damage.

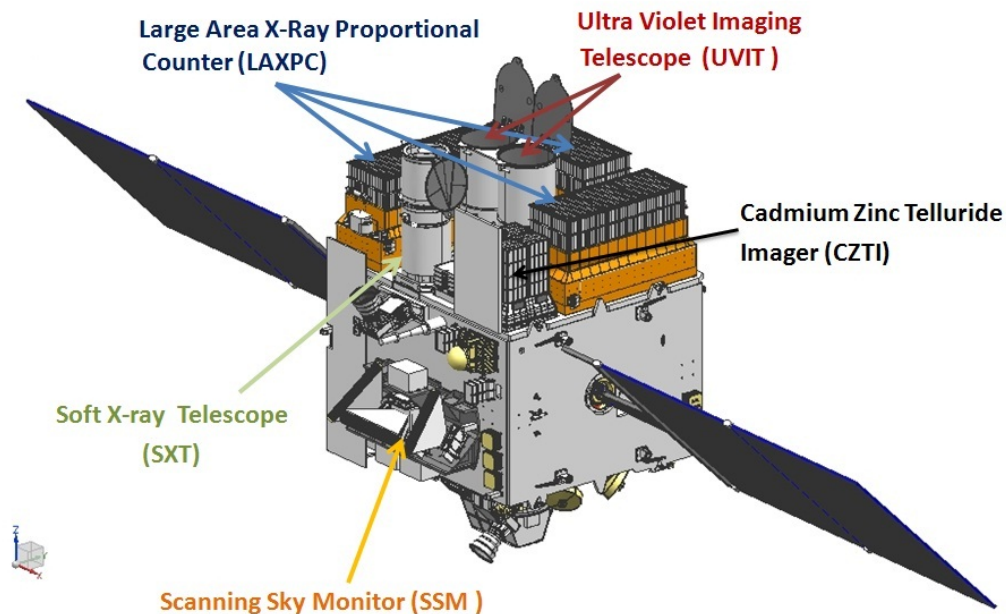


Figure 1.15: Labeled image of AstroSat. (Courtesy: ISRO/Astrosat)



Figure 1.16: Artistic image of Spektr-RG. (Courtesy: Roskosmos & DLR)

1.3.6 Spektr-RG

Spectrum-Roentgen-Gamma (Spektr-RG) is a Russian-German high-energy astrophysics mission, that was launched from Baikonur Cosmodrome on July 13, 2019 (see Figure 1.16). The sensors started the first of eight scheduled sky surveys in December 2019 after traveling to the Earth-Sun L2 Lagrange point. The mission will operate in scanning mode for four years, generating all-sky maps over six-month periods. When the survey is completed, the telescope will begin focusing on specific targets of interest. The original mission is scheduled to run for seven years.⁸

In English, the expedition is sometimes referred to as “Spectrum X-Gamma” (Spektr-RG). Despite this designation, the satellite does not have any gamma-ray sensor on-board, and the reference was kept for historical purposes only, as earlier plans for the mission included also gamma-ray detectors. There are two instruments on the Spektr-RG observatory:

- The Extended Roentgen Survey with an Imaging Telescope Array (eROSITA) equipment is made up of seven telescopes with 54 nested mirror segments that concentrate X-rays onto a CCD detector (0.2–10 keV) with an on-axis HEW of 18 arcsec. The field of view is 0.81 deg^2 , with a 138 eV energy resolution at 6 keV. The CCD design was based on the successful XMM-Newton CCD detectors, and the device and mirrors were developed by the Max Planck Institute of Extraterrestrial Physics.

⁸<https://www.mpe.mpg.de/eROSITA>

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- The Astronomical Roentgen Telescope – X-ray Concentrator (ART-XC) is likewise a nested shell design with seven telescopes, but it has fewer mirror segments (28 per telescope) and a 45 arcsecond resolution in a 36 arcminute field of view covering 5–30 keV. Each telescope has a CdTe crystal detector unit with double-side strip detectors with an effective area of 400 cm², a spectral resolution of 1.2 keV @ 14 keV, and a timing resolution of around 1 ms. The iridium-coated mirror system was designed and calibrated by NASA's Marshall Space Flight Center, and built by the Russian State Nuclear Center.

1.3.7 XRISM

The X-Ray Imaging and Spectroscopy Project (XRISM), originally known as XARM, is a joint mission between JAXA and NASA, with assistance from ESA. The mission's goal is to use high-throughput imaging and high-resolution spectroscopy to explore celestial X-ray objects throughout the Universe. XRISM (see Figure 1.17) is intended to restore and regain the majority of the science capabilities lost as a result of the Hitomi disaster, with an emphasis on the soft X-ray bands. The mission is scheduled to launch on a JAXA H-IIA rocket in the Japanese fiscal year 2022.⁹

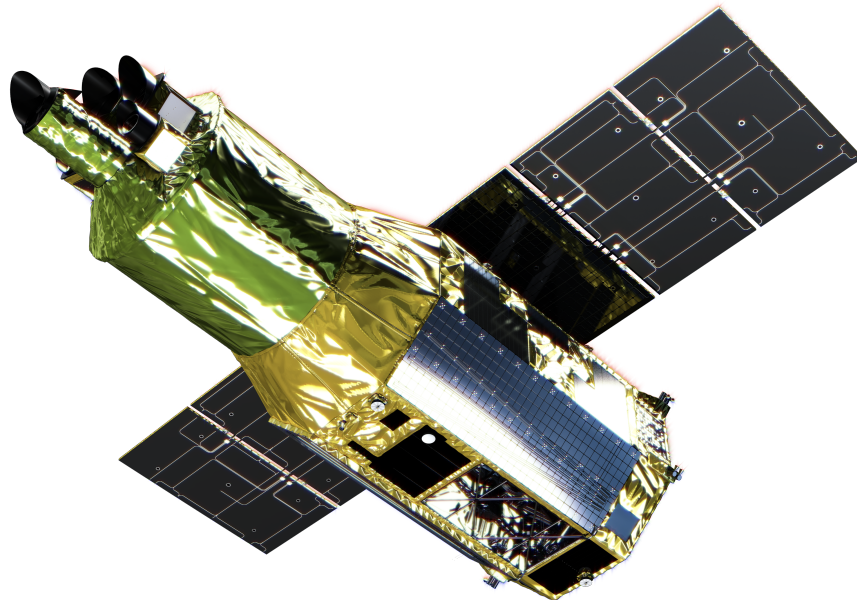


Figure 1.17: The XRISM spacecraft. (Courtesy: JAXA)

⁹<https://heasarc.gsfc.nasa.gov/docs/xrism/about/>

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Two instruments comprise the XRISM payload:

- Resolve, is a soft X-ray spectrometer that combines a lightweight X-ray Mirror Assembly (XMA) with an X-ray calorimeter spectrometer to deliver non-dispersive 5–7 eV energy resolution in the 0.3–12 keV bandpass with a FOV of roughly 3 arcmin.
- Xtend, is a soft X-ray imager that uses a similar lightweight X-ray Mirror Assembly to expand the observatory’s field of view to 38 arcmin on a side across the energy range 0.4–13 keV.

Their characteristics are identical to those of the SXS and SXI, which were flown on-board the Astro-H (Hitomi) satellite, respectively. Together with the X-ray Mirror Assemblies, NASA/GSFC develops the Resolve detection system and several of its components. The Science Data Center, which is responsible for creating analytical software for all instruments, the data processing pipeline, as well as assistance for Guest Observer (GO) Program, is also managed by NASA/GSFC.

1.3.8 Athena

Athena is the European Space Agency’s (ESA) L-class mission within the Cosmic Vision program, that will probe the Hot and Energetic Universe. It will operate in the range of 0.2–12 keV, and will provide spectroscopic and imaging capabilities exceeding the currently operating X-ray astronomy satellites by, at least, one order of magnitude on several parameters simultaneously. Athena (see Figure 1.18) will be launched into orbit at L2 in the early 2030s, designed for a 5-year mission duration.¹⁰

Athena will use the cutting-edge silicon pore optics (SPO) technology to achieve the science objectives with a 2 m² effective collecting area and a 5'' angular resolution (on-axis). Two instruments on a rotating platform will make up the focal plane. The Wide Field Imager (WFI) uses silicon DEPFET (depleted p-channel field-effect transistor) technology developed in the Max Planck Society’s semiconductor laboratory. The DEPFETs have a high energy resolution of < 170 eV (FWHM) at 7 keV, low noise, quick reading, and high temporal resolution, as well as strong radiation hardness. The equipment combines the Large Detector Array, which is designed to examine the brightest point sources of the X-ray sky with high throughput and low pile-up over a 40' × 40' FOV, with a separate Fast Detector of 80 μs resolution.

¹⁰<https://www.the-athena-x-ray-observatory.eu/>

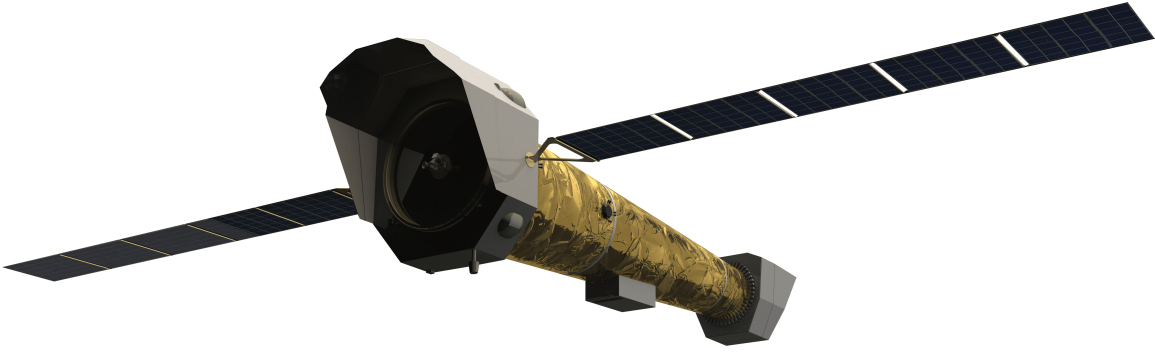


Figure 1.18: Artistic image of Athena (Courtesy: ESA)

Athena's second instrument, the cryogenic X-ray spectrometer called the 'X-ray Integral Field Unit' (X-IFU), will offer spatially resolved X-ray spectroscopy, covering an energy range of 0.2–12 keV with a spectral resolution requirement of 2.5 eV below 7 keV, and $E/\Delta E = 2800$ above 7 keV, over a hexagonal field of view of $5'$.

1.3.9 Lynx

The NASA-funded Lynx X-ray Observatory, was commissioned as part of the National Academy of Sciences 2020 Astronomy and Astrophysics Decadal Survey. Lynx has a potential to be the most powerful X-ray astronomy observatory ever built, allowing order-of-magnitude improvements in capabilities over the present Chandra X-ray Observatory and XMM-Newton space telescopes.¹¹

The Lynx X-ray Mirror Assembly (LMA) is the observatory's most important component, allowing for significant improvements in sensitivity, spectroscopic throughput, survey speed, and imaging compared to Chandra thanks to its superior off-axis performance (see in this context Figure 1.19). The Lynx design reference mission establishes a new technology known as Silicon Metashell Optics (SMO), which involves stacking thousands of extremely thin, highly polished segments of almost pure silicon into densely packed concentric shells. The SMO design is presently the most advanced in terms of demonstrated performance among the three mirror technologies evaluated for Lynx .

The Lynx X-ray Observatory is planned to have several instruments onboard. This includes the High Definition X-ray Imager (HDXI), Lynx's primary imager, offering excellent spatial resolution and sensitivity across a broad field of view (FOV) in the 0.1–10 keV bandpass with moderate energy resolution of the order ~ 100 eV. Over a $22' \times 22'$ FOV, its

¹¹www.lynxobservatory.org

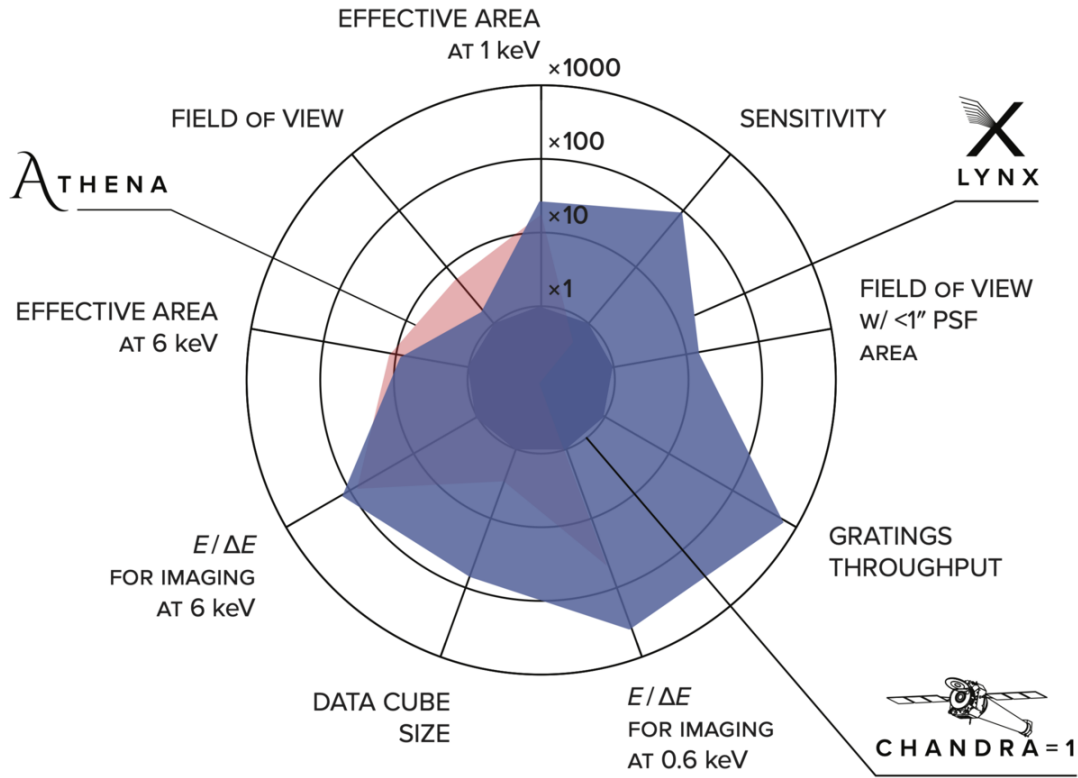


Figure 1.19: “Spider diagram” depicting the Lynx X-ray Observatory mission concept’s capabilities in comparison to the Chandra X-ray Observatory and the Athena X-ray Observatory (Gaskin et al. 2019).

$0.3''$ angular resolution will sufficiently sample the Lynx mirror point spread function. High frame rates reduce pileup and give a temporal resolution of at least $100 \mu\text{s}$. To enhance the off-axis PSF, the HDXI’s 21 separate sensors are placed out along the optimum focal surface.

The other instrument onboard, Lynx X-ray Microcalorimeter (LXM), is an imaging spectrometer that combines excellent spatial resolution (down to $0.5''$ scales) with high resolving power ($\sim 2,000$) in both the hard and soft X-ray bands over the $5' \times 5'$ FOV. The total number of pixels of this X-ray microcalorimeter surpasses 100,000, which is a significant improvement over previous and planned X-ray microcalorimeters (such as Hitomi’s SXS, or Athena’s X-IFU).

Chapter 2

Relativistic Iron Line in Broad-line Radio Quasar 4C+74.26

This chapter originally appeared as 'Signatures of the Disk–Jet Coupling in the Broad-line Radio Quasar 4C+74.26' by G. Bhatta, Ł. Stawarz, A. Markowitz, K. Balasubramaniam, et al. 2018, The Astrophysical Journal, Volume 866, Issue 2, article id. 132, 10 pp. (Bhatta et al. 2018). My contribution to the project was the X-ray spectral analysis, in particular modelling the NuSTAR spectrum of 4C+74.26 I have performed by combining the relativistic reflection model RELXILL with the warm ionized absorber model WARMABS (see Section 2.3.3).

Abstract

Here we explore the disk-jet connection in the broad-line radio quasar 4C+74.26, utilizing the results of the multiwavelength monitoring of the source. The target is unique in that its radiative output at radio wavelengths is dominated by a moderately-beamed nuclear jet, at optical frequencies by the accretion disk, and in the hard X-ray range by the disk corona. Our analysis reveals a correlation (local and global significance of 96% and 98%, respectively) between the optical and radio bands, with the disk lagging behind the jet by 250 ± 42 days. We discuss the possible explanation for this, speculating that the observed disk and the jet flux changes are generated by magnetic fluctuations originating within the innermost parts of a truncated disk, and that the lag is related to a delayed radiative response of the disk when compared with the propagation timescale of magnetic perturbations along relativistic outflow. This scenario is supported by the re-analysis of the

NuSTAR data, modelled in terms of a relativistic reflection from the disk illuminated by the coronal emission, which returns the inner disk radius $R_{\text{in}}/R_{\text{ISCO}} = 35^{+40}_{-16}$. We discuss the global energetics in the system, arguing that while the accretion proceeds at the Eddington rate, with the accretion-related bolometric luminosity $L_{\text{bol}} \sim 9 \times 10^{46} \text{ erg s}^{-1} \sim 0.2 L_{\text{Edd}}$, the jet total kinetic energy $L_{\text{j}} \sim 4 \times 10^{44} \text{ erg s}^{-1}$, inferred from the dynamical modelling of the giant radio lobes, constitutes only a small fraction of the available accretion power.

2.1 Introduction

A symbiosis between accretion disks and jets in active galactic nuclei (AGN) is one of the widely studied topics in high-energy astrophysics, crucial to our understanding of the AGN-related feedback in the evolution of galaxies and, in general, the structure formation in the Universe. The exact connection between the disk and the jet state transitions — a widely researched topic in the case of black-hole X-ray binaries (e.g. [Fender et al. 2004](#)) — in AGN has only been established so far in the broad line radio galaxies (BLRGs) 3C 111 and 3C 120, where the dips in the X-ray light curves of the accretion disk coronae are followed by the ejection of superluminal knots along pc-scale radio jets (e.g. [Marscher et al. 2002](#); [Chatterjee et al. 2009, 2011](#)).

In addition, [Tombesi et al. \(2012, 2013, 2017\)](#) presented the evidence for the presence of mildly-relativistic disk outflows in both sources, possibly related to the “X-ray dips/radio-outburst” cycles, and powerful enough to affect the surrounding interstellar medium in a feedback loop, as well as to collimate the radio jets. Any comparable characterization of the disk-jet connection in other radio galaxies, would require a long-term monitoring of particularly bright sources, for which the disk and the jet emission components are both *accessible* observationally. This, in fact, turns out exceedingly difficult in either blazars or narrow-line radio galaxies (NLRGs): in the case of blazars the Doppler boosted non-thermal jet emission mostly outshines the radiative output of accretion disks and disk coronae, whereas in NLRGs, where the jet is aligned at large angles to the line of sight, one typically deals with a severe obscuration of the central engine by hot dusty tori. This makes BLRGs the best-suited targets for investigating the disk-jet coupling, as in BLRGs the jets (at least their inner segments) are oriented only at intermediate viewing angles, which are smaller than the opening angles of obscuring tori, so that the disks and their coronae may be observed directly.

4C+74.26 (J2000.0 coordinates: R.A.=20^h42^m37^s.3 and Dec.= +75°08′02″.5), introduced by [Riley et al. \(1989\)](#), is one of the largest known radio sources associated with an active nucleus classified spectroscopically as a broad-line radio galaxy/quasar. It displays giant radio lobes of the FR II type ([Fanaroff & Riley 1974](#); [Saripalli et al. 1996](#);

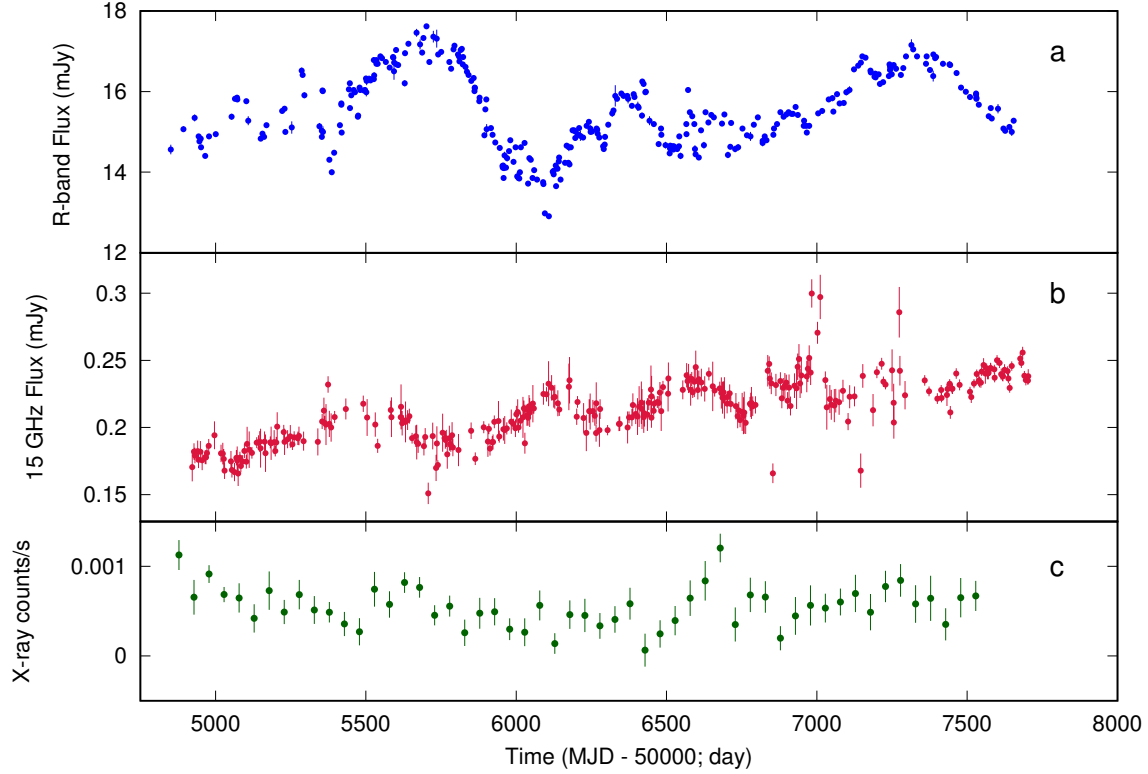


Figure 2.1: Multiwavelength long-term light curves of 4C+74.26 spanning $\sim$ eight years, and including the optical (R band) data mainly from the Suhora Observatory (upper panel a), the radio (15 GHz) data from the OVRO monitoring program (middle panel b), and the hard X-ray (14 – 50 keV) fluxes from the *Swift*-BAT Hard X-ray Transient Monitor program, weighted averaged in 50 day bins (lower panel c).

(Schoenmakers et al. 2001; Lara et al. 2001; Konar et al. 2004; Machalski 2011), with the total angular size of $\sim 10'$ at the redshift of $z = 0.104$ (Riley et al. 1989), yielding a projected linear size of ~ 1.01 Mpc for the modern cosmology. Pearson et al. (1992) first reported on the detection of the pc-scale radio jet in the source, and of the radio core with an inverted (i.e., self-absorbed) spectrum. Since no evidence for the counter-jet was found in the radio maps, and assuming that the jet-counterjet asymmetry is attributed solely to the Doppler beaming effect, an upper limit to the angle between the axis of the nuclear jet and the line of sight can be estimated as $\leq 49^\circ$. The jet can be followed up to hundreds-of-kpc scales in the Very Large Array (VLA) radio maps (Riley & Warner 1990), terminating in a strongly polarized and particularly X-ray-luminous hotspot (Erlund et al. 2007, 2010; Araudo et al. 2015). The total and the core luminosities of 4C+74.26 at 1.4 GHz are $P_{\text{tot}} = 10^{25.67} \text{ W Hz}^{-1}$ and $P_{\text{core}} = 10^{24.72} \text{ W Hz}^{-1}$, respectively (Kuźmicz & Jamroz 2012).

At X-ray frequencies, the source has been monitored by many instruments since 1993. In particular, Advanced Satellite for Cosmology and Astrophysics (ASCA), ROentgen SATellite (ROSAT), and *BeppoSAX* spectra revealed a power-law component with the photon index $\Gamma_X \sim 2$ and a neutral iron line with an equivalent width (EW) of ~ 100 eV, Compton reflection, and indications of a warm absorber (e.g. [Brinkmann et al. 1998](#); [Sambruna et al. 1999](#); [Reeves & Turner 2000](#); [Komossa & Meerschweinchen 2000](#); [Hasenkopf et al. 2002](#)). [Ballantyne & Fabian \(2005\)](#) reported on the analysis of the complex *XMM-Newton* spectrum of the source, consisting of the emissions from ionised and neutral reflectors, cold and warm absorbers, and the broad neutral iron line. [Larsson et al. \(2008\)](#), [Fukazawa et al. \(2011b\)](#) and [Patrick et al. \(2012b\)](#), based on the *Suzaku* data analysis, confirmed the presence of the iron line, but with an EW of only < 100 eV. On the other hand, [Gofford et al. \(2013\)](#) and [Tombesi et al. \(2014\)](#) claimed the detection of the iron line at 6.5 keV, suggestive of a mildly-ionized reflector instead of a neutral one, as well as a marginal detection of blue-shifted narrow absorption lines indicative of highly-ionized warm absorber. We note in this context that, in the optical range, [Robinson et al. \(1999\)](#) found the variations in the degree and the position angle of the polarized $H\alpha$ line, implying high-speed ($\geq 0.01c$) outflows along the 4C +74.26 jet.

More recently, [Di Gesu & Costantini \(2016\)](#), using the *XMM-Newton* and *Chandra* grating spectroscopy, confirmed the presence of a warm absorber in the source with outflow velocities $\sim 0.01c$. Also, [Lohfink et al. \(2017\)](#), based on the NuSTAR broad-band observations, confirmed the presence of the ionized reflection, and concluded that the disk is mildly recessed with an inner radius of $\sim$ ten times the gravitational radius.

So far, 4C +74.26 has not been detected in high-energy γ -rays with the Large Area Telescope (LAT) onboard the *Fermi* satellite ([Kataoka et al. 2011](#)), unlike the two other aforementioned BLRGs 3C 111 and 3C 120 (see [Grandi et al. 2012](#); [Tanaka et al. 2015](#), respectively).

In this paper, we report on the systematical analysis of the optical, radio, and hard X-ray monitoring data for 4C +74.26 (see Section 2.2 below for the description of the instrument used, as well as of the corresponding data acquisition and data processing). Based on the discrete correlation function and the power spectral analysis, we found that the optical (disk) emission in the source lags behind the radio (jet) emission by about 250 days (see Section 2.3). We discuss the possible explanation for this lag relying on the truncated disk model (Section 2.4), as supported by the re-analysis of the NuSTAR data. Throughout the paper we assume the modern cosmology with $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$, so that the luminosity distance of the source is $d_L = 459 \text{ Mpc}$, and 1 arcsec corresponds to 1.829 kpc.

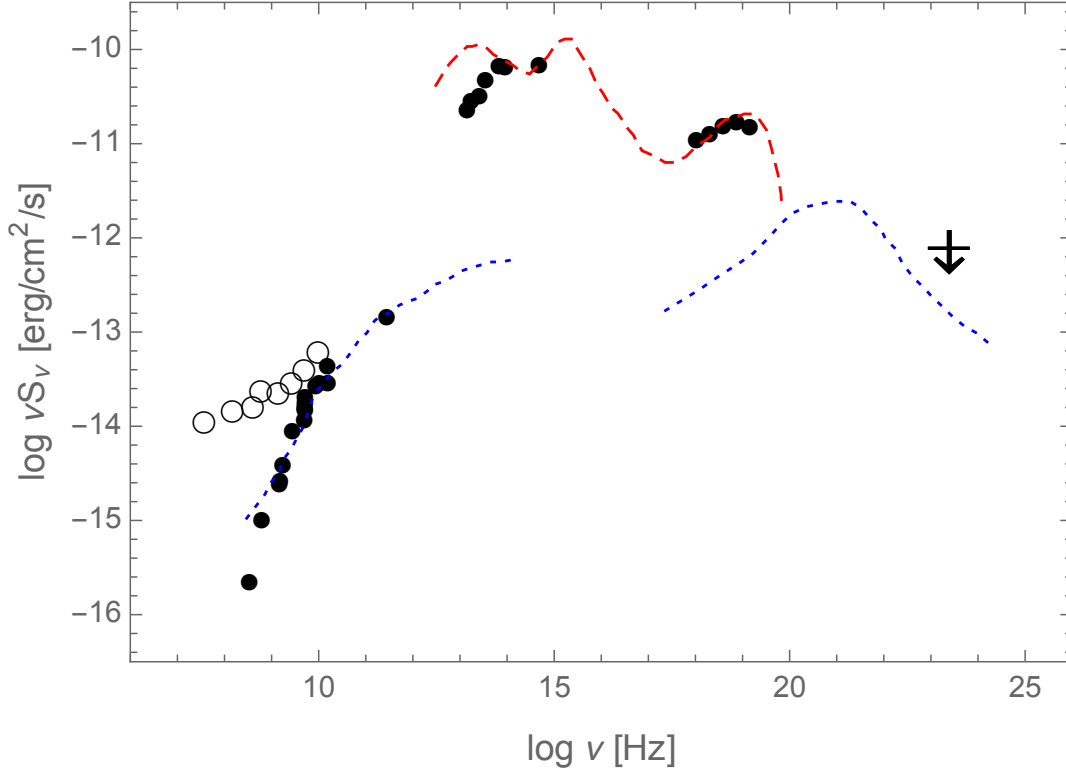


Figure 2.2: Broad-band SED of 4C+74.26 (see Section 2.2.3 for the description of the multifrequency data included in the figure). The core fluxes are denoted by black filled circles, and the total radio fluxes by empty circles. We matched the SED datapoints with the normalized “accretion-related” quasar template from [Koratkar & Blaes \(1999\)](#), (red long-dashed curve), and the “jet-related” 3C 273 template from [Soldi et al. \(2008\)](#), (blue short-dashed curve).

2.2 Observations and Data Processing

2.2.1 Monitoring data

Since 2006, we have been performing a long-term monitoring program of radio-loud AGN, initially focused at measuring the brightness of OJ 287 in the optical band. Observations were carried out at the Mt. Suhora Observatory of the Pedagogical University in Kraków, and at the Astronomical Observatory of the Jagiellonian University. Since 2009, we appended the list of targets with a sample of eight radio quasars described in Zola et al. (SSC2015). The measurements at Mt. Suhora were done with the 60-cm telescope and an Apogee CCD, mounted in the prime focus. A smaller, 50-cm telescope with an Andor CCD was used at the Jagiellonian University Observatory. Both telescopes are equipped with sets of wide band UBVRI filters purchased from the same manufacturer and made

according to the [Bessell \(1990\)](#) prescription. In addition, during the prolonged periods of cloudy weather at the two sites, data were also taken with the 14" robotic telescope at the Dark Sky Observatory, Appalachian State University, NC, USA. Since the sample of QSOs consists of objects with the brightness in the range between 12 and 16.5 magnitude (R filter), we decided to measure the targets in the R filter to maximize the S/N, due to the highest sensitivity of the back illuminated CCD chips at the red wavelengths.

We took several individual images of 4C+74.26 every few nights, along with the calibration images (bias, dark, and flat field, usually on the sky). On several occasions, multicolor data (BVRI) were also taken but since they are scarce, we did not use them for the purpose of this paper. The reduction was done by a single person to ensure results as uniform as possible; also, the same stars were used during the entire observing campaign and for all three sites as a comparison (GSC0103002595) and check (GSC0103002595) calibrators. We noticed no systematic shifts larger than 0.01 magnitude in the mean magnitude differences between comparison and check stars among the three sites over the entire period of monitoring. Therefore, all the measurements we took were simply combined.

The radio data for the target utilized in this paper, were taken from the 15 GHz monitoring performed with the 40-m telescope at the Owens Valley Radio Observatory (OVRO; [Richards et al. 2011a](#)).

The 14–50 keV data were taken from the Hard X-ray Transient Monitor program¹ ([Krimm et al. 2013](#)), conducted with the Burst Alert Telescope (BAT; [Barthelmy et al. 2005](#)) onboard the *Swift* satellite ([Gehrels et al. 2004](#)). Due to a relatively low flux level of the source, resulting in large errors as well as occasionally negative count rates in daily bins, the daily data with zero data flag were selected and binned in 50-day bins using error weighted mean, and in 100-day bin for the cross-correlation study.

The resulting long-term light curves of 4C+74.26 in the optical, radio, and hard X-ray bands, spanning nearly eight years of the monitoring, are shown in Figure 2.1. Note a very different angular resolution of the instruments utilized here: while our optical telescopes are characterised by point spread functions (PSF) of about $\gtrsim 2''$, the 40 m OVRO antenna at 15 GHz has a beam size of $\gtrsim 1'$, and the *Swift*-BAT PSF is $\sim 17'$. Still, keeping in mind the timescales covered in our monitoring program (from weeks up to $\sim$ eight years), any variability observed at optical, radio, and X-ray photon energy ranges, is expected to originate in the AGN itself, including the inner parts of the accretion disk, and the (sub)pc-scale jet.

¹<https://swift.gsfc.nasa.gov/results/transients>

2.2.2 NuSTAR Observations

Nuclear Spectroscopic Telescope Array (*NuSTAR*), a space-bound instrument operating in the hard X-ray band (3–79 keV) with the spectral resolution of ~ 1 keV, is perfectly suited for detailed spectral studies of accreting black holes. It consists of the two co-aligned focal plane modules, FPMA and FPMB, each with the field of view of ~ 13 arcmins, and the half-power diameter of an image of a point source of ~ 1 arcmin (see [Harrison et al. 2013](#), for more details). The archival NuSTAR data for 4C+74.26 were processed using the `nupipeline` script from the NuSTAR Data Analysis Software (NuSTARDAS) package v.1.3.1. The cleaned event files were generated using the NuSTAR CALDB calibration files. The data were extracted from a region of 50 arcsec radius, centered on the source, while the background was extracted from a 100 arcsec radius region near the source location containing no other sources. The FPMA and FPMB light curves and the spectral files were obtained using the tasks `nuproducts`. The spectra were binned using `grppha` in order to have at least 30 counts per re-binned channel, and the spectral fitting was performed in XSPEC² version 12.10.0 ([Arnaud 1996](#)).

Table 2.1:: Multifrequency Discrete Correlation Analysis

Bands	DCF value	Time lag (day)	Local sig. (%)	Global sig. (%)
Optical–Radio	0.42 ± 0.04	$+250 \pm 42$	96	98
X-ray–Optical	0.36 ± 0.11	-105 ± 58	89	87
X-ray–Radio	0.24 ± 0.10	$+210 \pm 61$	77	76

2.2.3 Broadband Spectral Energy Distribution

For inspecting the broad-band spectral energy distribution (SED) of the source 4C+74.26, in addition to the optical R-band, radio 15 GHz, and the NuSTAR data described above, we have also gathered the multifrequency observations at other radio frequencies from various previous studies as listed in Table 1 of (including the core and also the total fluxes; Zola et al. SSC2015), at infrared frequencies from [Matsuta et al. \(2012\)](#) and [Ichikawa et al. \(2017\)](#), as well as the *Fermi*-LAT upper limits derived in [Kataoka et al. \(2011\)](#). The resulting SED is presented in Figure 2.2.

²<https://heasarc.gsfc.nasa.gov/xanadu/xspec>

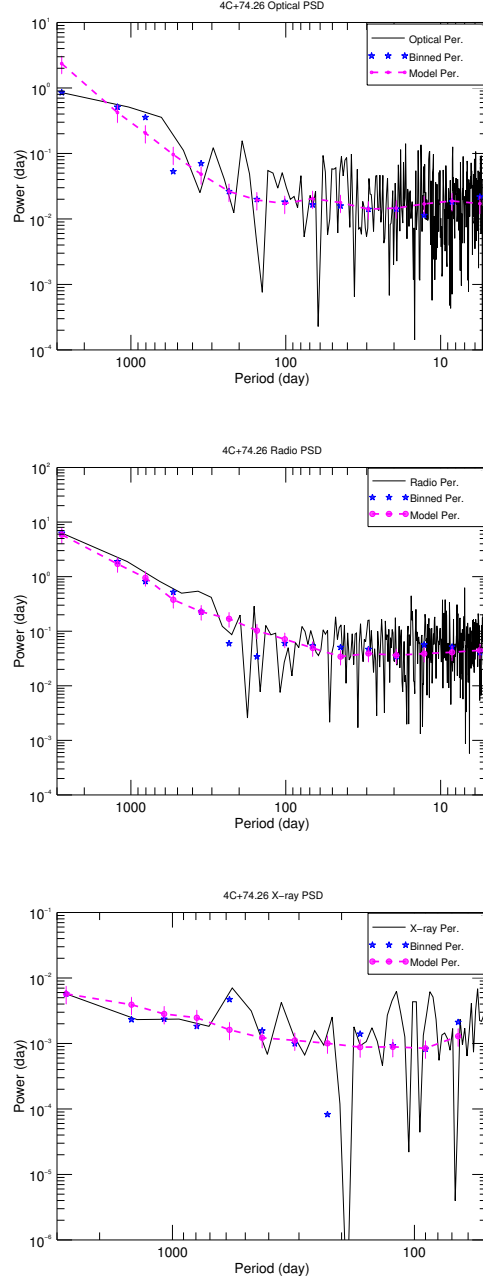


Figure 2.3: The unbinned (black curve) and binned (blue stars) periodograms for the optical, radio and hard X-ray light curves of 4C+74.26 are shown in the top, middle, and bottom panels, respectively. The corresponding magenta curves represent the reference models with the spectral slopes $\beta = 1.6 \pm 0.2$ (optical), 1.4 ± 0.1 (radio) and 0.9 ± 0.2 (X-ray), along with the associated errors estimated as 1σ deviations of the distribution in the simulated periodograms at a given frequency.

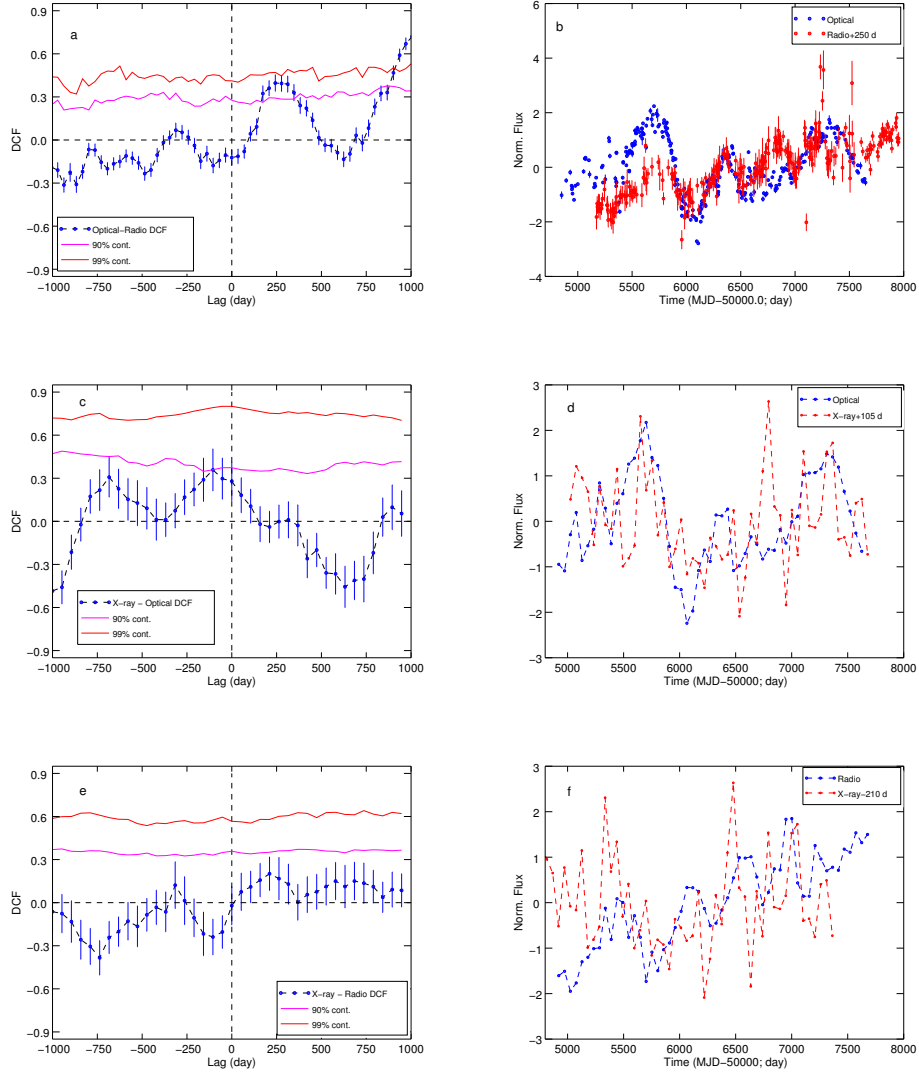


Figure 2.4: Multifrequency correlations of 4C+74.26. In the left panels, the DCFs between the optical and the radio (panel ‘a’), the X-ray and the optical (panel ‘c’), and the X-ray and the radio (panel ‘e’) light curves are shown with blue symbols. Here positive lag indicate the hard lag. The magenta and red curves in the left panels denote the 90% and the 99% local significance levels, respectively, calculated from the distributions of the DCFs between the simulated red-noise light curves (see Section 2.3.1). Right panels show the corresponding normalized light curves shifted by the most prominent time lags emerging from the DCF analysis, and in particular the radio lightcurve shifted by +250 d (panel ‘b’), the X-ray lightcurve by +105 d (panel ‘d’), and finally the X-ray lightcurve by –210 d (panel ‘f’).

2.3 Analysis

2.3.1 Power Spectral Density

In order to test the significance of the correlations between the optical, radio, and X-ray flux changes in 4C+74.26, using a robust statistical tool involving Monte Carlo simulations, first of all the variability of the target has to be quantified with the Power Spectral Density (PSD). It should be pointed out that, in general, AGN continuum variability at various frequencies has been established – using various techniques and methods – to be of a colored noise type (see in this context, e.g., [Markowitz et al. 2003](#); [Chatterjee et al. 2008](#); [Kelly et al. 2009, 2011](#); [Kastendieck et al. 2011](#); [Edelson et al. 2013](#); [Sobolewska et al. 2014](#); [Bhatta et al. 2016a](#); [Bhatta 2017](#); [Abdalla et al. 2017](#); [Ahnen et al. 2017](#); [Goyal et al. 2017, 2018](#)). Here, for the given source light curves, we therefore modelled the PSDs as single power-laws plus constant components corresponding to the Poisson noise levels, $P_f = A f^{-\beta} + \text{const}$, where f denotes the temporal frequency. The details of the Discrete Fourier Periodogram modeling, involving extensive simulations to estimate the best-fit power-law model following the method described in [Uttley et al. \(2002\)](#), can be found in [Bhatta et al. \(2016b,a\)](#). Figure 2.3 presents the periodograms and the corresponding PSD best-fit models with spectral slopes $\beta = 1.6 \pm 0.2, 1.4 \pm 0.1$ and 0.9 ± 0.2 for the optical, radio and X-ray PSDs, respectively.

2.3.2 Discrete Correlation Function

The discrete cross-correlation function (DCF) is one of the widely used methods to estimate cross correlations between unevenly sampled light curves of astrophysical sources ([Edelson & Krolik 1988](#); see also [Bhatta et al. 2018](#)). In the case of 4C+74.26, we evaluated the DCFs between the optical and the radio, the X-ray and the optical, and the X-ray and the radio flux changes. The left panels (a, c, and e) in Figure 2.4 present the resulting DCFs, while the right panels (b, d, and f) show the corresponding normalized light curves shifted by the most prominent time lag, for illustration. The significance of the DCF peaks was estimated using a large number of simulated light curves based on the PSD analysis discussed in Section 2.3.1. In particular, for the best-fit PSD parameters, 10,000 simulated light curves were generated in each frequency band (i.e., X-ray, optical, and radio bands) and sampled according to the corresponding observations. Subsequently DCF analysis was performed between the pairs of the simulated light curves. From the resulting distribution of the DCFs, local 90% and 99% significance contours, denoted respectively by the magenta and the red curves in the figure (left panels), were estimated (see [Max-Moerbeck et al. 2014](#); [Aleksić et al. 2015](#)).

The uncertainty in the observed lags were estimated using the flux randomization subset selection (FR/RSS) method (see [Peterson et al. 1998](#), and also [Bell et al. 2011](#)): from the original light curves, 10,000 random subsets containing only 63% of the total observations were selected, and the distributions of the peak DCFs were obtained; the standard deviation of this distribution of the lags corresponding to the peak DCFs was adopted as the measure of the lag uncertainty.

As shown in Figure 2.4 and summarized in Table 2.1, the optical and the radio light curves of 4C+74.26 are correlated with the time lag of $\sim 250 \pm 42$ d at the 96% significance level, even though the largest significant DCF value is only ~ 0.4 . In addition to the aforementioned local significance, we also evaluated a *global significance* of the observed lag to be 98%. Global significance accounts for the fact that, while searching the correlations over a wide range of time lags, we do not have a priori knowledge of what significance lag would emerge out from the analysis ([Bell et al. 2011](#), see also [Bhatta 2017](#)). Using the distribution of the simulated DCFs between optical and the radio frequency, global significance was estimated as a fraction of the DCFs below the observed local significance level i.e. the 96% level, at all the lags considered. It is therefore very likely that here we do see, for the first time in any AGN, a direct relation between the disk and the jet emission components, although the fact that radio (jet) leads the optical (disk) may seem counter-intuitive at first. We address this point in more detail in Section 2.4 below.

It should be pointed out that, as seen in the Figure 4a, the correlation coefficient between the two light curves appears to be the largest near +1,000 d. However, such seemingly strong correlations appearing in the DCF diagrams at the lags larger than $\sim$ half the duration of a given light curve, should be treated with extreme caution in the case of a coloured-noise type of a source variability, as for such the largest-amplitude flux changes expected on the longest timescales can introduce false correlation “trends” (e.g., [Press 1978](#); [Max-Moerbeck et al. 2014](#)). And in general, for larger and larger lags the number of pairs of the light curve data points become smaller and smaller, and this may also lead to spurious peaks in the DCF diagrams.

Unfortunately, the variability seen in hard X-ray band by *Swift*-BAT turns out heavily dominated by the Poisson noise on short (daily/weekly) timescales, and therefore we had to use the 100 d bins when correlating it with the optical and the radio light curves. With such, the resulting correlation time lags are detected at the local significance levels of only $< 90\%$.

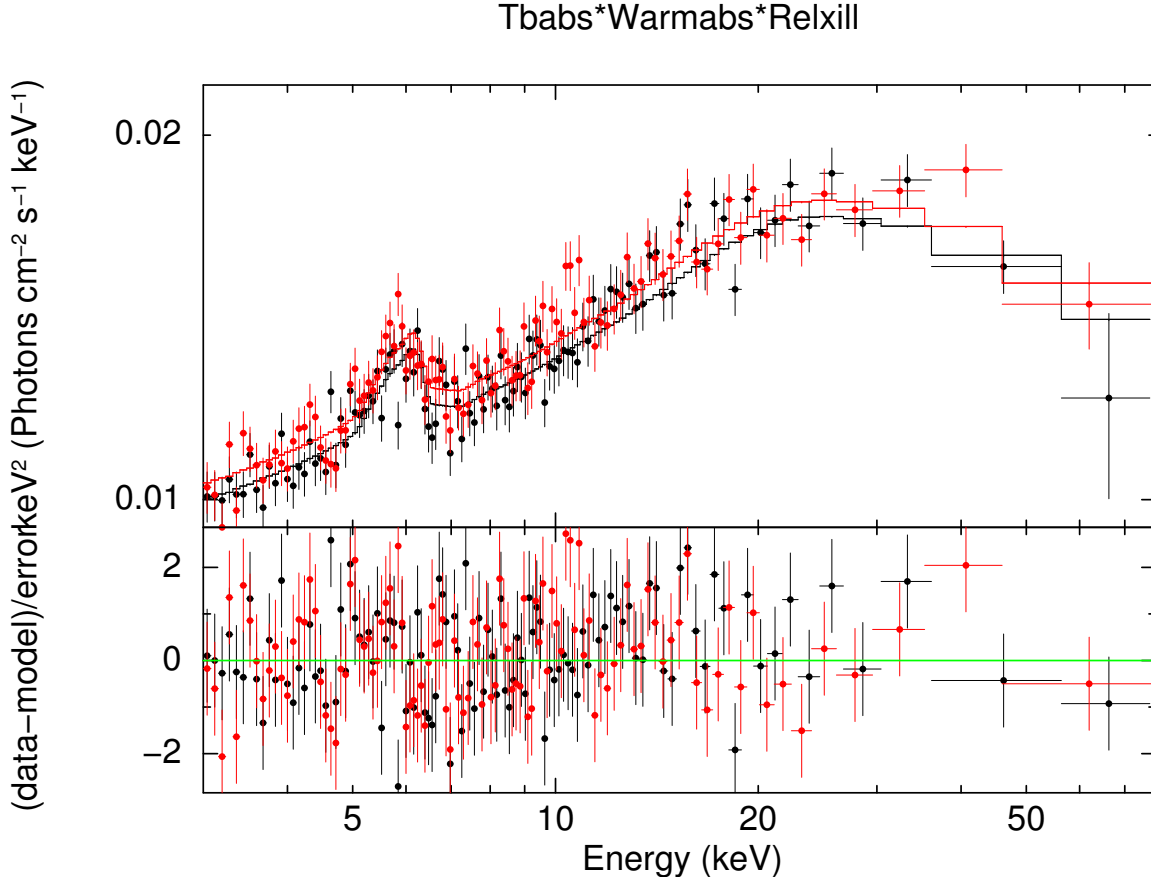


Figure 2.5: Spectral modeling of the NuSTAR data for 4C+74.26 (obs. ID 60001080006, 2014-10-30), assuming the convolved model `tbabs*warmabs*relxill` (upper panel), with the corresponding residuals (lower panel). For the model description and the best-fit model parameters see Section 2.3.3. Red and black symbols/curves correspond to the NuSTAR modules FPMA and FPMB.

2.3.3 X-ray Spectral Analysis

An in-depth analysis of the rich X-ray dataset for 4C+74.26, using the most recent observations with *XMM-Newton*, *Chandra*, and NuSTAR, has been reported by [Di Gesu & Costantini \(2016\)](#) and [Lohfink et al. \(2017\)](#). Here we re-analyze the NuSTAR data for the target in the hard X-ray regime, focusing predominantly on the characterization of the main parameters of the underlying accretion disk, in particular its inner radius, in the context of the multi-wavelength correlation studies reported in the previous Section 2.3.2.

4C+74.26 has been observed with NuSTAR four times between September 2014 and December 2014. Because of the source variability seen in the *Swift*-BAT light curve, for our spectral analysis we have selected only the longest NuSTAR exposure of 90.925 ks

(obs. ID 60001080006, 2014-10-30), and fitted simultaneously the FPMA and FPMB spectra with the XSPEC (Arnaud 1996). We used the latest update of the RELXILL [v1.0.2] model³, which convolves the XILLVER reflection code with the RELLINE code (Dauser et al. 2013), providing as such an accurate prescription for a reflection from a Compton-thick disk illuminated by a coronal power-law continuum, with a good treatment of strong gravity effects near the event horizon of a supermassive black hole (for details see García & Kallman 2010; García et al. 2013). In addition, in order to account for the presence of a warm absorber in the source (e.g. Di Gesu & Costantini 2016), as well as the Galactic absorption, we combined RELXILL with the TBABS (Wilms et al. 2000) and WARMABS models.

Guided by the previous studies reported in the literature, in the modelling we fixed the Galactic column density at $N_{\text{H,Gal}} = 2.31 \times 10^{21} \text{ cm}^{-2}$ (see Di Gesu & Costantini 2016). For the single-zone warm absorber with the outflow velocity of 3600 km s^{-1} , we assumed the column density $N_{\text{H,wa}} = 3.5 \times 10^{21} \text{ cm}^{-2}$, the ionization parameter $\log \xi_{\text{wa}} = 2.6$, and the turbulent velocity $v_{\text{turb}} = 100 \text{ km s}^{-1}$ (Di Gesu & Costantini 2016). For the coronal component and the accretion disk itself in the XILLVER model, we assumed the emissivity indices $\text{Index}_1 = \text{Index}_2 = 3$, the outer disk radius $R_{\text{out}}/R_{\text{g}} = 10^3$ (where R_{g} is the gravitational radius), the inclination $i = 45 \text{ deg}$, and the solar iron abundance $A_{\text{Fe}} = 1$; following Lohfink et al. (2017), we also fixed the cut-off energy as $E_{\text{cut}} = 180 \text{ keV}$, and considered only the maximum spin of the supermassive black hole, namely $a = 0.998$. The remaining model free parameters are the inner disk radius R_{in} , the power-law index of the incident spectrum Γ , the ionization of the accretion disk ξ , the reflection fraction R_{f} , and the normalization.

Our best-fit model ($\chi^2/\text{dof} = 0.99$), presented in Figure 2.5, returns $R_{\text{in}}/R_{\text{ISCO}} = 35 \pm 22$, where R_{ISCO} stands for the innermost stable circular orbit, $\Gamma = 1.83 \pm 0.02$, $\log \xi = 2.47 \pm 0.17$, and $R_{\text{f}} = 0.49 \pm 0.07$. In order to estimate even more robustly the model free parameters of our main interest, we studied the $\log \xi - R_{\text{in}}$, $R_{\text{f}} - R_{\text{in}}$, and $\log \xi - R_{\text{f}}$ confidence contours (Figure 2.6), obtaining the 3σ bounds $R_{\text{in}}/R_{\text{ISCO}} = 35_{-16}^{+40}$, $\log \xi = 2.47_{-0.19}^{+0.17}$, and $R_{\text{f}} = 0.44_{-0.09}^{+1.3}$. This implies that the accretion disk in 4C+74.26 is indeed most likely truncated at the radius of about a few tens of the ISCO; note that for the maximum black hole spin assumed here, $R_{\text{ISCO}} \simeq R_{\text{g}}$.

³<http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/>

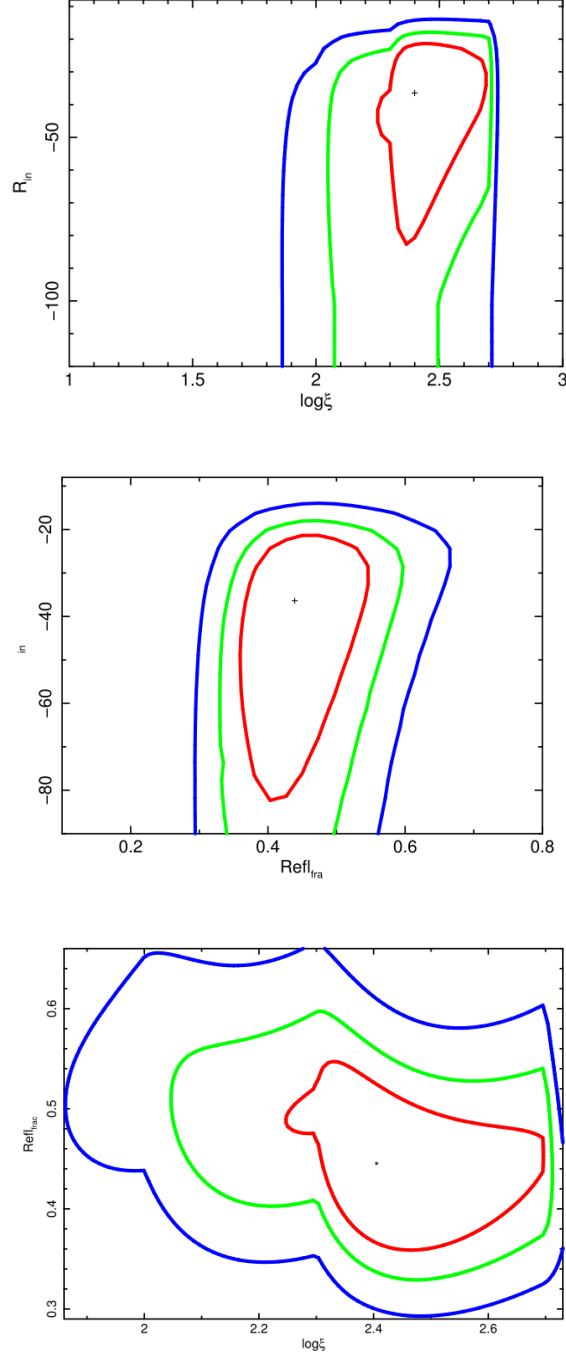


Figure 2.6: Confidence contours (see Section 2.3.3) for $\log \xi - R_{\text{in}}$ (upper panel), $R_f - R_{\text{in}}$ (middle panel), and $\log \xi - R_f$ (lower panel); red, green, and blue curves represent 1, 2, and 3σ contours respectively. The negative sign seen in the figure indicates that R_{in} is expressed in the units of R_{ISCO} , according to the nomenclature adopted in the `XILLVER` model.

2.4 Discussion and Conclusion

In the current work, with an aim to explore the disk-jet connection in AGN, we performed a multi-frequency study of 4C+74.26 using multifarious methods, including the broad-band spectral energy distribution modelling, the variability power spectral density analysis, the discrete cross-correlation of the multi-wavelength light curves of the source, and the detailed X-ray spectroscopy enabled by the high-quality and broad-band NuSTAR data.

A comparison of the source broad-band SED with those of other broad-line radio galaxies and radio-loud quasars compiled and analyzed by [Kataoka et al. \(2011\)](#), indicates that, in the case of 4C+74.26, the observed infrared-to-X-ray continuum could not be accounted by a non-thermal jet emission, but instead has to be accretion-related, including the direct disk emission component (optical frequencies), plus the disk emission re-processed by the circumnuclear dusty torus (infrared) and the disk corona (X-rays). This is illustrated in Figure 2.2 by matching the SED datapoints with the normalized “accretion-related” quasar template from [Koratkar & Blaes \(1999\)](#), red long-dashed curve), and the “jet-related” 3C 273 template from [Soldi et al. \(2008\)](#), blue short-dashed curve).

For a comparison with our PSD results, we note that PSDs of nearby radio-quiet Seyferts have been investigated extensively at X-ray (1 – 10 keV) frequencies during the last two decades. In the frequency range $10^{-8} - 10^{-3}$ Hz (timescales from years to hours), these PSDs are typically modelled by a broken power-law model $P(f) \propto f^{-\beta_L}$ or $f^{-\beta_H}$ below or above a break frequency f_0 , respectively; f_0 typically corresponds to timescales of hours–days, β_L is typically ≤ 1 , and β_H is typically $\sim 2 - 3$, with the timing properties showing strong similarities to those of black hole X-ray Binaries (see, e.g., [Uttley et al. 2002](#); [Markowitz et al. 2003](#)). These include the X-ray PSDs of several radio-loud but non-blazar AGN, in particular 3C 390.3 and 3C 120 ([Gliozzi et al. 2009](#); [Marshall et al. 2009](#)).⁴ The *Swift*/BAT (10–150 keV) lightcurves of Seyfert galaxies analyzed by [Shimizu & Mushotzky \(2013\)](#) also yielded flat PSD power-law slopes, $\beta_L \lesssim 1$, at timescales longer than days/weeks. Regarding optical-band AGN PSDs, *Kepler* monitoring of several radio quiet AGN has revealed steep power-law slopes ~ 3 over the range $10^{-7} - 10^{-5}$ Hz ([Mushotzky et al. 2011](#)). On the other hand, optical PSDs of several radio-loud AGN also based on *Kepler* data are consistent with somewhat flatter power-law forms with indices $\lesssim 2.0$ ([Wehrle et al. 2013](#); [Revalski et al. 2014](#)).

A cross-correlation study between the long-term optical (R-band) and the higher-frequency radio (15 GHz) light curves of the broad-line radio galaxy/quasar 4C +74.26, indicates that the radio (jet) emission leads the optical (disk) emission by $\sim 200 - 300$ days.

⁴For a summary of multi-wavelength PSD analysis for blazar sources, see [Goyal et al. \(2017, 2018\)](#) and references therein.

This seems counter-intuitive at first, since one could expect that any changes in the accretion disk should come first, and their imprint on the relativistic outflow follows only later. And since relativistic jets in AGN are widely believed to be launched by magnetic fields supported by the disks and entering the ergospheres of spinning black holes (Blandford & Znajek 1977), such changes could be naturally identified with magnetic perturbations within the innermost parts of the accretion disk. However, it takes some time for the accretion disk itself to respond radiatively to magnetic fluctuations, and for a standard “geometrically thin/optically thick” disk model (e.g. Shakura & Sunyaev 1973), the characteristic timescale for such a response is the thermal timescale, $\tau_{\text{th}} \sim \alpha^{-1} \tau_{\text{dyn}}$, where α is the disk viscosity, and $\tau_{\text{dyn}} = r^{3/2} / \sqrt{G\mathcal{M}_{\text{BH}}}$ is the orbital time scale at the distance r from the central black hole with mass $\mathcal{M}_{\text{BH}}$ (see, e.g., Czerny 2006). In the particular case of 4C+74.26, with a black hole mass of $\mathcal{M}_{\text{BH}} \simeq 10^{9.6} M_{\odot}$ (Gofford et al. 2015), meaning the gravitational radius $R_g \sim 6 \times 10^{14}$ cm, and assuming the disk viscosity $\alpha \sim 0.1$, this thermal timescale around the inner disk radius $R_{\text{in}} \sim 35 R_g$ emerging from the NuSTAR data modelling, reads as

$$\tau_{\text{th}} \sim \alpha^{-1} \frac{R_g}{c} \left(\frac{R_{\text{in}}}{R_g} \right)^{3/2} \sim 470 \text{ d}. \quad (2.1)$$

Meanwhile, the timescale for a magnetic perturbation to travel the projected distance ℓ_{proj} along the jet with the relativistic bulk velocity $\beta_j \sim 1$, is

$$\tau_j = \frac{\ell_{\text{proj}}}{c\beta_j} \frac{1 - \beta_j \cos \theta}{\sin \theta}, \quad (2.2)$$

where θ is the jet viewing angle (e.g., Stawarz et al. 2004). For example, with the anticipated $\theta = 45^\circ$ and the jet bulk Lorentz factor $\Gamma_j \simeq 10$, this timescale reads as $\tau_j \lesssim 50 \text{ d}$ for the projected distance $\ell_{\text{proj}} \lesssim 0.1 \text{ pc}$, i.e. where one should expect to find the dominant production zone of the 15 GHz photons in the 4C+74.26 jet. This supports the idea that both the observed disk variability at optical wavelengths and the jet variability at cm wavelengths are generated by magnetic field fluctuations within the innermost parts of the disk, and that the lag we observe between the disk and the jet emission is related to a much delayed radiative “response” of the disk to magnetic field fluctuations when compared with relativistic jet timescales at sub-parsec distances from the core, $\tau_{\text{th}} - \tau_j \sim \mathcal{O}(100 \text{ d})$.

We note in this context that numerical (MHD shearing box) simulations by Hirose et al. (2009) revealed that indeed “magnetic fluctuations lead radiation energy fluctuations by 5–15 orbits, a little less than a thermal time”, and that such a delay is also consistent with the stochastic modelling of optical variability power spectra in quasar sources by Kelly et al. (2009, 2011).

It should be also noted at this point, that at the source redshift, the observed R-band photons correspond to the blackbody temperature of 4,900 K. Taking the well-known formula for the temperature of a standard accretion disk (e.g., [Lasota 2016](#)),

$$\left(\frac{T}{10^{5.8} \text{ K}}\right) \simeq \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}}\right)^{1/4} \left(\frac{\mathcal{M}_{\text{BH}}}{10^8 M_{\odot}}\right)^{-1/4} \left(\frac{r}{2R_g}\right)^{-3/4}, \quad (2.3)$$

where $\dot{M}/\dot{M}_{\text{Edd}}$ is the accretion rate in the Eddington units (see below), one may therefore find that, for the source parameters as discussed above, the radius corresponding to the temperature of 4,900 K is $r \sim 200 R_g$, which is larger than the inner disk radius R_{in} estimated above by means of the spectral modelling of the X-ray data. However, not all of the emission of the accretion disk observed at optical frequencies is produced exclusively at large disk radii. In fact, one may easily check that, in the observed R-band, the segment of the disk extending from the inner disk radius $R_{\text{in}} \sim 35 R_g$ up to $\sim 50 R_g$ contributes as much as $\sim 10\%$ of the total disk intensity in the source,

$$I_{\nu} \propto \int_{R_{\text{in}}}^{R_{\text{out}}} dr r B_{\nu}(T) \propto R_{\text{in}}^2 T_{\text{disk}}^{8/3} \nu^{1/3} \int_{y_{\text{min}}}^{y_{\text{max}}} \frac{y^{5/3} dy}{(e^y - 1)} \quad (2.4)$$

where $B_{\nu}(T)$ denotes the intensity of a blackbody, $T_{\text{disk}} = 4.8 \times 10^5 (R_{\text{in}}/R_g)^{-3/4} \text{ K}$, $y_{\text{min}} = h\nu/kT_{\text{disk}}$, and $y_{\text{max}} = y_{\text{min}}(R_{\text{out}}/R_{\text{in}})^{3/4}$.

Still, one has to keep in mind that the above interpretation is not unique, that the significance of the optical/radio lags revealed by our cross-correlation analysis is still only modest, and also that the accretion disk parameters estimated in support of our interpretation via the X-ray modelling are subjected to relatively large uncertainties, despite an excellent quality of the NuSTAR data and state-of-the-art spectral models applied. For example, with the 3σ bounds $R_{\text{in}}/R_{\text{ISCO}} = 35_{-16}^{+40}$ obtained in Section 2.3.3, one *formally* obtains a rather wide range $190 \text{ d} \leq \tau_{\text{th}} \leq 15000 \text{ d}$. Also, in the framework of the scenario proposed, one could expect a significant correlation between the hard X-ray and optical and/or radio light curves. The fact that no such correlations are seen above 90% confidence levels (see Table 2.1) seems, on the other hand, to be predominantly due to a rather low signal-to-noise ratio in the *Swift*-BAT data (see Section 2.3.2); at the same time, we note that any correlated X-ray variability could in principle be diluted by an additional torus-reflected component (not considered in our NuSTAR data modelling).

Let us finally comment here on the overall energetics of 4C +74.26. The 14–195 keV flux of the source gives a value of the hard X-ray luminosity $L_X \simeq 1.3 \times 10^{45} \text{ erg s}^{-1}$, and hence, following [Ichikawa et al. \(2017\)](#), the accretion-related bolometric luminosity of $L_{\text{acc}} \simeq 8.6 \times 10^{46} \text{ erg s}^{-1}$, meaning that the accretion rate in Eddington units is $\dot{M}/\dot{M}_{\text{Edd}} \sim 0.2$. This is roughly consistent with the 3.4 μm –22 μm (WISE) luminosity of 4C +74.26, namely $L_{\text{IR}} \simeq 5.3 \times 10^{45} \text{ erg s}^{-1}$, for the anticipated $\sim 1\% - 10\%$ of the disk emission

being reprocessed by the hot dusty torus. Meanwhile, the jet kinetic power in 4C +74.26 turns out to be relatively low. This jet kinetic power can be estimated the most robustly by means of a spectral modelling of the radio emission of giant lobes in the source, accounting for the complete history of the energy evolution of relativistic particles injected into the expanding lobes by a pair of relativistic jets (see [Machalski et al. 2007](#), and the discussion therein). Using the data gathered in [Machalski \(2011\)](#), and the evolutionary DYNAGE code by [Machalski et al. \(2007\)](#), we have performed such a modelling, assuming the jet inclination of 45 deg. This resulted in an estimate for the age of the radio source of $\simeq 87$ Myr, and the total (time-averaged) jet kinetic power of $L_j \simeq 4 \times 10^{44} \text{ erg s}^{-1}$, implying a rather low jet production efficiency in the source, $L_j/L_{\text{acc}} \sim 0.01$. Interestingly, the total kinetic luminosity of the ionized nuclear outflow in 4C +74.26 has been found to be even lower than this, namely $L_{\text{out}} \sim 1.5 \times 10^{42} \text{ erg s}^{-1}$ ([Di Gesu & Costantini 2016](#)).

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Chapter 3

Ionized Iron Line in LINER-type Radio Galaxy CGCG 292–057

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Abstract

We present an analysis of the new, deep (94 ksec) *Chandra* ACIS-S observation of radio-loud active galaxy CGCG 292–057, characterized by a LINER-type nucleus and a complex radio structure that indicates intermittent jet activity. On the scale of the host galaxy bulge, we detected excess X-ray emission with a spectrum best fit by a thermal plasma model with a temperature of ~ 0.8 keV. We argue that this excess emission results from compression and heating of the hot diffuse fraction of the interstellar medium displaced by the expanding inner, ~ 20 kpc-scale lobes observed in this restarted radio galaxy. The nuclear X-ray spectrum of the target clearly displays an ionized iron line at ~ 6.7 keV, and is best fitted with a phenomenological model consisting of a power-law (photon index $\simeq 1.8$) continuum absorbed by a relatively large amount of cold matter (hydrogen column density $\simeq 0.7 \times 10^{23} \text{ cm}^{-2}$), and partly scattered (fraction $\sim 3\%$) by ionized gas, giving rise to a soft excess component and $K\alpha$ line from iron ions. We demonstrate that the observed X-ray spectrum, particularly the equivalent width of Fe XXV $K\alpha$ (of order 0.3 keV) can in principle, be explained in a scenario involving a Compton-thin gas located at the scale of the broad-lined region in this source and photoionized by nuclear illumination.

We compare the general spectral properties of the CGCG 292–057 nucleus, with those of other nearby LINERs studied in X-rays.

3.1 Introduction

The nearby galaxy CGCG 292–057 (redshift, $z = 0.054$; [Stoughton et al. 2002](#)) has some unusual properties revealed in studies at radio, infrared, optical, and UV wavelengths by [Kozieł-Wierzbowska et al. \(2012\)](#) and [Singh et al. \(2015\)](#). It is a complex, bulge-dominated system viewed nearly face-on, for which the spiral arm tails extend up to ~ 80 kpc, and has a bulge radius of ~ 30 kpc. The concentration index $C \equiv r_{90}/r_{50} = 2.81 \pm 0.03$, which is the ratio of radii containing 90% and 50% of the Petrosian r light, places the galaxy at the border between early-type and late-type galaxies (see [Strateva et al. 2001](#); [Shimasaku et al. 2001](#)). Its disturbed optical morphology indicates that it is a relatively recent merger, and the lack of an over-density at the position of the source, as observed in the Tenth Data Release of the Sloan Digital Sky Survey (SDSS; [Ahn et al. 2014](#)), suggests that it is not associated with any group or cluster of galaxies ([Singh et al. 2015](#)). Optical spectroscopy of the system reveals low-luminosity active nucleus with relatively strong low-ionization emission lines and faint high-ionization lines, consistently with the “low-ionization nuclear emission-line region” (LINER) classification (see [Ho 2008](#), for a review). The mass of the central supermassive black hole (SMBH), estimated based on the mass–stellar velocity dispersion relation ([Tremaine et al. 2002](#)), or various mass–bulge luminosity relations ([Bentz et al. 2009](#); [McConnell & Ma 2013](#)), is $\simeq (2.7 - 5.7) \times 10^8 M_{\odot}$. Based on IR and UV photometry, the star formation rate in the galaxy was estimated as $\simeq (1.5 - 2.8) M_{\odot} \text{ yr}^{-1}$ ([Singh et al. 2015](#), following the scaling relations as given in [Kennicutt 1998](#)).

However, what is particularly interesting about CGCG 292–057 is its multi-scale and multi-component radio morphology, displayed in Figure 3.1. On arc-second scales, radio maps of the galaxy reveal a pair of compact lobes extending linearly from the radio core, with a total size of ~ 20 kpc, characteristic of a “medium symmetric object” (MSO; see, e.g., [Augusto et al. 2006](#)). These lobes are confined to the central bulge and interact directly with the interstellar medium (ISM) of the host. Furthermore, this “inner” radio structure is embedded within the arcmin-scale “outer” radio lobes, which extend ~ 250 kpc from the galaxy center; the entire radio structure, therefore, may be classified as a “double-double radio galaxy” (DDRG; see [Mahatma et al. 2019](#)). The outer lobes are characterized by a monochromatic 1.4 GHz radio power of $\sim 2 \times 10^{24} \text{ W Hz}^{-1}$, which places the source at the low end of the border between the classification of a Fanaroff-Riley type I and type II radio galaxy; these lobes have an additional pair of diffuse wings, giving the system a

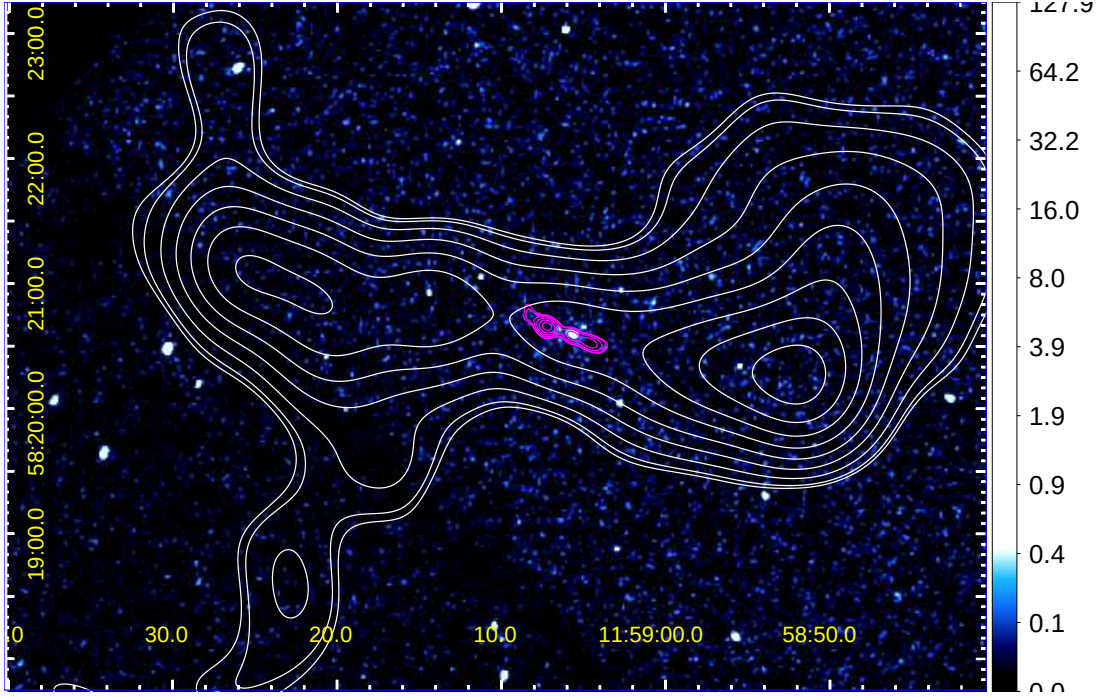


Figure 3.1: The *Chandra* ACIS-S image of CGCG 292–057, with the superimposed 606 MHz radio contours from GMRT. The white contours display the outer structure of the radio source, corresponding to the beam size $45'' \times 45''$, while the magenta contours map the inner radio structure with a beam size $5.9'' \times 4.6''$ with a beam position angle of 46.2° . The contour levels are spaced by a factor of $\sqrt{2}$, starting from 4 mJy beam^{-1} (white) and $1.5 \text{ mJy beam}^{-1}$ (magenta). The *Chandra* image displays the 0.5–7 keV counts, smoothed with a 3 px-radius Gaussian.

clear “X-shaped” appearance (see [Cheung 2007](#); [Cheung et al. 2009](#)). This morphological complexity is most likely reflective of intermittent jet activity of the system’s central SMBH.

The duty cycle of active galactic nuclei (AGN) is, in general, a subject of ongoing debate. This debate pertains to the various observational manifestations of the activity, timescales, and feedback processes involved. On extended timescales, up to 10^8 yrs, major galaxy mergers are broadly considered to be the cause of enhanced accretion flow onto central SMBHs, thus providing material for black hole growth and spin evolution, and fuelling the dominant phase of the central activity (see, e.g., [Hopkins et al. 2006](#); [Sikora et al. 2007](#)). During this phase, as well as in later stages, AGN are likely to pass through subsequent epochs of enhanced and dormant activity. Intermittent behaviour of this type is likely to be caused by minor mergers or instabilities in the accretion flow (e.g., [Czerny et al. 2009](#)).

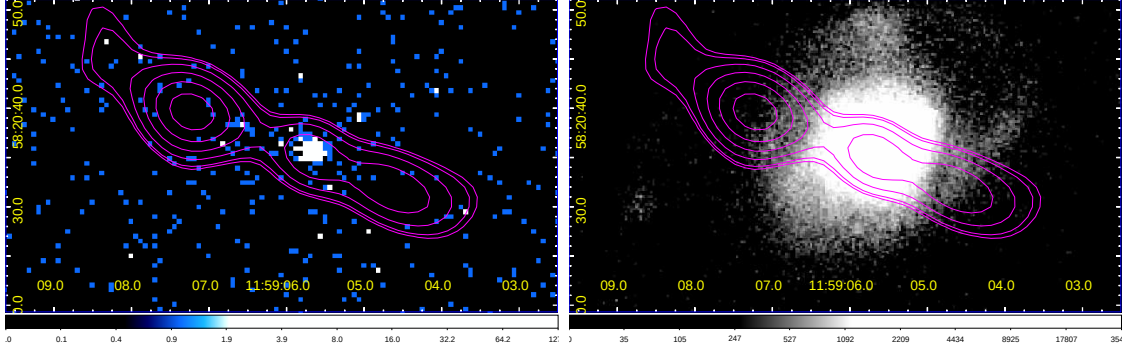


Figure 3.2: The *Chandra* ACIS-S image (0.5–7 keV counts) and the PanSTARRS optical (g-band) image of CGCG 292–057 host galaxy (left and right panels, respectively), both with the superimposed 606 MHz GMRT contours of the inner radio structure (same as in Figure 3.1).

In this framework, the large-scale morphology of radio galaxies with X-shaped radio lobes, could in principle be due to the Lense-Thirring precession, in which the jet axis changes abruptly following the flip in the SMBH spin during an ongoing merging process (see, e.g., the discussion in [Machalski et al. 2016](#), and references therein). On the other hand, DDRGs, where the inner and outer lobes are well-aligned, are consistent with the development of perturbations in the accretion rate and subsequent intermittent radio activity along the same direction of the outflow (see, e.g., [Konar et al. 2019](#), and references therein). Moreover, radio galaxy population studies indicate the existence of far too many compact (linear sizes ≤ 1 kpc) and presumably young (ages $< 10^5$ yrs) sources, as compared to the number of galaxies with old extended radio structures ([O’Dea & Baum 1997](#)). A likely explanation for this inconsistency is that the jet activity is in general highly modulated, and the source is effectively reborn every $\sim 10^4 - 10^5$ yrs ([Reynolds & Begelman 1997](#)).

Interestingly enough, in the case of CGCG 292–057, one can potentially witness all the aforementioned processes at work, imprinted in the complex morphology of its radio jets/lobes, as well as in its host galaxy. Due to the presence of such peculiar characteristics, we studied this source with the *Chandra* X-ray Observatory, making use of the unprecedented combination of the excellent angular resolution and high sensitivity of the ACIS instrument. Below we report on the analysis of the deep *Chandra* exposure of the source, including a detailed profile analysis of the surface brightness covering the galactic bulge, as well as the spectroscopy of the unresolved nucleus. Preliminary results of the analysis were presented in [Balasubramaniam et al. \(2017\)](#). Throughout the paper we assume modern Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, so that the luminosity distance of the source for the given redshift $z = 0.054$ is $d_L = 240 \text{ Mpc}$, and the conversion scale reads as 1.05 kpc/arcsec .

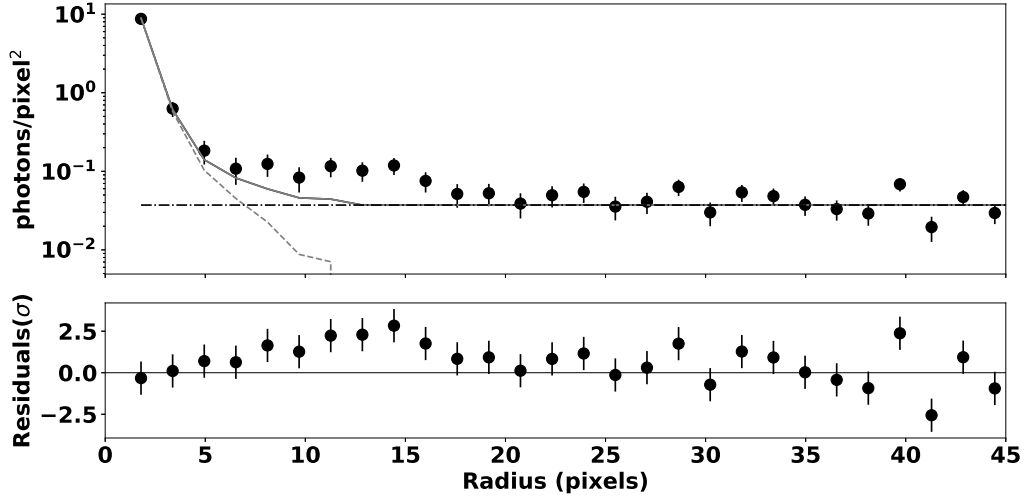


Figure 3.3: *Upper:* X-ray surface brightness profile resulting from extracting the counts of a concentric stack of annular regions centered on the CGCG 292–057 nucleus. The dot-dashed curve denotes the table model for the core PSF, horizontal dotted line corresponds to the constant background, and the solid red curve gives the PSF+background model. *Lower:* residuals of the surface brightness profile fitting with the PSF+background model.

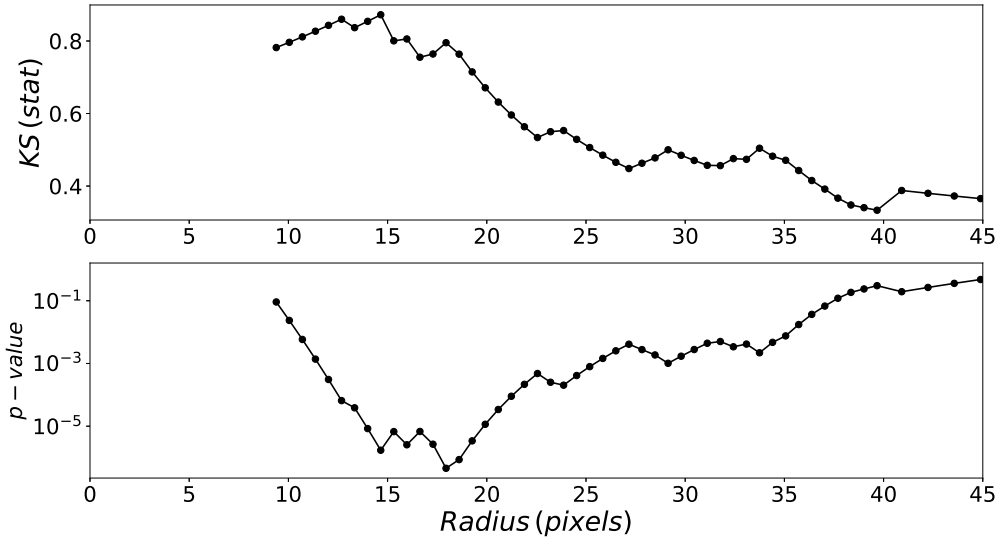


Figure 3.4: KS statistics and p -values corresponding to the null hypothesis that the samples of surface brightness profiles within the annuli 10 px—X px and X px—45 px were drawn from the same distribution, as functions of a running variable X.

3.2 Chandra Data Analysis

We observed CGCG 292–057 with *Chandra* on 2015 Aug 14 (ObsID 17116; cycle 16) with an exposure totaling 93.8 ksec. The source (J2000 position, RA = 11h59m5.7s, Decl. = +58d20'36'') was placed at the aim-point of the back-illuminated ACIS-S3 CCD with the data collected in VFAINT mode. The X-ray data analysis was performed with the CIAOv.4.12 software (Fruscione et al. 2006) using CALDBv.4.9.1. We processed the data by running the CIAO tool `chandra_repro`. Spectral modeling was performed with Sherpa (Freeman et al. 2001), specifically on unbinned spectra, using the Cash and C-stat fitting statistics and the Nelder-Mead and Levenberg-Marquardt optimization methods.

Below in § 3.2.1 we present the profile analysis of the surface brightness profile for our target, and in § 3.2.2 we present spectral modeling of the unresolved nucleus.

3.2.1 Surface Brightness Profile

The target was detected with a total number of 393 net counts within the 0.5 – 7.0 keV range and 5 px source extraction radius. Figure 3.2 displays the ACIS-S image of the central region of CGCG 292–057, along with overlaid 606 MHz contours from the Giant Metrewave Radio Telescope (GMRT) marking the inner radio structure of the source (see Koziel-Wierzbowska et al. 2012). As shown, the active nucleus of the system is clearly detected in X-ray, surrounded by diffuse emission with a low-surface brightness.

We extracted the radial profile of the counts from the exposure-corrected *Chandra* map using concentric annular regions centered on the CGCG 292–057 nucleus. The resultant surface brightness profile was fit with a model including the core PSF and a constant background, with both the PSF normalization and the background (constant) amplitude set free. Instead of a 2D Gaussian approximation for the core PSF, we built a table model from the averaging of over 100 PSF simulations, as described in Appendix 3.5.1. The corresponding best-fit model along with the residuals are given in Figure 3.3. As shown, positive residuals are seen within a range starting at around 10 px extending to $\lesssim 20$ px from the core, signalling the presence of an additional, extended, X-ray emission component.

As the significance of the excess may not seem high, we calculated the Kolmogorov-Smirnov (KS) test to quantify the probability that the samples of surface brightness profiles within the annuli 10 px—X px, and X px—45 px, with a running variable $X \in (10 \text{ px}, 45 \text{ px})$, were drawn from the same distribution. The results of the test, i.e. the KS statistics and the corresponding p -values as functions of X, are presented in Figure 3.4. As shown, $p < 10^{-6}$ for $X \simeq 18$ px, implying that the emission seen between 10 px and

Table 3.1.: Simultaneous fitting of the ISM (= source) and the BKG (= background).

Region	Model [†] /Parameter	Value/Value with 1σ errors	Unit [‡]
BKG:	powerlaw		
	Photon index Γ_{bkg}	0.87 ± 0.15	
	PL amplitude	$(8.62 \pm 1.48) \times 10^{-7}$	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ at 1 keV
	ISM: zphabs * xsapc		
	Hydrogen column density $N_{\text{H}}^{(\text{ISM})}$	$0.53^{+0.14}_{-0.14}$	10^{22}cm^{-2}
ISM:	Temperature kT_{ISM}	$0.81^{+0.23}_{-0.35}$	keV
	Normalization	$(2.21 \pm 0.65) \times 10^{-6}$	$10^{-14}(1+z)^2 n_e n_{\text{H}} V / 4\pi d_L^2$
	C-stat./DOF	455/887	
BKG:	powerlaw		
	Photon index Γ_{bkg}	0.87 ± 0.18	
	PL amplitude	$(8.44 \pm 1.64) \times 10^{-7}$	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ at 1 keV
	ISM: zphabs * powerlaw		
	Hydrogen column density $N_{\text{H}}^{(\text{ISM})}$	$0.35^{+0.35}_{-0.35} \times 10^{-7}$	10^{22}cm^{-2}
ISM:	Photon index Γ_{ISM}	4.01 ± 1.78	
	PL amplitude	$(1.87 \pm 1.86) \times 10^{-7}$	$\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ at 1 keV
	C-stat./DOF	455/887	

[†] all the models include the Galactic hydrogen column density $N_{\text{H, Gal}} = 1.43 \times 10^{20} \text{cm}^{-2}$; thermal model assumes solar abundance;

[‡] normalization for the model *xsapc* assumes uniform ionized plasma with electron and H number densities n_e and n_{H} , respectively, and volume V in cgs units.

18 px — which is beyond the 3σ radius for the photon counts from the unresolved core (see Appendix 3.5.1) — is significantly distinct from the constant background present outside of the 18 px radius.

Notably, this excess emission, located at physical distances of $\sim 5 \text{ kpc}$ from the core (up to $\sim 9 \text{ kpc}$, for the conversion scale $\sim 1 \text{ kpc}''$ and $1 \text{ px} \simeq 0.5''$), coincides with the edges of the inner radio structure (MSO) of CGCG 292–057 (the radio lobe radius $\sim 10 \text{ kpc}$). It is, therefore, natural to relate this feature with the compact radio jets/lobes in the system. In particular, the X-ray excess could either be non-thermal emission of the compact lobes (Stawarz et al. 2008), or a hot diffuse phase of the ISM, compressed and heated by the expanding young radio lobes (Reynolds et al. 2001).

In order to investigate possible differences in the position of the excess emission along and across the major axis of the inner radio lobes, we have also extracted the radial profiles of the net counts separately for the four quadrants of the concentric annular regions, oriented in such a way that the East and West quadrants correspond to the surface brightness profiles *along* the jet axis, while the North and South quadrants to the surface brightness profiles *across* the jet axis. The results are presented in Appendix 3.5.2. As shown, due to the limited photon statistics in separate quadrants, even with the size of the annulus bins increased from 2 px up to 7 px, the differences are not significant statistically, although there is a tentative evidence of an elongation of the X-ray emission along the jet direction (in particular, in the East quadrant when compared to the South and North ones).

Table 3.2.: Simultaneous fitting of the AGN (= source) and the BKG (= background).

Model*	Model parameter	Value/Value with 1σ errors	Units [◇]
Model A: zphabs * powerlaw			
C-stat./DOF: 817/887	Hydrogen column density N_{H}	0.028 [†]	10^{22} cm^{-2}
	Photon index Γ	-0.37 ± 0.04	
	PL amplitude	$(1.28 \pm 0.06) \times 10^{-6}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
	BKG Photon index Γ_{bkg}	0.86 ± 0.17	
	BKG PL amplitude	$(8.23 \pm 1.41) \times 10^{-7}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
Model B: zphabs * powerlaw + xszgauss			
C-stat./DOF: 815/884	Hydrogen column density N_{H}	0.052 [†]	10^{22} cm^{-2}
	Photon index Γ	-0.31 ± 0.05	
	PL amplitude	$(1.35 \pm 0.08) \times 10^{-6}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
	Source frame line energy E_l	6.76 [†]	keV
	Line normalization	$3.17 \times 10^{-7\ddagger}$	$\text{cm}^{-2} \text{ s}^{-1}$
	BKG Photon index Γ_{bkg}	0.86 ± 0.15	
	BKG PL amplitude	$(8.23 \pm 1.23) \times 10^{-7}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
Model C: zphabs * xsapec			
C-stat./DOF: 867/884	Hydrogen column density N_{H}	3.15 ± 0.36	10^{22} cm^{-2}
	Temperature kT	$> 10^{\ddagger}$	keV
	Normalization	$1.05 \times 10^{-4\ddagger}$	$10^{-14}(1+z)^2 n_e n_{\text{H}} V / 4\pi d_{\text{L}}^2$
	BKG Photon index Γ_{bkg}	1.08 ± 0.19	
	BKG PL amplitude	$(10.65 \pm 1.92) \times 10^{-7}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
Model D: zphabs(1) * xsapec + zphabs(2) * powerlaw			
C-stat./DOF: 784/884	Hydrogen column density $N_{\text{H}}^{(1)}$	1.38 ± 0.39	10^{22} cm^{-2}
	Temperature kT	0.12 ± 0.06	keV
	Normalization	$0.00664_{-0.0025}^{+0.0025}$	$10^{-14}(1+z)^2 n_e n_{\text{H}} V / 4\pi d_{\text{L}}^2$
	Hydrogen column density $N_{\text{H}}^{(2)}$	3.96 ± 0.96	10^{22} cm^{-2}
	Photon index Γ	1.09 ± 0.35	
	PL amplitude	$(1.45 \pm 0.82) \times 10^{-6}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
	BKG Photon index Γ_{bkg}	0.86 ± 0.19	
	BKG PL amplitude	$(8.24 \pm 1.61) \times 10^{-6}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
Model E: zphabs(1) * xsapec(1) + zphabs(2) * xsapec(2)			
C-stat./DOF: 785/884	Hydrogen column density $N_{\text{H}}^{(1)}$	5.01 ± 0.43	10^{22} cm^{-2}
	Temperature $kT^{(1)}$	17.27 ± 3.37	keV
	Normalization ⁽¹⁾	$(1.13 \pm 0.08) \times 10^{-4}$	$10^{-14}(1+z)^2 n_e n_{\text{H}} V / 4\pi d_{\text{L}}^2$
	Hydrogen column density $N_{\text{H}}^{(2)}$	1.09 ± 0.06	10^{22} cm^{-2}
	Temperature $kT^{(2)}$	0.22 ± 0.01	keV
	Normalization ⁽²⁾	$1.5 \times 10^{-4\ddagger}$	$10^{-14}(1+z)^2 n_e n_{\text{H}} V / 4\pi d_{\text{L}}^2$
	BKG Photon index Γ_{bkg}	0.86 ± 0.17	
	BKG PL amplitude	$(8.22 \pm 1.39) \times 10^{-7}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
Model F: zphabs(1) * (1-fsc) * powerlaw + zphabs(2) * (fsc * powerlaw + xszgauss)			
C-stat./DOF: 784/882	Hydrogen column density $N_{\text{H}}^{(1)}$	$6.86_{-0.58}^{+0.67}$	10^{22} cm^{-2}
	Scattering fraction f_{sc}	$0.033_{-0.009}^{+0.011}$	
	Hydrogen column density $N_{\text{H}}^{(2)}$	$0.09_{-0.01}^{+0.13}$	10^{22} cm^{-2}
	Photon index Γ	$1.80_{-0.05}^{+0.42}$	
	PL amplitude	$(4.57_{-2.16}^{+4.54}) \times 10^{-5}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV
	Source frame line energy E_l	$6.76_{-0.03}^{+0.03}$	keV
	Line normalization	$(5.43_{-2.32}^{+2.81}) \times 10^{-7}$	$\text{cm}^{-2} \text{ s}^{-1}$
	Equivalent width of the line EW	330_{-160}^{+210}	eV
	BKG Photon index Γ_{bkg}	$0.86_{-0.14}^{+0.12}$	
	BKG PL amplitude	$(8.25_{-1.51}^{+1.71}) \times 10^{-7}$	$\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV

* all the models include the Galactic hydrogen column density $N_{\text{H, Gal}} = 1.43 \times 10^{20} \text{ cm}^{-2}$; thermal models assume solar abundance; [◇] in the models including redshifted Gaussian line the source-frame line width frozen at $\sigma_l = 10 \text{ eV}$; [◇] normalization for the model xsapec assumes uniform ionized plasma with electron and H number densities n_e and n_{H} , respectively, and volume V in cgs units; [†] lower and upper 1σ bounds unconstrained when using Nelder-Mead optimization method;

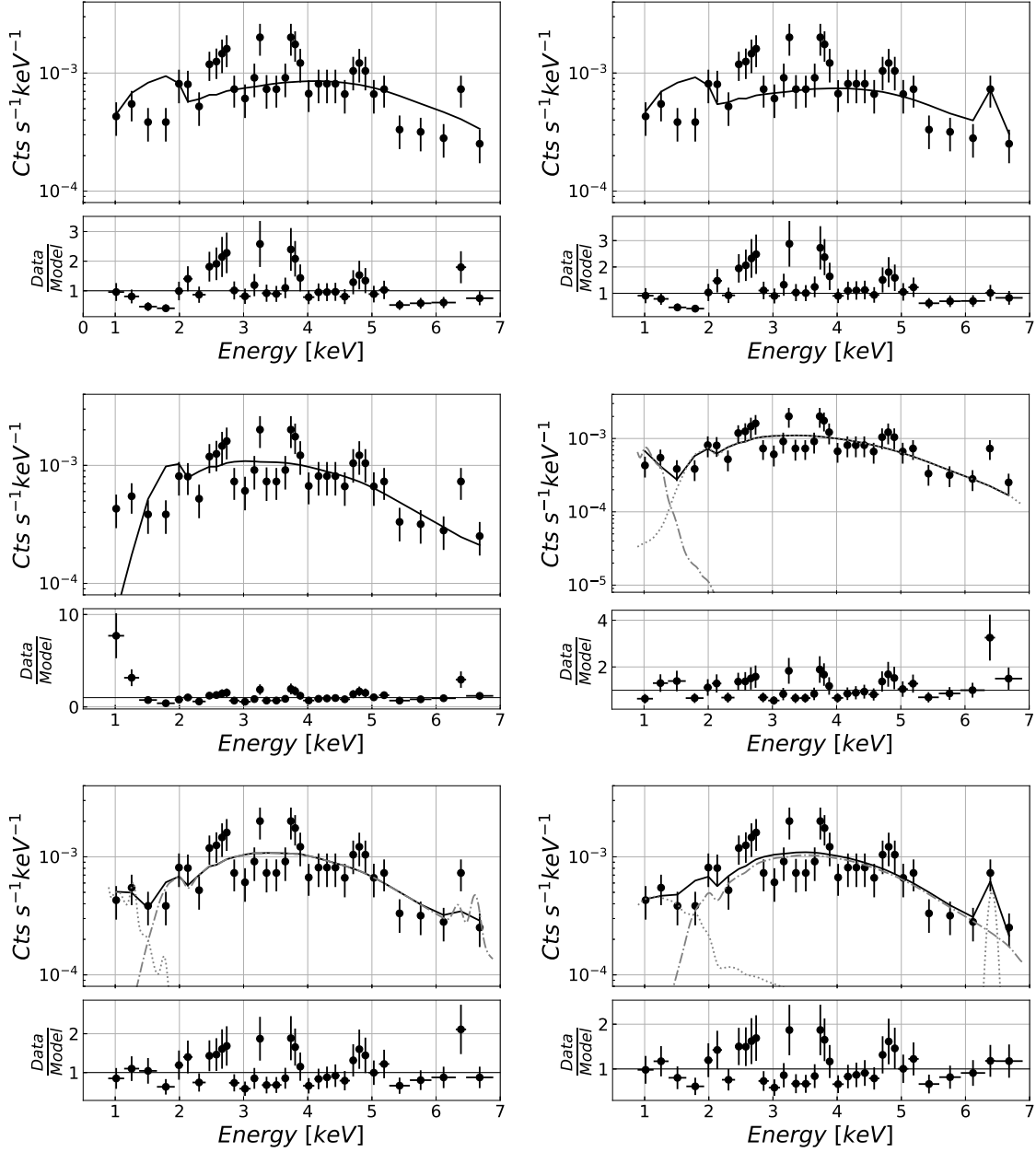


Figure 3.5: The 0.5 – 7 keV spectrum of the AGN emission component within CGCG 292–057 (binned to reach a signal-to-noise ratio of 3 in each bin, for representation purposes only, as the fits were performed on the unbinned spectra), fitted with various emission models: A (top left panel) a power-law model “PL”, B (top right) a power-law with a Gaussian line “PL+G”, C (middle left) a thermal model “APEC”, D (middle right) a combination of thermal and power-law components “APEC+PL”, E (bottom left) a combination of two thermal components “2 × APEC”, and F (bottom right) a scattered power-law with a Gaussian line “Scattered PL+G”; see Table 3.2 for the resulting best-fit model parameters.

3.2.2 Spectral Analysis

For spectral modeling, we defined the following extraction regions corresponding to the emission components identified in the X-ray brightness profile in CGCG 292–057 from the previous section (3.2.1; cf., Figure 3.3).

- (i) The “AGN” region is extracted using a circular region with a 5 px radius centered on the central X-ray peak. The region includes at least 95.45% of photons emitted by the active nucleus (for all the simulated PSFs; see Appendix 3.5.1 and in particular the 2σ confidence line in Figure 3.8), and on the other hand minimizes contamination from the extended (excess) emission component.
- (ii) The “ISM” emission is defined with an annulus with an inner radius of 10 px and an outer radius of 15 px. This annulus contains the bulk of the excess extended emission component with only minimal pollution from the AGN ($< 0.27\%$ of the photons from the core; see the 3σ line in Figure 3.8).
- (iii) The background, “BKG”, was taken from an annulus with the inner radius of 20 px and the outer radius of 30 px, and corresponding to the outer regions characterized by a flat (constant) X-ray surface brightness.

The spectra for these regions and the corresponding calibration files (ARF and RMF) were extracted with the CIAO script `specextract`. First, we simultaneously fitted the 0.5 – 7.0 keV spectra of the ISM region (= source) and the BKG region (= background), assuming an absorbed thermal model for the former (`zphabs * xsapc`, redshift $z = 0.054$) and an unabsorbed power-law model for the latter, both including the Galactic hydrogen column density $N_{\text{H,Gal}} = 1.43 \times 10^{20} \text{ cm}^{-2}$. In the thermal model, we have also fixed the plasma abundance to solar. The results of the fitting (including 1σ errors calculated using the Nelder-Mead optimization method) are summarized in Table 3.1. As follows, the excess emission seen in the ISM region, could be well represented by a thermal emission of a hot gas with the temperature of $\sim 0.8 \text{ keV}$ and non-negligible intrinsic absorption $\sim 5 \times 10^{21} \text{ cm}^{-2}$.

Next we repeated the fit, replacing the absorbed thermal model for the ISM region with an absorbed (`zphabs`, $z = 0.054$) power-law model. The results of this fitting are again summarized in Table 3.1. In this case, the intrinsic absorption turns out to be negligible, and the poorly constrained photon index reads as relatively steep, $\sim 4.0 \pm 1.8$. Consequently, we conclude that the thermal fit to the ISM region (corresponding to the excess in the surface brightness profile over the constant background), returns more plausible parameters, and as such is favored.

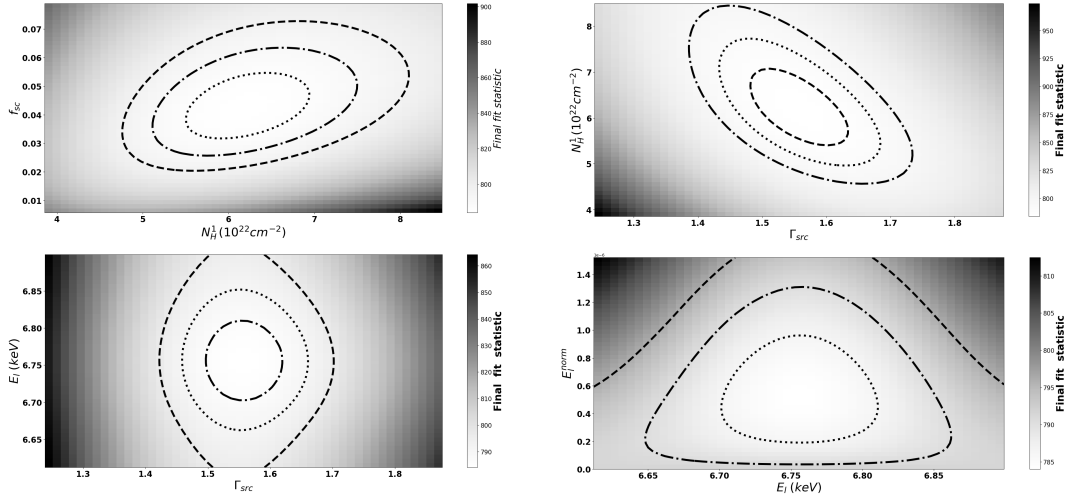


Figure 3.6: Confidence contours of 1, 2, and 3 σ on the two-thaw-parameters plane for the model F applied to the 0.5–7.0 keV *Chandra* spectrum of CGCG 292–057 nucleus, calculated using the Levenberg-Marquardt optimization method: hydrogen column density $N_{\text{H}}^{(1)}$ vs. scattering fraction f_{sc} (upper left panel), power-law photon index Γ vs. source-frame line energy E_l (upper right), power-law photon index Γ vs. hydrogen column density $N_{\text{H}}^{(1)}$ (lower left), source-frame line energy E_l vs. line normalization (lower right).

Finally, we performed simultaneous fitting for the 0.5 – 7.0 keV spectra of the AGN (= source) and the BKG (= background) regions, assuming various emission models for the former (at $z = 0.054$), and, as before, an unabsorbed power-law model for the latter, all including the Galactic hydrogen column density $N_{\text{H,Gal}} = 1.43 \times 10^{20} \text{ cm}^{-2}$. The emission models assumed for the AGN include: (A) an absorbed power-law, (B) an absorbed power-law with a Gaussian line, (C) an absorbed thermal model, (D) a combination of an absorbed thermal model with an absorbed power-law, with different absorbers, (E) a combination of two absorbed thermal models, again allowing for two different absorbers, and (F) an absorbed scattered power-law model with a Gaussian line and two different absorbers. In all the thermal models, we froze the abundance at the solar value; in the models including a redshifted Gaussian line, the source-frame line width was frozen at $\sigma_l = 10 \text{ eV}$. The results of the fitting (including 1 σ errors calculated using the Nelder-Mead optimization method) are summarized in Table 3.2 and Figure 3.5.

Note that clear residuals, reminiscent of line emission, are visible in the AGN spectrum below 5 keV; if real, those could signal, e.g., the presence of a collisionally ionized gas within the central parts of the CGCG 292–057 host (see in this context [Beuchert et al. 2018](#)). Detailed modeling of those features is, however, beyond the scope of the current paper, since such an analysis and line identification are all hampered by an insufficient energy resolution and limited photon statistics of the currently available *Chandra* dataset.

The main conclusions emerging from our modeling, as described above, are as follows: (i) simple power-law fits imply very flat, unphysical, photon indices and negligible, although hardly constrained, hydrogen column densities; (ii) a basic thermal model can be rejected, because of the unconstrained, very high, gas temperature; (iii) multi-component models, including two-temperature thermal plasma or thermal plus power-law emission components, do not provide any significant improvement in this respect either; (iv) the source spectrum clearly displays an ionized iron line at ~ 6.7 keV. Keeping this in mind, we introduced our phenomenological “absorbed scattered power-law” model (F), which returns very reasonable source parameters and provides a satisfactory fit, and as such, should, in our opinion, be considered as the most plausible option, even though lower and upper 1σ bounds for one of the model parameters could not be constrained with the Nelder-Mead optimization method. In Figure 3.6 we provide the complementary confidence contour plots of the main model parameters, calculated using the Levenberg-Marquardt optimization method. The unabsorbed $2 - 10$ keV flux of the power-law emission component in this model reads as $S_{2-10\text{ keV}} \simeq (0.73 \pm 0.20) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, and the corresponding luminosity as $L_{2-10\text{ keV}} \simeq 5 \times 10^{41} \text{ erg s}^{-1}$.

3.3 Discussion

3.3.1 Ionized Iron Line

In type-2 AGN, direct emission of the accretion disk is expected to be observed through a high-column density, cold, circumnuclear gas; some fraction of this emission may, in addition, be scattered by photoionized, optically-thin, medium located at further distances from the center (e.g., [Matt et al. 1996](#)). The *Chandra* spectrum of the active nucleus in CGCG 292–057 conforms to this general scenario, as it is best fitted with a phenomenological model consisting of a direct, relatively steep-spectrum (photon index $\Gamma \simeq 1.8$), X-ray continuum emission absorbed by a relatively large amount of cold matter (with the equivalent hydrogen column density $N_{\text{H}}^{(1)} \simeq 0.7 \times 10^{23} \text{ cm}^{-2}$), and partly scattered (fraction $f_{sc} \sim 3\%$) by ionized gas giving rise to a soft excess component (moderated by a relatively small column density of $N_{\text{H}}^{(2)} \simeq 10^{21} \text{ cm}^{-2}$) and pronounced $K\alpha$ lines from iron ions.

We note that photoionized, Compton-thin gas, scattering the direct X-ray continuum of the accretion disk/disk corona, is not the only viable option for the production of the FeXXV and FeXXVI $K\alpha$ lines in AGN. Alternative models proposed in literature, in this context, include a high-temperature (> 5 keV) diffuse thermal plasma ([Koyama et al. 1989](#); [Smith et al. 2001](#)), cosmic-ray electrons interacting with a low-temperature (~ 0.3 keV)

thermal plasma (Valinia et al. 2000; Masai et al. 2002), and a Compton-thick accretion disk illuminated by an external X-ray source (Róžańska et al. 2002; Miller et al. 2006).

Hereafter, however, we exclusively discuss the scenario in which the ionized iron line, detected in the spectrum of CGCG 292–057, results from a Compton-thin gas photoionized by nuclear (direct AGN) illumination, referring, in particular, to the calculations of the resulting line equivalent width performed by Bianchi & Matt (2002). In this context, we note that in the Compton-thin regime the ratio between the reflected and transmitted fluxes of the ionizing continuum is expected to be of the order of the Thomson optical depth (assuming the geometrical factor of the order of unity),

$$\tau \simeq \frac{N_{\text{H}}^{(1)}}{1.5 \times 10^{24} \text{ cm}^{-2}} \sim 0.045, \quad (3.1)$$

which is indeed very close to the observed (best-fit) value of the scattering fraction $f_{sc} \simeq 0.033$.

The primary parameter in the Bianchi & Matt (2002) model is the “X-ray-defined” ionization parameter, namely

$$U_x \equiv \frac{\int_{\nu_L}^{\nu_H} \frac{L_\nu}{h\nu} d\nu}{4\pi r^2 c n_e}, \quad (3.2)$$

where L_ν is the luminosity spectral density of the AGN continuum. The integration is over the frequency range corresponding to the photon energy range, 2 – 10 keV, r is the distance of the ionized scattering medium from the source of the photoionizing photons (i.e. from the active nucleus), and n_e is the electron number density characterizing the scattering medium. Since the direct (unabsorbed) AGN continuum is best fitted as a power-law with photon index $\Gamma \simeq 1.8$, the electron number density can be expressed as

$$n_e \simeq N_{\text{H}}^{(1)} / \Delta r \sim 2 \times 10^4 \left(\frac{r}{\text{pc}} \right)^{-1} \left(\frac{\Delta r}{r} \right), \quad (3.3)$$

where Δr is the equivalent depth of the ionized absorber involved in re-processing the AGN continuum emission. From equation 3.2 we obtain

$$U_x \sim 30 \left(\frac{S_{2-10 \text{ keV}}}{10^{-13} \text{ cgs}} \right) \left(\frac{r}{\text{pc}} \right)^{-2} \left(\frac{n_e}{\text{cm}^{-3}} \right)^{-1} \sim 10^{-3} \left(\frac{r}{\text{pc}} \right)^{-1} \left(\frac{\Delta r}{r} \right). \quad (3.4)$$

Unfortunately, observational constraints on the distance scale r are lacking, with the exception that it must be smaller than the AGN source extraction region in the *Chandra* data analysis, namely $r < 5 \text{ px} \simeq 2.5'' \sim 2.6 \text{ kpc}$. On the other hand, a characteristic scale at which one may naturally expect the presence of high-density medium, subjected to a substantial photoionization by the nuclear X-ray emission continuum, is the radius of the “Broad Line Region” (BLR), most likely marking a transition between a Compton-thick accretion disk and a clumpy torus of hot circumnuclear dust (see, e.g., Czerny

2019). In order to estimate this radius, in the specific context of CGCG 292–057, first we note that with the given observed flux of the $H\alpha$ emission line of the source (Kozieł-Wierzbowska et al. 2012; Singh et al. 2015), the corresponding luminosity reads as $L_{H\alpha} \simeq 2.5 \times 10^{40} \text{ erg s}^{-1}$. Hence, the bolometric luminosity of the accreting matter can be found as

$$L_{\text{bol}} \simeq 2 \times 10^3 L_{H\alpha} \sim 5 \times 10^{43} \text{ erg s}^{-1} \quad (3.5)$$

(Netzer 2009), and the corresponding Eddington ratio

$$\lambda_{\text{Edd}} \equiv \frac{L_{\text{bol}}}{L_{\text{Edd}}} \sim (0.7 - 1.4) \times 10^{-3} \quad (3.6)$$

for the available SMBH mass estimates (see Section 3.1 above). Given the values for the disk luminosity and accretion rate — reinforcing the classification of the analyzed source as a low-luminosity AGN — we use the best-fit relation between the BLR radius R_{BLR} and the monochromatic disk luminosity $[\lambda L_{\lambda}]_{5100\text{\AA}}$ as derived by Bentz et al. (2013), namely,

$$\log \left(\frac{R_{\text{BLR}}}{\text{l.d.}} \right) = 1.527 + 0.533 \times \log \left(\frac{[\lambda L_{\lambda}]_{5100\text{\AA}}}{10^{44} \text{ erg/s}} \right), \quad (3.7)$$

where we approximate $[\lambda L_{\lambda}]_{5100\text{\AA}}$ as simply

$$[\lambda L_{\lambda}]_{5100\text{\AA}} \simeq \zeta_{5100\text{\AA}}^{-1} L_{\text{bol}} \sim 0.1 L_{\text{bol}}, \quad (3.8)$$

noting the range for the bolometric correction factor, $\zeta_{5100\text{\AA}} \simeq 5.5 - 12.5$, stated in the literature (see Runnoe et al. 2012, and references therein). With such, the BLR radius in CGCG 292–057 reads as

$$R_{\text{BLR}} \sim 6.8 \text{ l.d.} \sim 5.7 \times 10^{-3} \text{ pc}. \quad (3.9)$$

Finally, keeping in mind all the estimates presented above, and assuming $r \sim R_{\text{BLR}}$ as well as, for rather illustrative purposes, $\Delta r \sim r$, we obtain $n_e \sim 3 \times 10^6 \text{ cm}^{-3}$, and $U_x \sim 0.1$. Given such a value of the ionization parameter, the model calculations by Bianchi & Matt (2002) — performed assuming a photon index, of the illuminating continuum, of 2.0, gas number density 10^6 cm^{-3} , and gas temperature 10^6 K — for the hydrogen column density of the order of $N_{\text{H}}^{(1)}$, imply an Fe XXV equivalent width of the order 300 eV, in excellent agreement with our best-fit value $\text{EW} \simeq 330_{-160}^{+210} \text{ eV}$. This indicates the scenario involving a Compton-thin gas, located at the distance within the BLR and photoionized by a nuclear illumination, can, in principle, explain the *Chandra* observations of CGCG 292–057. If the scattering medium is, however, located at some larger distance from the core, $r \gg R_{\text{BLR}}$, another source of ionization (additional to the AGN illumination) would be needed in order to account for the observed line intensity.

3.3.2 Jet—ISM Interactions

Interestingly, pronounced 6.7 keV (ionized) iron emission lines, with no accompanying 6.4 keV (neutral) features, have recently been reported in the spectra of two other restarted or young radio galaxies, namely 0710+43 (Siemiginowska et al. 2016) and PMN J1603–4904 (Müller et al. 2014; Goldoni et al. 2016). Based on those examples (0710+43, PMN J1603–4904, and CGCG 292–057), it would be tempting (although premature) to speculate that the ionized iron line emission is somehow related to the presence of compact (galactic-scale) radio lobes of newly triggered relativistic jets. In particular, an expansion of such lobes through the host could lead to the injection of suprathermal/non-thermal electrons into the ISM, providing an additional source of ionization of the iron atoms in the environment (see in this context Masai et al. 2002)

What is much less speculative, however, is the impact the newly triggered relativistic jets may have on the diffuse phase of the ISM through which the jets propagate. As argued in Section 3.2.1, in the surface brightness profile of CGCG 292–057 we see excess X-ray emission, best fitted as a thermal plasma component with the temperature of $kT_{\text{ISM}} \simeq 0.8$ keV, present at kpc distances from the center. The best-fit normalization of this emission component (see Table 3.1), implies the electron number density,

$$n_e \simeq \left(\frac{2.2 \times 10^{-6} 4\pi d_L^2}{10^{-14} (1+z)^2 \mu V} \right)^{1/2} \sim 5.8 \times 10^{-3} \text{ cm}^{-3}, \quad (3.10)$$

assuming uniform ionized plasma, i.e. $\mu \equiv n_H/n_e \simeq 0.82$, within the emission volume

$$V \simeq \frac{4}{3} \pi (R_{\text{out}}^3 - R_{\text{in}}^3) \sim 1,370 \text{ kpc}^3, \quad (3.11)$$

where $R_{\text{out}} = 15 \text{ px} \sim 7.75 \text{ kpc}$ and $R_{\text{in}} = 10 \text{ px} \sim 5.17 \text{ kpc}$ follows from the applied source extraction region for the ISM emission component. The corresponding gas pressure therefore reads as,

$$p_{\text{ISM}} \simeq n_e kT_{\text{ISM}} \sim 7.5 \times 10^{-12} \text{ erg cm}^{-3}. \quad (3.12)$$

Since the excess thermal component coincides with the edges of the inner radio structure of the target, it may naturally be explained as resulting from compression and heating of the hot diffuse fraction of the host galaxy, displaced by expanding radio lobes. In such a case, assuming: (i) typical values of the jets' advance velocities $v_{\text{adv}} \sim 0.01 - 0.1c$, for radio galaxies with linear sizes of the order of $\ell \sim 10 \text{ kpc}$ (see Kawakatu et al. 2008), meaning the jet lifetime $\tau_j \sim \ell/v_{\text{adv}} \sim 0.3 - 3 \text{ Myr}$, (ii) rough pressure equilibrium between the compact lobes and the surrounding ISM, $p_\ell \simeq p_{\text{ISM}}$, and (iii) the lobes' volumes are of the same order as V estimated above, then the required jet kinetic power reads as

$$L_j^{(\text{in})} \sim 4p_\ell V/\tau_j \sim 10^{43} - 10^{44} \text{ erg s}^{-1}. \quad (3.13)$$

This, in fact, results in a very plausible value, keeping in mind that the bolometric luminosity of the nucleus, as estimated above (equation 3.5), implies the mass accretion rate in the source is at least one order of magnitude larger than $L_j^{(\text{in})}$, namely

$$\dot{M}_{\text{acc}} c^2 \simeq \eta_d^{-1} L_{\text{bol}} \sim 10^{45} \text{ erg cm}^{-1} \quad (3.14)$$

where we assumed the radiative disk efficiency η_d at the level of a few percent, as appropriate at lower accretion rates (see [Sharma et al. 2007](#)). Moreover, the 1.4 GHz luminosity spectral density of the outer radio structure in the source, $L_{1.4 \text{ GHz}} \simeq 2 \times 10^{24} \text{ W Hz}^{-1}$, by means of the calorimetric scaling relation, established for the evolved radio sources by [Willott et al. \(1999](#), see also equation 2 in [Rusinek et al. 2017](#)), implies the comparable jet kinetic power

$$L_j^{(\text{out})} = 5.0 \times 10^{22} \left(\frac{L_{1.4 \text{ GHz}}}{\text{W Hz}^{-1}} \right)^{6/7} \text{ erg s}^{-1} \sim 3 \times 10^{43} \text{ erg s}^{-1}. \quad (3.15)$$

The fact that the estimated values of jet kinetic power, supplying the outer and inner structures in this source, are of the same order, is reminiscent of the analogous finding claimed by [Machalski et al. \(2016\)](#) for the restarted radio galaxy with MSO-like inner radio structure, 3C 293.

3.3.3 Comparison with Other LINERs

Narrow $K\alpha$ lines from He- and H-like iron ions are being routinely detected in the X-ray spectra of optically-selected quasars and Seyfert 1s, i.e. radio-quiet type-1 AGN characterized by higher accretion rates ([Patrick et al. 2012a](#)), and have also been reported in the spectra of lower-luminosity AGN such as nearby LINERs, NGC 4579 and NGC 4102 ([Terashima et al. 1998](#); [González-Martín et al. 2009a, 2011](#)). We note that the lines' variability established in NGC 4579 rules out a thermal (hot ISM plasma) origin of those spectral features (see [Terashima et al. 2000](#)).

The overall spectral shape of the X-ray radiative output of the CGCG 292–057 nucleus, is reminiscent of the other LINERs studied in X-rays, for which the instruments such as *Chandra* or *XMM-Newton* reveal power-law emission continua, moderated by intrinsic absorption with a wider range of column densities. Still, the 2–10 keV luminosity of our target, $\simeq 5 \times 10^{41} \text{ erg s}^{-1}$, the estimated EW of the Fe XXV line, $\simeq 330 \text{ eV}$, and the nuclear hydrogen column density $\simeq 0.7 \times 10^{23} \text{ cm}^{-2}$, are all at the high ends of the corresponding distributions derived for LINERs (see [González-Martín et al. 2006, 2009b,a](#)). Also, the BH mass in the system, $\simeq (3 - 6) \times 10^8 M_\odot$, as well as the derived Eddington ratio $\simeq 10^{-3}$, both seem higher than the average values characterising the LINER population (see [González-Martín et al. 2009b](#); [Eracleous et al. 2010](#)).

Interestingly, the anti-correlation between the X-ray photon index and the 2–10 keV luminosity (expressed in the Eddington units), as claimed by [Younes et al. \(2011\)](#) for LINERs with broad $H\alpha$ emission (equation 3 therein), in the case of CGCG 292–057, for which $L_{2-10\text{ keV}}/L_{\text{Edd}} \simeq 10^{-5}$, yields $\Gamma \simeq 1.66$; this is, in fact, quite close to the best-fit value of $1.8^{+0.42}_{-0.05}$. Yet, at the same time with the bolometric disk luminosity in the system, as given above in equation 3.5, we get $L_{\text{bol}}/L_{2-10\text{ keV}} \sim 100$, which is much larger than the bolometric correction factor of the order of 10 claimed by, e.g., [Ho \(2009\)](#) or, more recently, [Netzer \(2019\)](#). In other words, the system studied here appears under-luminous in X-rays for its bolometric disk luminosity, when compared with the general population of LINERs. Related, it also appears over-luminous in radio, as its “X-ray defined radio-loudness parameter” — introduced by [Terashima & Wilson \(2003\)](#) in the context of low-luminosity AGN as simply the ratio of the total 5 GHz luminosity to the 2–10 keV luminosity — reads as $\log L_{5\text{ GHz}}/L_{2-10\text{ keV}} \simeq -1.2$, meaning a radio-loud object indeed (see also [Younes et al. 2012](#)). Here we took $L_{5\text{ GHz}} \simeq 3.8 \times 10^{40} \text{ erg s}^{-1}$, following from scaling down the 1.4 GHz luminosity of the outer lobes with the mean radio spectral index of 0.76 ([Kozieł-Wierzbowska et al. 2012](#)). Note that with such, the “standard” radio-loudness parameter, i.e. the ratio of the 5 GHz and optical B -band ($\lambda_B = 4400\text{Å}$) luminosity spectral densities,

$$\mathcal{R} \equiv \frac{L_{\nu_5}}{L_{\nu_B}} \simeq 1.4 \times 10^6 \left(\frac{L_{5\text{ GHz}}}{L_{\text{bol}}} \right) \sim 10^3, \quad (3.16)$$

places the source on the $\mathcal{R} - \lambda_{\text{Edd}}$ plane almost exactly in between the populations of “Seyferts+LINERs hosted by disk galaxies” and “radio galaxies hosted by ellipticals”, as presented and discussed in detail by [Sikora et al. \(2007\)](#) in the general context of the AGN jet production efficiency. In the above, we assumed that the monochromatic B -band luminosity $[\nu L_\nu]_B \simeq 0.1 \times L_{\text{bol}}$.

3.4 Summary

The galaxy CGCG 292–057 is a complex, post-merger system at the border between early-type and late-type galaxies, with a LINER-type nucleus and multi-scale/multi-component radio morphology, reflecting intermittent jet activity of the central SMBH. We observed this source with the *Chandra* ACIS-S instrument with an exposure totalling 93.8 ks.

In our *Chandra* exposure, we clearly detected the active nucleus of the system (with the total number of 393 net counts within the 0.5 – 7.0 keV range and 5 px radius), surrounded by a diffuse, low-surface brightness, emission. We carefully studied the *Chandra* PSF and the source radial surface brightness profile, and in this way we found evidence

(with significance quantified by the Kolmogorov-Smirnov test) for the presence of an excess X-ray emission component at kpc distances from the center. This component is best fitted by a thermal plasma model with the temperature of ~ 0.8 keV. We argued that the excess emission results from compression and heating of the hot diffuse fraction of the interstellar medium displaced by expanding compact radio jets in the source, for which the kinetic power was estimated as $L_j \sim (0.1 - 1) \times 10^{44} \text{ erg s}^{-1}$, in agreement with the overall energetics of the studied AGN, and, in particular, the estimated bolometric disk luminosity $L_{\text{bol}} \sim 5 \times 10^{43} \text{ erg s}^{-1}$ and the mass accretion rate $\dot{M}_{\text{acc}} c^2 \sim 10^{45} \text{ erg s}^{-1}$.

The 0.5 – 7.0 keV spectrum of the CGCG 292–057 nucleus clearly displays an ionized iron line at ~ 6.7 keV (with no accompanying neutral feature at 6.4 keV). We modeled the spectrum assuming various emission models, and concluded that a simple power-law or either thermal fits imply unphysical photon indices or equivalently very high and unconstrained plasma temperatures. The best fit is obtained assuming a phenomenological model consisting of a relatively steep-spectrum (photon index $\Gamma \simeq 1.8$), direct, X-ray continuum emission absorbed by a relatively large amount of cold matter (with the equivalent hydrogen column density $N_{\text{H}}^{(1)} \simeq 0.7 \times 10^{23} \text{ cm}^{-2}$), and partly scattered (fraction $f_{\text{sc}} \sim 3\%$) by ionized gas, giving rise to a soft excess component and pronounced $K\alpha$ lines from iron He-like ions. The X-ray luminosity of the direct nuclear continuum reads, in this model, as $L_{2-10 \text{ keV}} \simeq 5 \times 10^{41} \text{ erg s}^{-1}$.

Following detailed calculations by [Bianchi & Matt \(2002\)](#), we demonstrated that the scenario involving a Compton-thin gas, located at the distance of the Broad-Line Region in the source ($R_{\text{BLR}} \sim 6 \times 10^{-3} \text{ pc}$), and photoionized by nuclear illumination, with the corresponding ionisation parameter $U_x \sim 0.1$, can explain the *Chandra* observations of CGCG 292–057, and, in particular, the observed equivalent width of the Fe XXV $K\alpha$ line, which is of the order of 0.3 keV.

We compare the general spectral properties of the CGCG 292–057 nucleus, with those of other nearby LINERs studied in X-rays, and argue that the system appears under-luminous in X-rays for its bolometric disk luminosity, and at the same time over-luminous in radio. In fact, on the “radio-loudness vs. accretion rate” plane, CGCG 292–057 is located almost exactly in between the populations of Seyferts+LINERs, which are typically hosted by disk galaxies, and radio galaxies, which are typically hosted by ellipticals (see in this context [Sikora et al. 2007](#)).

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3.5 Appendix

3.5.1 Modeling the Chandra PSF

We performed High Resolution Mirror Assembly (HRMA) PSF simulations for the core, using the Chandra Ray Tracer (ChaRT) online tool ([Carter et al. 2003](http://cxc.harvard.edu/ciao/PSFs/chart2/runchart.html))¹. For these simulations, the source spectrum file (corresponding to the model fit A, i.e. absorbed power-law; see Table 3.2) was uploaded to ChaRT, obtaining a set of rays, which were next projected onto the detector plane with the MARX software ([Davis et al. 2012](https://space.mit.edu/cxc/marx))². The resulting PSF files were normalized to the observed count rate, and filtered with the source region at a bin factor of 1.

Because of limited photon statistics, it is reasonable to expect quite substantial differences in each particular realization of the PSF due to random photon fluctuations. To investigate this effect in more detail, we repeated PSF simulations several times, and modeled the resulting PSF profiles with a 2D Gaussian. In this way, we estimate the Full Width at Half Maximum (FWHM) of the central point source in the given image. We then investigated the point of convergence for the fluctuations in the PSF simulations by deriving the mean values, $\langle \text{FWHM} \rangle_N \pm \Sigma_N$, for an increasing number, N , of PSF simulations performed, as well as the successive difference in the mean values of FWHM, namely $|\langle \text{FWHM} \rangle_N - \langle \text{FWHM} \rangle_{N-1}|$. The results of this analysis, for N up to 100, are presented in the left panel of Figure 3.7. As shown in the figure, the mean FWHM converges to $\simeq 2.85$ px after only about 20 iterations, N , at which point the standard

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

²<https://space.mit.edu/cxc/marx>

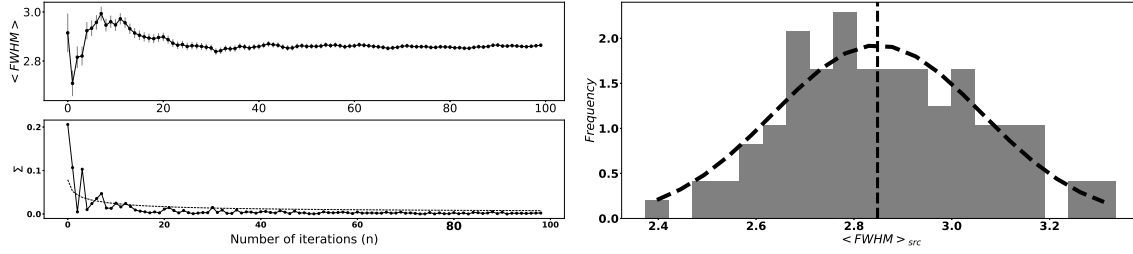


Figure 3.7: *Left:* the estimated mean FWHM of the PSF modeled with 2D Gaussian, $\langle \text{FWHM} \rangle_N \pm \Sigma_N$, as a function of the number N of PSF simulations performed (upper panel); the successive difference in the mean values $|\langle \text{FWHM} \rangle_N - \langle \text{FWHM} \rangle_{N-1}|$, along with the standard error of the mean Σ_N (dashed curve), are shown on the lower panel. *Right:* Histogram of the emerging FWHM values after 100 PSF simulations, along with the best-fit normal distribution $\langle \text{FWHM} \rangle_{100} \simeq 2.84$ px and $\Sigma \simeq 0.21$ px.

error of the mean, which decreases as $\Sigma_N \simeq \Sigma/\sqrt{N}$ (as in fact expected for a normal distribution of FWHM values with a standard deviation of the population Σ) exceeds the differential error $|\langle \text{FWHM} \rangle_N - \langle \text{FWHM} \rangle_{N-1}|$.

Right panel of Figure 3.7 presents the histogram of the emerging FWHM values after 100 PSF simulations along with the best-fit normal distribution returning, $\langle \text{FWHM} \rangle_{100} \simeq 2.84$ px and $\Sigma \simeq 0.21$ px. Given this, the radius for the extraction region encompassing 3σ of the photons from a point source formally reads as, $\simeq (3/2\sqrt{2\ln 2}) \times \frac{1}{2}\langle \text{FWHM} \rangle_{100} \simeq 1.8 \pm 0.1$ px. However, the source PSF is not well represented by a 2D Gaussian and particularly with limited photon statistics, broad wings of the PSF do matter. To illustrate this, in Figure 3.8 we plot the enclosed photon count fraction for each simulated PSF. As shown, the real 2σ radius ranges between 2.5 px and 5 px, depending on a particular PSF realization, and the 3σ radius is, in all cases, at ~ 10 px. Hence, in the analysis of the surface brightness presented in this paper, instead of a 2D Gaussian approximation, we build a table model for the core PSF as a result from the averaging of over 100 PSF simulations.

3.5.2 Surface Brightness Profiles Along and Across the Jet Axis

We have also extracted the radial profiles of the net counts separately for the four quadrants of the concentric annular regions centered on the CGCG 292–057 nucleus, oriented to the East, to the West, to the North, and to the South from the center. The East and West quadrants correspond therefore to the surface brightness profiles *along* the axis of the inner jets in the system, while the North and South quadrants to the surface brightness

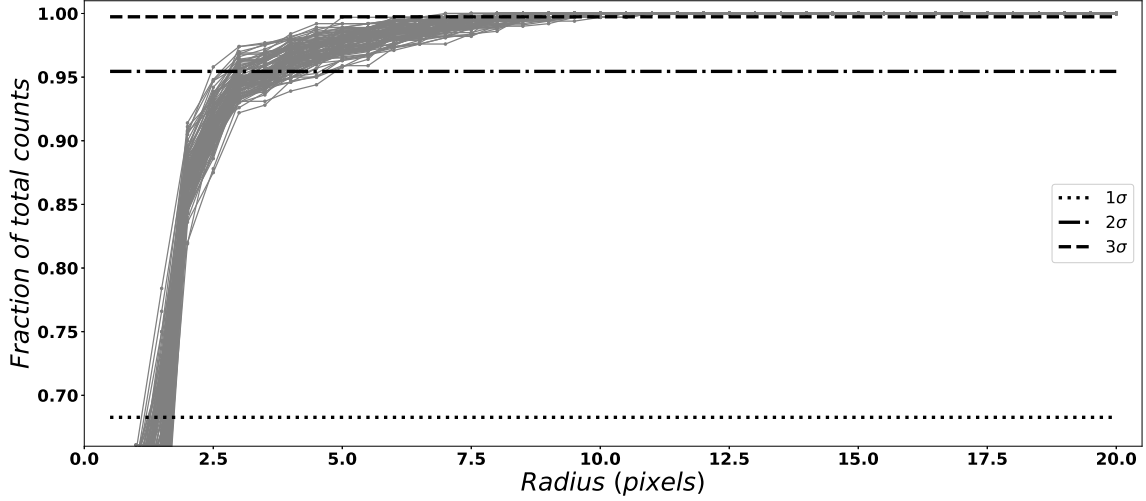


Figure 3.8: Enclosed count fraction for 100 simulated PSF images; horizontal dotted lines from bottom to top correspond to 1σ , 2σ , and 3σ count fractions, respectively.

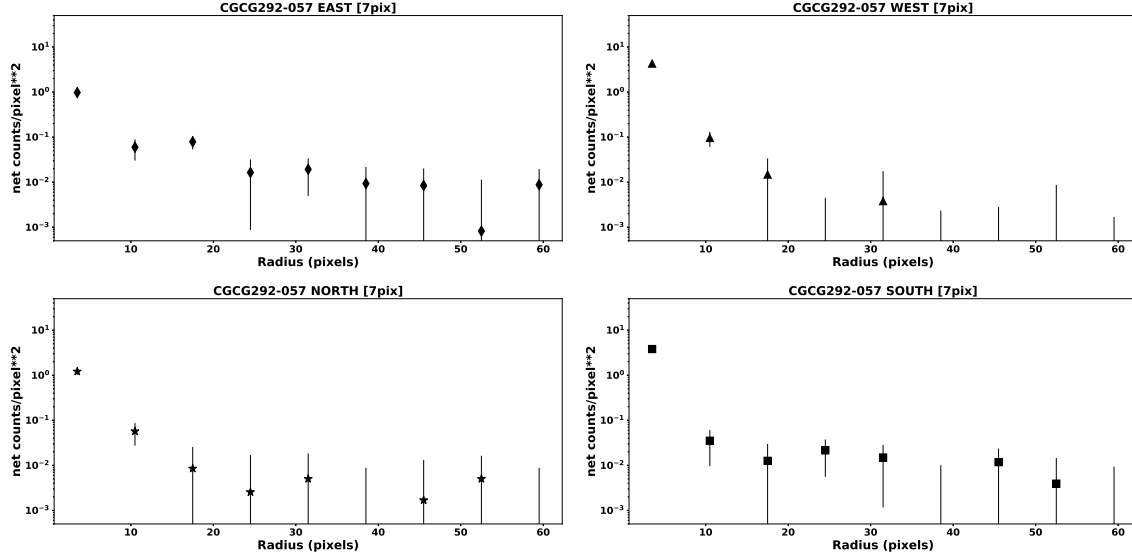


Figure 3.9: X-ray surface brightness profiles resulting from extracting the net counts from four quadrants of a concentric stack of annular regions (each with the bin size of 7 px) centered on the CGCG 292–057 nucleus. The quadrants are oriented to the East, to the West, to the North, and to the South from the center (top-left, top-right, bottom-left, and bottom-right panels, respectively).

profiles *across* the jet axis. Due to the limited photon statistics in separate quadrants, we had to increase the size of the annuli from 2 px (as adopted in Figure 3.3) up to 7 px. The resulting profiles are presented in Figure 3.9.

Chapter 4

Neutral Iron Line in Young Radio Galaxy NGC 3894

This chapter originally appeared as 'X-ray Emission of the γ -ray Loud Young Radio Galaxy NGC 3894' by K. Balasubramaniam et al. 2021, arXiv:2106.13193, accepted for publication in The Astrophysical Journal in August 2021 (Balasubramaniam et al. 2021).

Abstract

The radio source 1146+596 is hosted by an elliptical/S0 galaxy NGC 3894, with a low-luminosity active nucleus. The radio structure is compact, suggesting a very young age of the jets in the system. Recently, the source has been confirmed as a high-energy (HE, > 0.1 GeV) γ -ray emitter, in the most recent accumulation of the *Fermi* Large Area Telescope (LAT) data. Here we report on the analysis of the archival *Chandra* X-ray Observatory data for the central part of the galaxy, consisting of a single 40 ksec-long exposure. We have found that the core spectrum is best fitted by a combination of an ionized thermal plasma with the temperature of $\simeq 0.8$ keV, and a moderately absorbed power-law component (photon index $\Gamma = 1.4 \pm 0.4$, hydrogen column density $N_{\text{H}}/10^{22} \text{ cm}^{-2} = 2.4 \pm 0.7$). We have also detected the iron $K\alpha$ line at 6.47 ± 0.07 keV, with a large equivalent width of $\text{EW} = 0.96 (0.53 - 1.94)$ keV. Based on the simulations of the *Chandra*'s Point Spread Function (PSF), we have concluded that, while the soft thermal component is extended on the scale of the galaxy host, the hard X-ray emission within the narrow photon energy range 6.0–7.0 keV originates within the unresolved core (effectively the central kpc radius). The line is therefore indicative of the X-ray reflection

from a cold neutral gas in the central regions of NGC 3894. We discuss the implications of our findings in the context of the X-ray Baldwin effect. NGC 3894 is the first young radio galaxy detected in HE γ -rays with the iron $K\alpha$ line.

4.1 Introduction

The elliptical/lenicular galaxy NGC 3894, a member of a non-interacting pair located at RA(J2000)=11h48m50.36s and Dec(J2000)=+59°24′56.43″ (de Vaucouleurs et al. 1991), hosts a compact radio source 1146+596 (Condon & Dressel 1978). The first Very-Long-Baseline Interferometry (VLBI) of the system at 5 GHz (Wrobel et al. 1985), suggested an asymmetric core-jet morphology on parsec scales. Subsequent VLBI monitoring of the asymmetric double-lobed structure revealed properties more consistent with a ‘Compact Symmetric Object’ (CSO) classification (see O’Dea 1998; O’Dea & Saikia 2021, for reviews). In particular, the 1981–1996 VLBI monitoring data analyzed by Taylor et al. (1998), indicated that the twin jets in the system were characterized by only sub-relativistic expansion, and oriented at rather large, $\sim 50^\circ$ angle from the line-of-sight. As such, 1146+596/NGC 3894 became recognized as one of the nearest and the youngest low-power radio galaxy.

Very recently, Principe et al. (2020), who analyzed the earlier VLBI data together with five additional Very Long Baseline Array (VLBA) datasets, confirmed the youth scenario for 1146+596, with the projected size of ~ 4 pc and the jet advance speed $\sim (0.3 - 0.4) c$, but at the same time a considerably smaller jet viewing angle of $\sim 10^\circ - 20^\circ$. The corresponding dynamical age of the radio structure reads as ~ 60 years.

Redshifted HI absorption has been detected towards both the approaching and receding jets of 1146+596 (van Gorkom et al. 1989; Peck & Taylor 1998; Gupta et al. 2006). Distinct absorption features have been interpreted as related to either gaseous clouds falling onto the nucleus, or a circumnuclear hot dusty torus. The corresponding neutral hydrogen column densities has been estimated as $N_{\text{HI}} \simeq 4 \times 10^{20} \text{ cm}^{-2}$ on average, with the $(2 - 14) \times 10^{20} \text{ cm}^{-2}$ range found for distinct components of the radio structure (see also in this context Perlman et al. 2001; Emonts et al. 2010).

The infrared (IR) studies of NGC 3894 using various telescopes, such as the Infrared Astronomical Satellite (IRAS), the *Spitzer* Space Telescope, and the Wide-field Infrared Survey Explorer (WISE; Willett et al. 2010; Kosmaczewski et al. 2020), reinforced the ‘Low-ionization nuclear emission-line region’ (LINER) classification of the nucleus (see in this context Condon & Broderick 1988; Kim 1989; Gonçalves & Serote Roos 2004), and indicated a rather low star formation rate in the host, at the level of $\sim 0.5 M_\odot \text{ yr}^{-1}$.

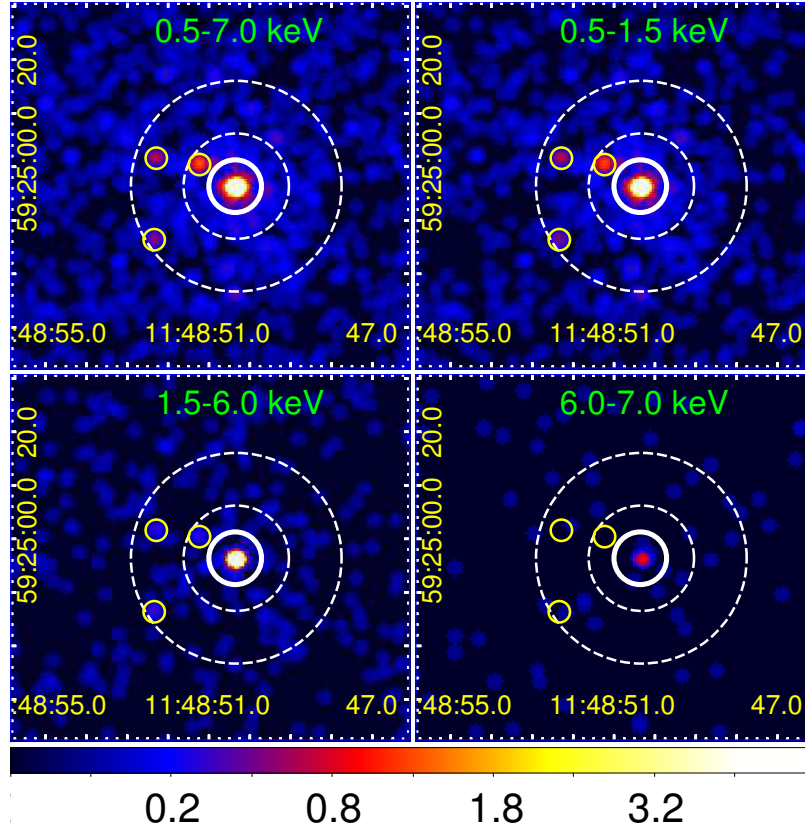


Figure 4.1: *Chandra* images of NGC 3894, smoothed with 3σ kernel, within the full *Chandra* photon energy range 0.5–7.0 keV (upper left panel), the soft band 0.5–1.5 keV (upper right), the medium band 1.5–6.0 keV (bottom left), and the hard band 6.0–7.0 keV (bottom right). The applied core extraction region with the $10\text{ px} \simeq 5''$ radius is denoted in all the panels by a white solid circle; the background for the core spectral analysis was chosen as an annulus with the inner and outer radii of $10''$ and $20''$, respectively, as represented in the panels by white dashed circles (with the two prominent point sources, marked in the figure by yellow solid circles, removed).

At optical frequencies, the high-resolution imaging performed with the telescopes of Lick Observatory and also the *Hubble* Space Telescope (Kim 1989; Perlman et al. 2001), revealed the presence of dust lanes and ionized gas distributed along the major axis of the host, nearly perpendicular to the radio axes, likely related to the hot dusty torus.

Finally, NGC 3894 was recently identified as a counterpart to the HE γ -ray source 4FGL J1149.0+5924 listed in the *Fermi*-LAT 8-year Source Catalog (4FGL; Abdollahi et al. 2020; Principe et al. 2020). As such, it is one of only several young radio galaxies detected in the HE γ -ray range (see McConville et al. 2011; Müller et al. 2015; Migliori et al. 2014, 2016; D’Ammando et al. 2016; Lister et al. 2020).

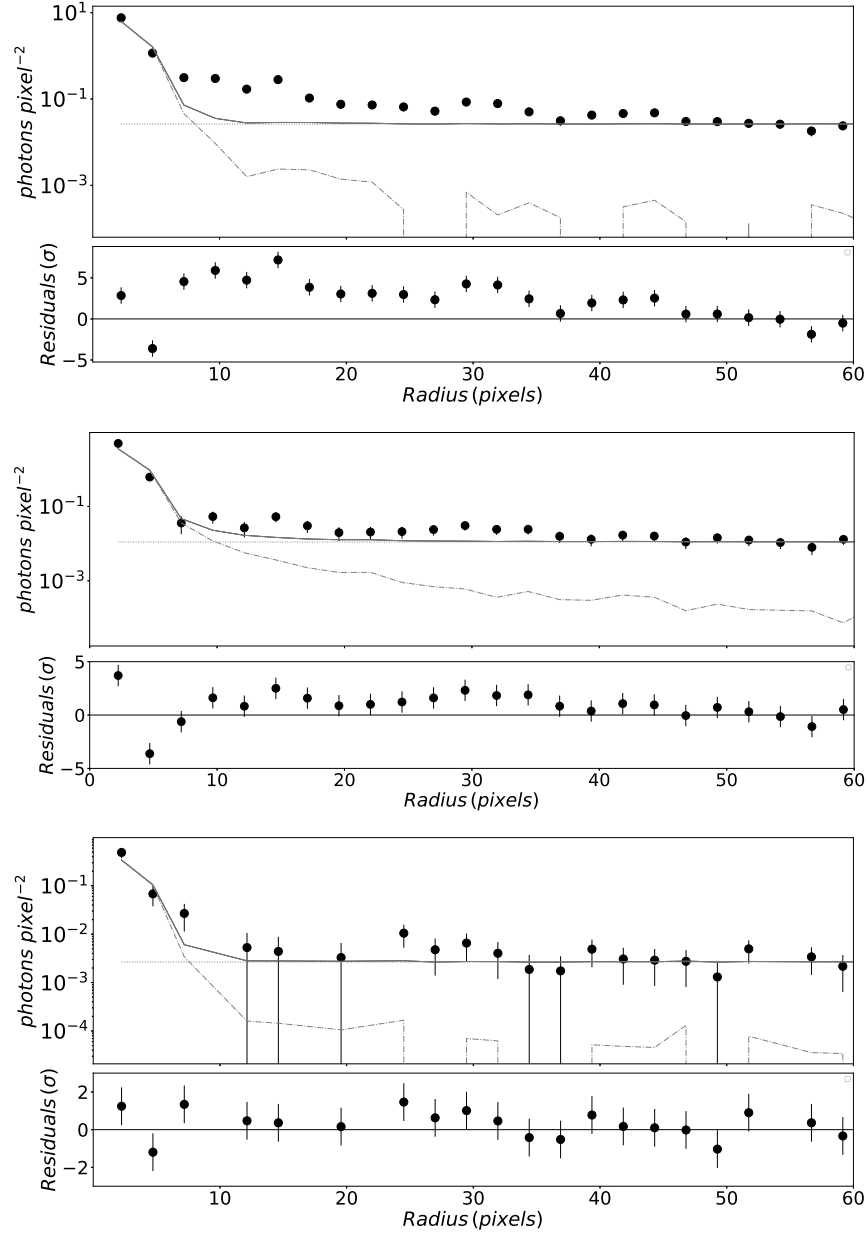


Figure 4.2: The X-ray surface brightness profiles of NGC 3894, within the narrow photon energy ranges 0.5–1.5 keV (soft band; upper panel), 1.5–6.0 keV (medium band; middle panel), and 6.0–7.0 keV (hard band; lower panel). Long dashed grey curves denote the table models for the core PSFs simulated specifically for the corresponding bands, while the horizontal dashed lines denote the constant background levels. Residuals of the surface brightness profile fitting with the PSF+background models are given in each panel.

All in all, one can conclude that 1146+596/NGC 3894 is a relevant source, well studied and characterized at radio, IR, optical, and HE γ -ray ranges, but at the same time lacking any detailed X-ray spectroscopy and imaging. Here we therefore analyzed the archival *Chandra* data for the system, consisting of a single 40 ksec exposure with the Advanced CCD Imaging Spectrometer (ACIS) detector. Along with presenting the results of the *Chandra* data analysis, we also update the broad-band Spectral Energy Distribution (SED) of the source. Throughout the paper we assume Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, so that the luminosity distance of the source for the given redshift $z = 0.01075$ is $d_L = 50.1 \text{ Mpc}$, and the conversion scale reads as 0.238 kpc/arcsec .

4.2 Chandra Data Analysis

The *Chandra* ACIS-S observation of the galaxy NGC 3894 were conducted in 2009 July, during the Observing Cycle 10 (PI: E. Perlman), with the exposure totalling to 38.4 ksec. The source was placed at the aim-point on the back-illuminated ACIS CCD. The data were collected in the VFaint mode and the observation was made in the timed exposure mode. The target was detected with the total number of net counts of 457 within the $10 \text{ px} \simeq 5''$ radius from the core, in the full photon energy range $0.5 - 7.0 \text{ keV}$ utilized in our analysis. Figure 4.1 presents the resulting *Chandra* images of NGC 3894, smoothed with 3σ kernel, within the full $0.5-7.0 \text{ keV}$ range, the soft band $0.5-1.5 \text{ keV}$, the medium band $1.5-6.0 \text{ keV}$, and the hard band $6.0-7.0 \text{ keV}$.

The X-ray data analysis was performed with the CIAO v.4.13 software (Fruscione et al. 2006) using CALDB v.4.8.5. We processed the data by running the CIAO tool `chandra_repro`. Spectral modeling was done in XSPEC¹ version 12.11.1 (Arnaud 1996), using the Chi-square fitting statistics and the Nelder-Mead optimization method, and also with Sherpa² (Freeman et al. 2001), when working on unbinned data, using the Cash statistics and the Nelder-Mead optimization method. The uncertainties of spectral parameters provided in the text, are 1σ errors. Below in §4.2.1 we present the detailed PSF simulations and the surface brightness profile analysis in the narrow energy ranges (soft, medium, and hard), due to the fact that the source spectrum appears relatively hard, and also due to the presence of a strong iron fluorescence; in §4.2.2 we present spectral modelling.

¹<https://heasarc.gsfc.nasa.gov/xanadu/xspec>

²<https://cxc.cfa.harvard.edu/sherpa/>

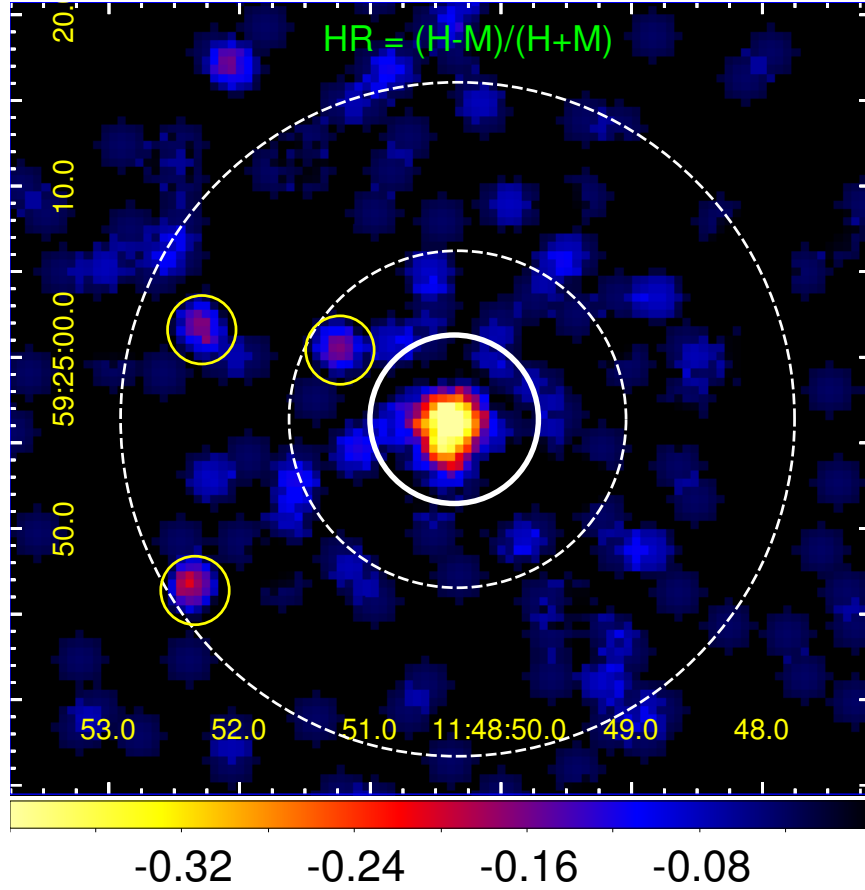


Figure 4.3: The hardness ratio ACIS-S image of the central parts of NGC 3894, defined as $HR = (H-M)/(H+M)$ for the medium 1.5–6.0 keV (M) and hard 6.0–7.0 keV (H) bands.

4.2.1 Surface Brightness Profiles

In order to correct for the *Chandra* dithering motion, the limited size of detector pixels, and detector effects, we performed the High Resolution Mirror Assembly (HRMA) PSF simulations for the NGC 3894 nucleus, using the Chandra Ray Tracer (ChaRT) online tool (Carter et al. 2003)³. For these, the source spectrum file was uploaded to ChaRT, obtaining a set of rays, which were next projected onto the detector plane with the MARX software (Davis et al. 2012)⁴. The resulting PSF files were normalized to the observed count rate, and filtered with the source region at bin factor 1.

³<http://cxc.harvard.edu/ciao/PSFs/chart2/runchart.html>

⁴<https://space.mit.edu/cxc/marx>

Table 4.1.: Spectral modelling of the binned nuclear spectrum of NGC 3894

Model	N_{H} $\times 10^{22} \text{ cm}^{-2}$	kT keV	APEC norm. [†] $\times 10^{-6} \text{ XSPEC}$	E_{ℓ} keV	Line norm. [†] $\times 10^{-6} \text{ XSPEC}$	Γ	PL norm. [†] $\times 10^{-6} \text{ XSPEC}$	χ^2/DOF
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(i)	2.02 ± 0.63	0.79 ± 0.06	3.44 ± 0.42	—	—	1.14 ± 0.36	19.92 ± 10.70	64.27/72
(ii)	2.21 ± 0.66	0.79 ± 0.06	3.46 ± 0.42	6.47 ± 0.05	1.34 ± 0.60	1.28 ± 0.37	24.21 ± 13.61	59.21/70
(iii)	2.37 ± 0.71	0.79 ± 0.06	3.48 ± 0.42	6.47 ± 0.07	2.04 ± 0.94	1.40 ± 0.41	28.57 ± 17.28	57.90/69

Col(1) — model fit; Col(2) — intrinsic hydrogen column density; Col(3–4) — temperature and normalization of the collisionally ionized thermal plasma; Col(5–7) — Gaussian line energy, width, and normalization; Col(8–9) — photon index and normalization of the power-law emission component; Col(10) — χ^2 fitting statistics/DOF.

All the models include Galactic hydrogen column density $N_{\text{H,Gal}} = 1.83 \times 10^{20} \text{ cm}^{-2}$; thermal component assumes solar abundance. The 0.5–7.0 keV unabsorbed flux of the power-law component reads as $F_{0.5-7.0 \text{ keV}} \simeq 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. The 6.47 keV line equivalent width (1 σ range) reads as $\text{EW} = 0.59 (0.36 - 1.10) \text{ keV}$ for the fit with frozen $\sigma_{\ell} = 0.01 \text{ keV}$, and

$\text{EW} = 0.96 (0.53 - 1.94) \text{ keV}$ for σ_{ℓ} set free.

[†] The XSPEC normalizations are: (a) for the APEC component $10^{-14} (1+z)^2 n_e n_{\text{H}} V / 4\pi d_L^2$, assuming uniform ionized plasma with electron and H number densities n_e and n_{H} , respectively, and volume V , all in cgs units; (b) for the Gaussian line component total photons/cm²/s in the line; (c) for the power-law component photons/keV/cm²/s at 1 keV.

Because of limited photon statistics we are dealing with here, one should expect possibly quite substantial differences in each particular realisation of the PSF, due to random photon fluctuations. For this reason, we have repeated the PSF simulations 50 times, and then averaged them, obtaining in this way the final PSF model that was used for the surface brightness profile fitting.

The PSF simulations as described above have been performed separately for the three bands, namely the soft band 0.5–1.5 keV, the medium band 1.5–6.0 keV, and the hard band 6.0–7.0 keV. We note an extremely low photon statistics in the lattermost case, amounting to only 26 net photons within the $< 10 \text{ px} \simeq 5''$ source extraction region. Despite this obstacle, the 6.0–7.0 keV PSF could still be characterized reasonably well.

After the extensive PSF simulations, we extracted observed counts from the exposure-corrected Chandra map in a concentric stack of annular regions centred on the galactic nucleus up to $\sim 60 \text{ px}$ (without removing any point sources), and fit the resulting radial profile of the X-ray surface brightness of the target with the model including the core PSF, and a constant background. During the fitting procedure, the PSF (table model) normalization, as well as the background amplitudes, were in all the cases set free. The corresponding best-fit lines along with the residuals, are given in Figure 4.2.

As shown in the figure, in the case of the soft *Chandra* band, a clear source extension beyond the core PSF is seen, manifesting as positive residuals in the fit at the level of (and above) 3σ , up to $\sim 30 \text{ px} \simeq 3.5 \text{ kpc}$ from the core. This extension cannot be ascribed solely to the three identified point sources, although their contribution to the surface brightness can be seen in the radial profile of the soft-band emission around 15 px and 30–35 px from the core. In the medium band, on the other hand, no significant extension beyond the central PSF can be found, except of a minor excess around the position of the three point sources (positive residual $< 3\sigma$). In the hard band, finally, no source extension — either due to a diffuse component, or due to the identified point sources — is present

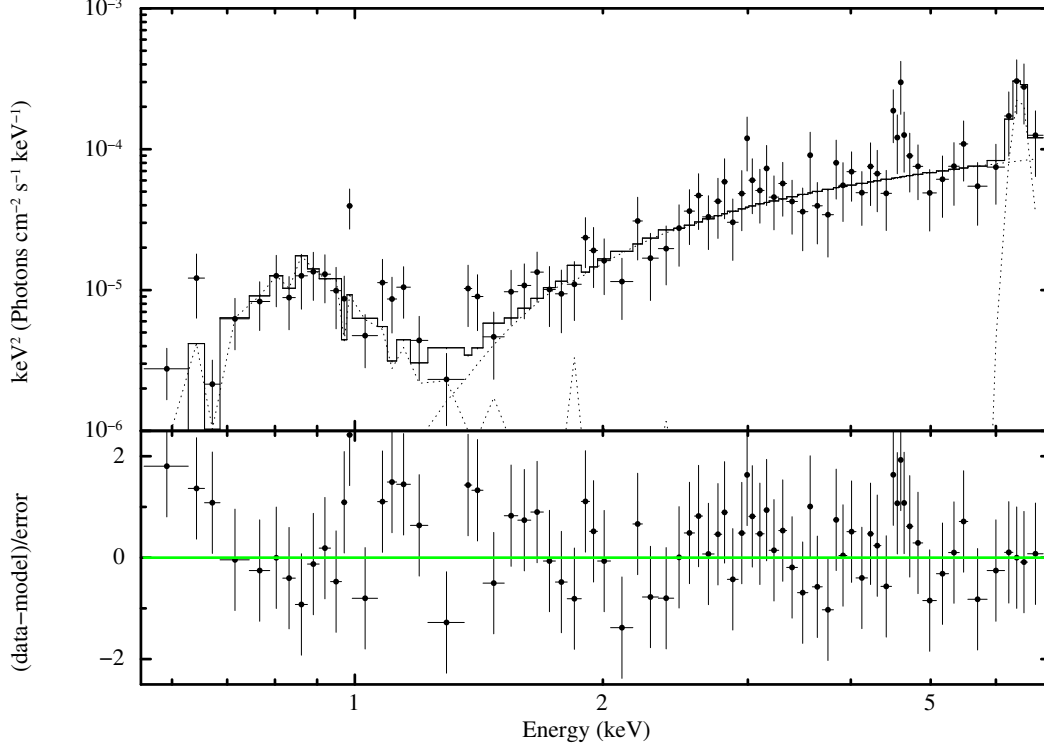


Figure 4.4: Background-subtracted 0.5 – 7 keV *Chandra* spectrum of the unresolved X-ray core in NGC 3894, grouped with minimum 5 photons, and fitted with emission model `zphabs*(powerlaw+zgauss)+apec` with the line width set free and the thermal gas abundance frozen at the solar value (see Model (iii) in Table 4.1 for the resulting best-fit model parameters).

beyond the central PSF (effectively the central $< 5'' \simeq 1.2$ kpc radius), although a very limited photon statistics in this band should be kept in mind.

Likewise, no prominent extended structures can be seen on the hardness ratio $HR=(H-M)/(H+M)$ map presented in Figure 4.3, where we utilized solely the medium (M) and hard (H) bands. This reinforces our conclusion that the 6.0–7.0 keV signal comes predominantly from the unresolved core of the system, and therefore that the iron fluorescence we see (see the following section) is most likely indicative of the X-ray reflection from a cold neutral absorber in the active nucleus of NGC 3894. At the same time we emphasize that, in the analyzed *Chandra* dataset, the target is unresolved down to a few tens of parsecs, which is the scale of the extension in the Fe $K\alpha$ emission observed in several nearby Compton-thick sources (Marinucci et al. 2013, 2017; Fabbiano et al. 2018a,b).

4.2.2 Spectral Modelling

Based on the analysis of the X-ray surface brightness profiles in NGC 3894 presented in the previous Section 4.2.1 (see Figure 4.2), for the spectral modelling of the active nucleus in the system, we have selected a circular region with the radius of 10 px centred on the core. For this source extraction region, the background was chosen as an annulus with the inner radius of 20 px and the outer radius of 40 px (with the prominent point sources removed – see Figure 4.1).

Fitting the Binned Data

The 0.5 – 7.0 keV spectra for the selected source region and the background, with the corresponding calibration files (arf and rmf), were extracted with the CIAO script `spec-extract`. The fitting was performed in XSPEC on the background-subtracted binned source spectrum (group minimum 5), including the Galactic absorption with the hydrogen column density $N_{\text{H,Gal}} = 1.83 \times 10^{20} \text{ cm}^{-2}$ (HI4PI Collaboration et al. 2016).

Even though the source spectrum appears relatively hard, the simplest model consisting of an absorbed power-law emission component, `zphabs*powerlaw`, provided a very poor fit to the data. The fit could, on the other hand, be improved significantly by including an additional component representing a collisionally ionized thermal plasma (with the metallicity frozen at the solar value), `zphabs*powerlaw+apec`, hereafter referred to as model (i). Still, the best-fit slope of the power-law continuum turned out unusually hard. Moreover, positive residuals indicated the presence of emission lines, including a line around 6.4 keV, consistent with the neutral iron $K\alpha$ emission, and a feature around 4.6 keV, most likely representing instrumental artefact (in particular, the Si escape peak following the Fe 6.4 keV emission; see Grimm et al. 2009).

As the next step, we have therefore added a simple redshifted Gaussian line component to the model, `zphabs*(powerlaw+zgauss)+apec`, obtaining a satisfactory fit to the data with the line width σ_ℓ either (ii) frozen at 10 eV, or (iii) kept as a free model parameter. The best-fit values of the (i)-(iii) model parameters are summarized in Table 4.1; the background-subtracted source spectrum fitted with latter model (iii), is shown in Figure 4.4.

As follows, the thermal emission dominates the radiative output of the source in the soft *Chandra* band, i.e. below 1.5 keV. This component is well modelled as a collisionally ionized plasma (`apec`) with solar abundance and 0.8 keV temperature, although we note at the same time some lower-significance positive residuals, which could signal the presence of a photoionized plasma component in addition to the collisionally ionized one, similarly

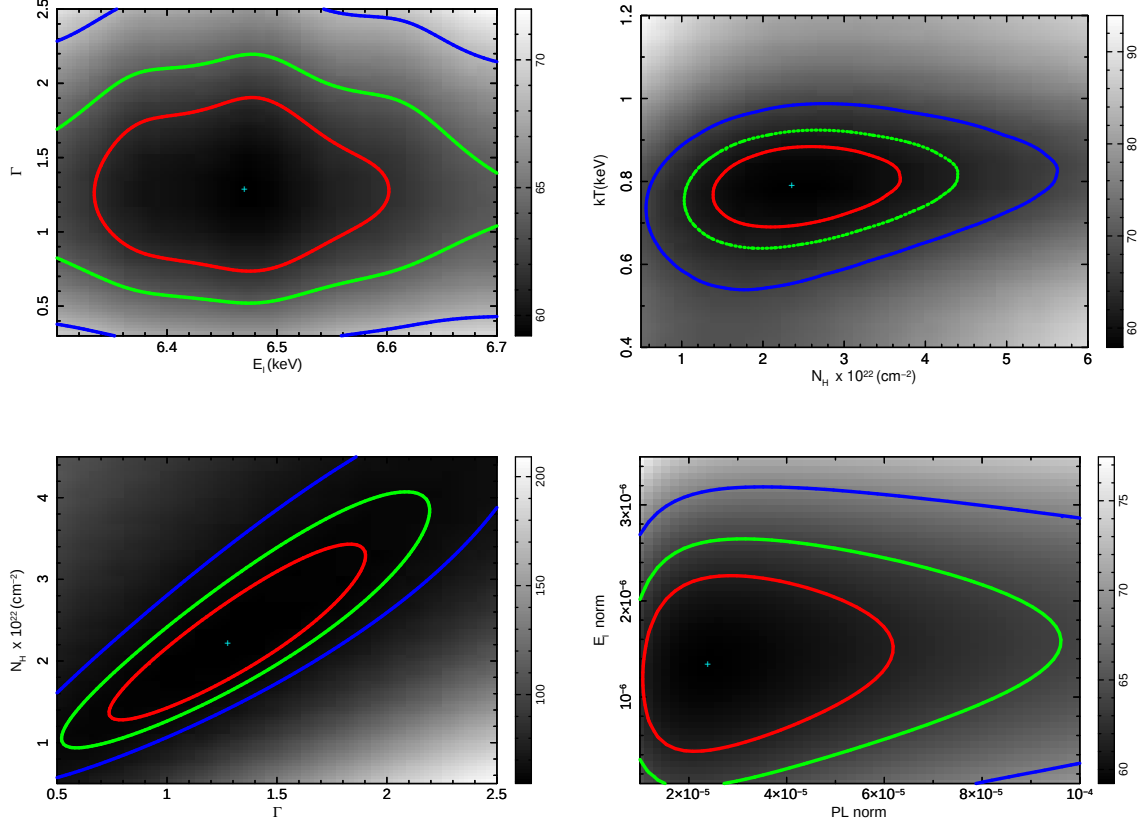


Figure 4.5: Confidence contours of 1σ , 2σ , and 3σ on the two-thaw-parameters plane for the model (iii) applied to the 0.5–7.0 keV Chandra spectrum of NGC 3894, calculated using the Levenberg–Marquardt optimization method: line energy E_l vs. power-law photon index Γ (upper left panel), hydrogen column density N_H vs. temperature of the thermal component kT (upper right), power-law photon index Γ vs. hydrogen column density N_H (lower left), and normalization of the power-law component vs. line normalization (lower right). The grayscale in all the panels corresponds to the final fit statistic values.

as seen in the another extremely compact CSO with the LINER-type nucleus detected in HE γ -rays, PKS 1718-649 (see the discussion in [Beuchert et al. 2018](#)). A limited photon statistics combined with a limited *Chandra* energy range extending down to only 0.5 keV, precludes us from a more detailed investigation of this possibility.

Meanwhile, the medium and hard *Chandra* bands (1.5–7.0 keV) are dominated by a non-thermal emission, well approximated by a power-law model with a prominent iron line at 6.4–6.5 keV, seen through the cold gas with the equivalent hydrogen column density $N_H \simeq (2.4 \pm 0.7) \times 10^{22} \text{ cm}^{-2}$. The 0.5–7.0 keV unabsorbed flux of the power-law

component reads as $F_{0.5-7.0 \text{ keV}} \simeq 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, corresponding to the isotropic luminosity of $L_X \simeq 6 \times 10^{40} \text{ erg s}^{-1}$. The neutral iron line equivalent width reads as either $\text{EW} \simeq 0.59 \text{ keV}$ for the fit with frozen $\sigma_\ell = 0.01 \text{ keV}$, or $\text{EW} \simeq 0.96 \text{ keV}$ for the fit with the line width kept as a free parameter (best-fit value $\sigma_\ell = 0.12 \pm 0.08 \text{ keV}$).

In order to compare the models (i)-(iii), we apply the F-test, obtaining the p -value 0.05669 for the models (i) and (ii), 0.21572 for the models (ii) and (iii), and finally 0.06425 for the models (i) and (iii).

Hence, we conclude that the `zphabs*(powerlaw+zgauss)+apec` models (ii) and (iii), which include in addition the redshifted iron line with the width σ either frozen at 0.01 keV or left free, respectively, fit the data better than the `zphabs*powerlaw+apec` model (i), and as such are preferred at the significance level of $\simeq 94\%$.

In Figure 4.5 we present the confidence contours corresponding to the model (iii) parameters. As shown, the probability distribution for the photon index of the power-law component, Γ , is correlated with the possible values of the intrinsic column density N_H , and so with the normalization of the PL component. Keeping this in mind, the 1σ uncertainty range for the EW of the iron line in the model,

$$\text{EW} = \frac{F_\ell}{F_{\text{PL}}(E_\ell)} = \frac{\text{Line norm.}}{\text{PL norm.} \times (E_\ell/\text{keV})^{-\Gamma}}, \quad (4.1)$$

where F_ℓ is the total photon flux in the line, and $F_{\text{PL}}(E_\ell)$ is the photon flux density of the power-law component at the position of the line, could be estimated as $\text{EW} \sim (0.53 - 1.94) \text{ keV}$ using 200 trials, while for the model (ii) it would read as 0.36–1.10 keV.

We have also investigate the scenario with a warm ionized absorber (`warmabs`) replacing the cold neutral absorber (`zphabs`), but this did not yield any acceptable fits to the data. The fit could not be improved either by replacing the phenomenological model `powerlaw+zgauss` with a more self-consistent description of a reflection component (e.g., `pexmon`), but that could be only due to the limited *Chandra* photon energy range extending up to only 7 keV, and as such precluding from any precise characterization of a Compton hump component.

Finally, we note that the same *Chandra* dataset for NGC 3894, has been analyzed before by [She et al. \(2017\)](#), in their investigation of hundreds of nearby galaxies (distances up to 50 Mpc) with available ACIS pointings. The analysis differ from ours with respect to the source and background extraction regions; the analysis results were however comparable, except of no iron line detected in the analysis by [She et al.](#). In the Appendix 4.5.2 below, we discuss this issue in more detail, arguing that with a small source extraction region and large binning of the source spectrum, the iron line could be overlooked indeed.

Table 4.2:: Spectral modelling of the un-binned nuclear spectrum of NGC 3894 together with the background

Model	N_{H} $\times 10^{22} \text{ cm}^{-2}$	Γ	PL norm. $\times 10^{-6}$	E_{ℓ} keV	Line norm. $\times 10^{-6}$	Γ_{bck}	Bck PL norm. $\times 10^{-6}$	C-stat/DOF
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(a)	$1.24^{+0.63}_{-0.91}$	0.74 ± 0.33	$12.57^{+8.64}_{-5.05}$	—	—	0.70 ± 0.22	$3.05^{+0.83}_{-0.67}$	689.21/751
(b)	$1.92^{+0.71}_{-0.68}$	1.24 ± 0.39	$24.96^{+20.27}_{-11.02}$	6.50 ± 0.06	$1.98^{+0.91}_{-0.80}$	0.70 ± 0.22	$3.05^{+0.83}_{-0.67}$	681.665/749
(c)	$2.13^{+0.73}_{-0.70}$	1.50 ± 0.42	$33.01^{+28.80}_{-15.14}$	6.51 ± 0.06	$2.27^{+0.91}_{-0.81}$	0.70 ± 0.22	$3.05^{+0.83}_{-0.68}$	672.87/748

Col(1) — model fit; Col(2) — intrinsic hydrogen column density; Col(3–4) — photon index and normalization of the power-law emission component; Col(5–6) — Gaussian line energy and normalization; Col(7–8) — photon index and normalization of the power-law emission representing the background; Col(9) — Cash fitting statistics/DOF.

The iron line equivalent width (1σ range) reads as $\text{EW} \simeq 0.79$ (0.45 – 1.58) keV for the fit (b) with no 4.6 keV line, and $\text{EW} \simeq 1.10$ (0.65 – 1.69) keV for the fit (c) including 4.6 keV line. In the model (c), the best-fit normalization of the 4.6 keV line is $1.09^{+0.52}_{-0.46} \times 10^{-6}$

Fitting the Un-binned Data

In the case of low-count spectra, as the one we are dealing with here, spectral fittings performed on the binned data with the χ^2 statistics, could lead to biased results regarding the best-fit model parameters and a significance of the line detection. We have therefore repeated the spectral analysis with Sherpa, this time on un-binned data using the Cash statistics (and the Nelder-Mead optimalization method as before), fitting simultaneously the source and the background regions. The problem we have encountered, however, was that the background spectrum — in particular its lower-energy segment below 1 keV — could not be fitted well in this approach, with any of several models selected. For this reason, the un-binned data fitting was performed exclusively within the 1.5–7.0 keV photon energy range, where all the ISM-related absorption effects, as well as contributions from the extended thermal components, are expected to be negligible. For the background, we have assumed a single unabsorbed power-law model. For the source, we have assume either : (a) an absorbed single power-law model, `zphabs*powerlaw`, (b) an absorbed single power-law model with a redshifted Gaussian, `zphabs*(powerlaw+zgauss)` , (c) an absorbed single power-law with a redshifted Gaussian line plus an another Gaussian with the line energy frozen at 4.6 keV (in order to account for the instrumental feature due to the Si escape), `zphabs*(powerlaw+zgauss)+gaussian`. The widths of the lines were frozen at $\sigma = 0.1$ keV. The results of the fitting are summarized in Table 4.2, and for the model (c) also presented in Figure 4.6. As follows, the results of the modelling are in a very good agreement with the ones presented in the previous section (χ^2 fitting of the binned spectrum), returning in particular the equivalent width of the iron line, with the best-fit position 6.50 keV, as large as $\text{EW} \simeq 0.79$ (0.45 – 1.58) keV for the model (b), and even 1.10 (0.65 – 1.69) keV for the model (c), where the ranges enclosed by brackets correspond to 1σ errors calculated using 200 trials. Moreover, since the change in Cash statistics is distributed approximately as $\Delta\chi^2$, for the model comparison test here we chose the Maximum Likelihood Ratio test, which returns the p -values 0.02352 for models (a)

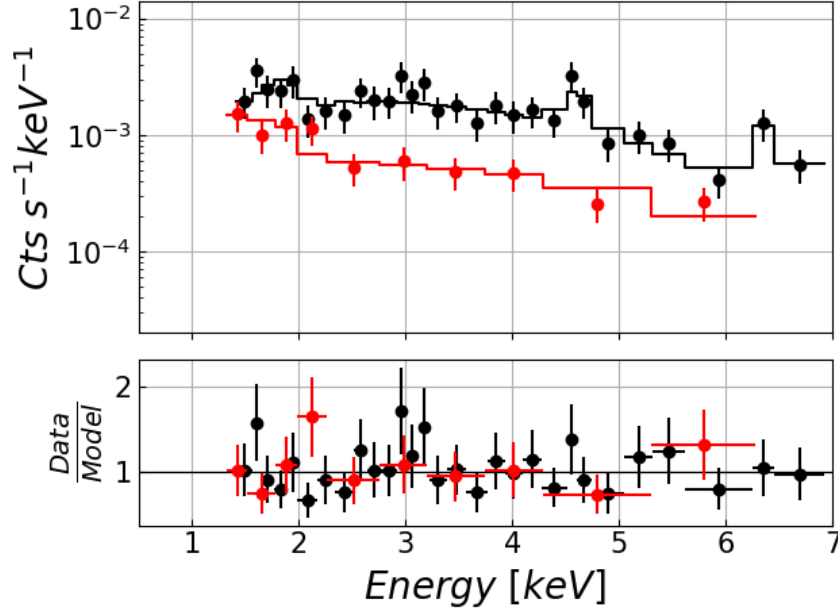


Figure 4.6: 1.5 – 7 keV *Chandra* spectrum of the unresolved X-ray core in NGC 3894 (black symbols), and the background (red symbols), along with the model curves following from simultaneous fitting `zphabs*(powerlaw+zgauss)+gaussian` performed on the un-binned data using Cash statistics (see Model (c) in Table 4.2 for the resulting best-fit model parameters).

and (b), 0.00301 for the models (b) and (c), and finally 0.00098 for the models (a) and (c). This implies that the model (c), despite being the most complex one, best describes the data, and should be selected over the models (a) and (b) with high significance.

4.2.3 Broad-band SED

The background-subtracted 0.5–7.0 keV *Chandra* spectrum of the central parts of NGC 3894 ($5'' \simeq 1.2$ kpc source extraction region), along with the *Fermi*-LAT spectral datapoints following from the analysis by Principe et al. (2020), as well as historical radio-to-UV flux measurements collected from the literature (see Appendix 4.5.1 below), are presented in the updated broad-band SED Figure 4.7. No extinction correction has been applied to the optical datapoints. As shown, the radiative output of the system is dominated by the starlight of the host at near-infrared to optical frequencies (H -band absolute magnitude of -21.80 ; see Perlman et al. 2001), with a likely contribution from the circumnuclear hot dust in the mid-IR range. We note in this context that, in the WISE color-color diagram, our target lies outside of the Stern et al. (2012) or Mateos et al. (2012) “Active Galactic

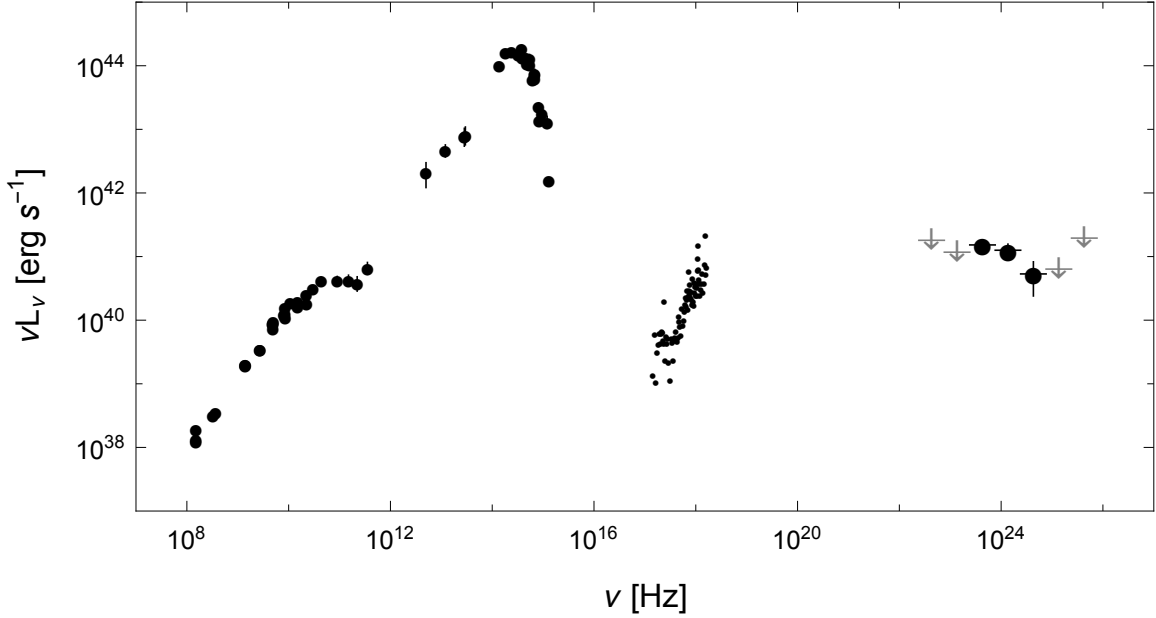


Figure 4.7: The background-subtracted 0.5–7.0 keV *Chandra* spectrum of the central parts of NGC 3894, along with the *Fermi*-LAT spectral datapoints following from the analysis by [Principe et al. \(2020\)](#), as well as historical radio-to-UV flux measurements for the target collected from the literature (see Appendix 4.5.1 below). No extinction correction has been applied to the optical/UV datapoints; likewise, the X-ray datapoints represent the observed fluxes, not corrected for the absorption.

Nucleus (AGN) cuts” (see [Kosmaczewski et al. 2020](#)), but at the same time that the efficiency of the mid-IR colour selections strongly decreases for low-luminosity AGN (see the related discussion in [Stern et al. 2012](#); [Boorman et al. 2018](#)).

The non-thermal radiative output of the active nucleus in NGC 3894, on the other hand, reaches isotropic luminosities $\lesssim 10^{41} \text{ erg s}^{-1}$ in the radio-to-mm/sub-mm range, and $\lesssim 10^{42} \text{ erg s}^{-1}$ at HE γ -ray frequencies.

4.3 Discussion

4.3.1 The Iron Line Fluorescence

The best-fit line energy for the iron fluorescence detected in the *Chandra* data for NGC 3894, $E_\ell \simeq 6.47 \pm 0.07 \text{ keV}$ (see § 4.2.2), is consistent with the position of a neutral $K\alpha$ line, 6.4 keV, within the errors, although a slight blue-shift could suggest a blend with

ionized iron features with much lower intensity. Iron fluorescence seems restricted to the unresolved core, which however corresponds in our case to the inner kpc radius around the galactic nucleus (see § 4.2.1).

Till now, neutral iron $K\alpha$ line has been found in the two other young radio galaxies of the CSO type, namely 1404+286 (aka OQ+208; [Guainazzi et al. 2004](#); [Sobolewska et al. 2019a](#)), and 2021+614 ([Sobolewska et al. 2019b](#)), none of which is however detected at HE γ -rays with *Fermi*-LAT.

We also note that iron fluorescence features in the X-ray spectra of the three other CSOs 1934–638, 1946+708, and 1607+268, claimed based on the Beppo-SAX or first XMM-*Newton* observations ([Risaliti et al. 2003](#); [Tengstrand et al. 2009](#)), have not been confirmed with the *Chandra* or the following XMM-*Newton* data ([Siemiginowska et al. 2016](#); [Sobolewska et al. 2019b](#)). On the other hand, yet another CSO 0710+439 has been found to display a very strong ionized iron line at $E_\ell \simeq 6.62 \pm 0.04$ keV, with large $\text{EW} \sim 1$ keV ([Siemiginowska et al. 2016](#)). Ionized iron line at 6.7 keV with the $\text{EW} \sim 0.3$ keV has been also found in the two other radio galaxies with young inner structures (although not strictly of the CSO morphological type), namely PMN J1603-4904 ([Müller et al. 2014](#); [Goldoni et al. 2016](#)), and CGCG 292–057 ([Balasubramaniam et al. 2020](#)).

When comparing NGC 3894 with 1404+286 and 2021+614 (see Table 1 in [Kosmaczewski et al. 2020](#), and references therein), we note that all the three sources are similarly compact (linear sizes of ~ 4 pc, ~ 10 pc and ~ 16 pc, respectively), but the latter two are (a) much more X-ray luminous (by approximately two and three orders of magnitude, respectively), and moreover (b) Compton-thick, i.e. characterized by the equivalent hydrogen column densities $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$, which is about two order of magnitude larger than N_{H} inferred in our analysis for NGC 3894. At the same time, the equivalent width of iron $K\alpha$ line in 1404+286 and 2021+614 is lower, $\text{EW} \sim 0.6$ keV and ~ 0.2 keV, respectively.

It may therefore be that, in our relatively simple modelling of the *Chandra* spectrum with a limited energy range and limited photon statistics, we seriously under-estimate the true absorbing column density (and hence also the intrinsic X-ray luminosity), for example due to the complex structure of the circumnuclear cold neutral gas and dust in the source. And indeed, the “narrow” neutral iron lines with equivalent widths of the order of 1 keV, are expected rather for Compton-thick AGN, while for the objects with $N_{\text{H}} < 10^{23} \text{ cm}^{-2}$ the iron $K\alpha$ EWs are typically of the order of 100 eV only (e.g., [Fukazawa et al. 2011a](#)). Investigating this possibility in more detail, awaits however deeper X-ray exposures of our target with the instruments such as XMM-*Newton* and Nu-STAR (but see also the discussion in the following sub-section).

In this context, we note that the result of our analysis regarding the EW value are in a accord with the “X-ray Baldwin effect”, or the “Iwasawa–Taniguchi effect” established for Seyfert galaxies of both type 1 and 2 (Iwasawa & Taniguchi 1993), which states an anti-correlation between the EW of the Fe K α emission line at 6.4 keV, and the X-ray continuum luminosity (see, e.g., Page et al. 2004; Fukazawa et al. 2011a; Ricci et al. 2014; Boorman et al. 2018, and references therein).

In particular, we refer to the work by Boorman et al. (2018), who analyzed exclusively the heavily obscured (Compton-thick) AGN, i.e. the sources for which the intrinsic (i.e., un-absorbed) X-ray fluxes at < 10 keV photon energies are difficult to assess. For those, instead of the X-ray luminosities, Boorman et al. used the mid-IR $12\ \mu\text{m}$ luminosities based on the WISE and *Spitzer* Multiband Imaging Photometer (MIPS) data, obtaining a statistically significant correlation

$$\log\left(\frac{\text{EW}_{\text{FeK}\alpha}}{\text{eV}}\right) = (2.87 \pm 0.05) - (0.08 \pm 0.04) \times \log\left(\frac{L_{12\ \mu\text{m}}}{10^{44} \text{ erg s}^{-1}}\right). \quad (4.2)$$

For the WISE $12\ \mu\text{m}$ luminosity of NGC 3894, $L_{12\ \mu\text{m}} \simeq 1.01 \times 10^{42} \text{ erg s}^{-1}$ (Kosmaczewski et al. 2020), this correlation would therefore imply $\text{EW} \simeq 1.07_{-0.28}^{+0.37} \text{ keV}$, which is in a (surprisingly) very good agreement with the best-fit value following from our spectral analysis.

4.3.2 X-ray and Radio Absorbers

Our spectral analysis reveal that the nuclear power-law X-ray emission component is seen through the cold absorbing material with the equivalent hydrogen column density $N_{\text{H}} \simeq 2.5 \times 10^{22} \text{ cm}^{-2}$. This best-fit value turns out about ~ 2 dex larger than the average value for the neutral hydrogen column density N_{HI} inferred from the HI absorption features, assuming the spin temperature of the HI gas of 100 K, and a covering factor of the order of unity (Peck & Taylor 1998; Perlman et al. 2001; Gupta et al. 2006; Emonts et al. 2010). Interestingly, this would be then in agreement with the linear relation claimed by Ostorero et al. (2017, see section 6.1, sample D' therein), namely

$$\log N_{\text{HI}} = 6.7_{-4.2}^{+4.8} + 0.63_{-0.22}^{+0.19} \times \log N_{\text{H}}, \quad (4.3)$$

with the intrinsic spread $\epsilon_{\text{H}} = 0.92_{-0.21}^{+0.30}$, which — for our best-fit value N_{H} — implies that N_{HI} should fall (with 68% probability) within a factor of about eight from $\sim 6.5 \times 10^{20} \text{ cm}^{-2}$. This agreement reinforces the main conclusions by Ostorero et al. that, in CSOs, “the X-ray and radio absorbers are either co-spatial or different components of a continuous structure”.

And conversely, if the absorbing gas column density is significantly under-estimated in our *Chandra* spectral modelling, as speculated in the previous sub-section, the average N_{HI} value according to the [Ostorero et al.](#) correlation, should be larger than observed. For example, assuming a Compton-thick limit of $N_{\text{H}} = 1.5 \times 10^{24} \text{ cm}^{-2}$, from equation 4.3 we obtain the expected $N_{\text{HI}} \simeq 8.5 \times 10^{21} \text{ cm}^{-2}$. Still, we emphasize a rather large intrinsic spread in the correlation 4.3 (factor of about eight), interpreted as due to a spread in the HI gas spin temperature (which may vary substantially from the typically assumed “universal” value of 100 K; see the discussion in [Ostorero et al. 2017](#)).

4.3.3 The Overall Energetic of the Active Nucleus

The optical velocity dispersion of the central $3.5''$ of the galaxy was measured by [van den Bosch et al. \(2015\)](#), with the 10 m Hobby–Eberly Telescope (HET) at McDonald Observatory, as $\sigma = 326.0 \pm 10.1 \text{ km s}^{-1}$. [van den Bosch et al.](#) provided also the best-fit relation between the velocity dispersion and the black hole mass

$$\log \left(\frac{\mathcal{M}_{\text{BH}}}{M_{\odot}} \right) = \alpha + \beta \times \log \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right), \quad (4.4)$$

with $\alpha = 8.24 \pm 0.06$, $\beta = 5.28 \pm 0.37$, and the intrinsic scatter $\epsilon_{\mathcal{M}} = 0.40 \pm 0.21$, consistent with [McConnell & Ma \(2013\)](#). With such, for NGC 3894 we obtain $\mathcal{M}_{\text{BH}} \sim 2 \times 10^9 M_{\odot}$ withn a factor of 2.5, which is in a very good agreement with the value obtained by [Willett et al. \(2010\)](#), based on the [Oiv] $25.8 \mu\text{m}$ transition line. The estimate does not change if the $\mathcal{M}_{\text{BH}} - \sigma$ scaling relation for ellipticals and bulge-like systems from [Graham et al. \(2011\)](#) is used instead ($\alpha = 8.13 \pm 0.05$, $\beta = 5.13 \pm 0.34$). We note that, on the other hand, the estimate based on the bulge–luminosity relation using the g and r photometry from the Sloan Digital Sky Survey (SDSS), returns the black hole mass lower by one order of magnitude (see [Willett et al. 2010](#)).

With $\mathcal{M}_{\text{BH}} \sim 2 \times 10^9 M_{\odot}$, the corresponding Eddington luminosity reads as $L_{\text{Edd}} \sim 3 \times 10^{47} \text{ erg s}^{-1}$, and the X-ray radiative output of the NGC 3894 unresolved core, in the Eddington units, as $L_{\text{X}}/L_{\text{Edd}} \sim 2 \times 10^{-7}$. Likewise, the jet/lobe-related HE γ -ray emission of the source, as estimated by [Principe et al. \(2020\)](#), turns out to be one order of magnitude larger than that, namely $L_{\gamma}/L_{\text{Edd}} \sim 2 \times 10^{-6}$.

Unfortunately, the bolometric accretion-related luminosity in the target, L_{bol} , is unknown and hard to assess with the available optical spectroscopy of the nuclear region (see [Kim 1989](#); [Gonçalves & Serote Roos 2004](#)). For a rough estimate, one could try to use the observed X-ray core emission, assuming that it provides a limit on the disk coronal radiative output, and hence on the direct disk continuum emission. However, the ratio

L_X/L_{bol} is known to vary widely among the youngest radio galaxies of the CSO type, from $\gtrsim 0.1$ down to $< 10^{-3}$ (see [Wójtowicz et al. 2020](#)).

Alternatively, one may use the observed IR flux, assuming that it provides a limit on the emission of the circumnuclear dust in the source. Hot dusty tori in active galaxies are, in general, expected to reprocess about $\eta_{\text{DT}} \sim 10\%$ of the accretion disk bolometric luminosity. With such, the integrated $8 - 1000 \mu\text{m}$ luminosity of NGC 3894 as estimated by [Kosmaczewski et al. \(2020\)](#), would then imply an upper limit on the accretion disk luminosity $L_{\text{bol}} \sim 5 \times 10^{43} \text{ erg s}^{-1}$, or in terms of the accretion rate $\lambda_{\text{Edd}} \equiv L_{\text{bol}}/L_{\text{Edd}} \sim 10^{-4}$. We stress, however, that the above estimate is highly uncertain, because of the uncertain value of the radiative efficiency factor η_{DT} , and also due to the fact that the “calorimetric” properties of circumnuclear dust can only reflect the nuclear power output averaged over some longer period of time, rather than the accretion disk luminosity at a given (present) moment.

Finally, we estimate the jet kinetic power P_j in the radio source 1146+596. In particular, assuming the minimum power condition, linear size and kinematic age of the radio structure $LS \simeq 4 \text{ pc}$ and $\tau_j \sim 60 \text{ yr}$ ([Principe et al. 2020](#)), as well as the VLBA 5 GHz flux of 387.6 mJy ([Helmboldt et al. 2007](#)), corresponding to the monochromatic radio power $L_{5 \text{ GHz}} \sim 0.6 \times 10^{40} \text{ erg s}^{-1}$, from equation 4 in [Wójtowicz et al. \(2020\)](#) we obtain $P_j \sim 2 \times 10^{42} \text{ erg s}^{-1}$, or $P_j/L_{\text{Edd}} \sim 0.7 \times 10^{-5}$. This implies that the observed X-ray luminosity (exclusively the power-law emission component), could, in principle, be contributed by the jet emission, as it represents only a small fraction of the jet kinetic power, of the order of a few percent. The HE γ -ray emission, on the other hand, if due to the jets/compact lobes, would require a much higher radiative efficiency, at the level of $\gtrsim 10\%$. Still one has to keep in mind that the above estimate for P_j , relies on the assumed minimum power condition, and as such corresponds to rather a lower limit for a true jet kinetic power in the source.

4.4 Conclusions

In this paper we report on our analysis of the archival *Chandra* X-ray Observatory data for the central part of the elliptical/S0 galaxy NGC 3894, hosting a radio source 1146+596, one of the youngest and nearest confirmed CSOs, and one of only several young radio galaxies (of “non-blazar” type) detected at HE γ -rays with the *Fermi*-LAT. The analyzed data consist of a single 40 ksec-long ACIS exposure. We have found that the core spectrum is best fitted by a combination of a collisionally ionized thermal plasma with the temperature of $\simeq 0.8 \text{ keV}$, and a moderately absorbed power-law component (photon index $\Gamma \simeq 1.4 \pm 0.4$, hydrogen column density $N_{\text{H}}/10^{22} \text{ cm}^{-2} \simeq 2.4 \pm 0.7$). We have also

detected the iron $K\alpha$ line at $\simeq 6.47 \pm 0.07$ keV, with a relatively large equivalent width of $EW = 0.96$ ($0.53 - 1.94$) keV. The soft thermal component is undoubtedly extended on the scale of the galaxy host. The iron fluorescence, on the other hand, seems restricted to the unresolved inner kpc radius around the galactic nucleus. The results summarized above, following from fitting the binned data, were supported by the additional analysis performed on the un-binned data, strengthening our claim of the iron line detection.

We conclude that the detected iron line is therefore most likely indicative of the X-ray reflection from a cold neutral absorber in the central regions of NGC 3894. Yet the emerging relatively large EW of the feature, seems rather confusing, keeping in mind only a moderate obscuration implied by our spectral analysis. For this reason, we speculate that in our relatively simple modelling of the *Chandra* data with a limited energy range and limited photon statistics, we could seriously under-estimate the true absorbing column density in the source. This speculation seems supported by the agreement of our best-fit EW Fe $K\alpha$ value with the $EW_{\text{Fe}K\alpha} \propto L_{12\mu\text{m}}^{-0.08}$ anticorrelation following from the Iwasawa–Taniguchi (or the “X-ray Baldwin”) effect, established for heavily obscured AGN by Boorman et al. (2018), for a given $12\mu\text{m}$ luminosity of the target as measured with WISE.

A moderate X-ray obscuration in the NGC 3894 nucleus seems, on the other, supported by the agreement of our best-fit N_{H} value and the average neutral hydrogen column density N_{HI} inferred from the redshifted HI absorption seen against the continuum emission of the central compact radio structure, with the $N_{\text{HI}} \propto N_{\text{H}}^{+0.63}$ correlation claimed by Ostorero et al. (2017).

We also update on the broad-band SED of NGC 3894, and discuss the overall energetics of the active nucleus in the system. In particular, based on the optical velocity dispersion of the central $3.5''$ of the galaxy measured by van den Bosch et al. (2015), we estimate the black hole mass in the system as $\mathcal{M}_{\text{BH}} \sim 2 \times 10^9 M_{\odot}$ within a factor of 2.5. We also attempt to estimate roughly the accretion rate in the source, based on the observed IR luminosity (considered as a proxy for the radiative output of the circumnuclear hot dusty torus), as $\lambda_{\text{Edd}} \sim 10^{-4}$. Such a low accretion rate is in agreement with the LINER classification of the active nucleus in NGC 3894. Finally, we also estimate the minimum kinetic power of compact jets in 1146+596 as $P_{\text{j}} \sim 2 \times 10^{42} \text{ erg s}^{-1}$.

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4.5 Appendix

4.5.1 Low-Frequency Spectral Measurements

The radio source 1146+596 is known to be variable on year timescales. For instance, according to the continuous OVRO monitoring since 2008 (Richards et al. 2011b), the 15 GHz flux densities vary from ~ 400 to 500 mJy. The few integrated measurements at 8 GHz indicate similar variations from 436 to 520 mJy (see Table 4.3). From available images in the RFC database⁵, this level of change can be attributed to changes in the VLBI core, with observed 8 GHz flux densities of 66 mJy in 1994 Aug, and 155 to 183 mJy in 2017 Apr and Aug, respectively. The VLBI-scale jet knots appear variable as well, but with typical 5-8 GHz flux densities observed at levels of ~ 10 's mJy (Principe et al. 2020).

Historical IR–optical–UV flux density measurements of NGC 3894 collected from the literature⁶, with no extinction correction applied, are summarized in Table 4.4.

4.5.2 Additional Spectral Modelling

She et al. (2017) investigated 719 galaxies located within 50 Mpc, with available *Chandra*-ACIS pointings; their sample of objects included NGC 3894. With a smaller source extraction region and a closer background when compared to our analysis, She et al. binned the background-subtracted source spectrum of the target with minimum 15 photons, and applied the spectral model including a thermal emission component and an absorbed power-law, obtaining comparable results with respect to the temperature of the thermal plasma, $kT \sim 0.85$ (0.20 – 1.10) keV, the equivalent hydrogen column density, $N_{\text{H}}/10^{22} \text{ cm}^{-2} \simeq 2.77$ (1.70 – 4.14), as well as the normalization and slope of the power-law component, $\Gamma = 1.23$ (0.65 – 1.90). No iron line was detected by She et al..

In order to address the discrepancy regarding a presence of the iron line in the nuclear

⁵<http://astrogeo.org/rfc/>

⁶see also <http://ned.ipac.caltech.edu>

Table 4.3:: Historical integrated radio flux density measurements of NGC 3894.

ν [GHz]	$S_\nu \pm \Delta S_\nu$ [mJy]	Catalog/Names* & Reference
90	160 ± 20	Puschell (1981)
30	362 ± 22	OCRA-p (Lowe et al. 2007)
22	390 ± 20	Lee et al. (2017)
15	441 ± 2	OVRO-40m (Richards et al. 2011b)
10.7	600 ± 48	S4 1146+59 (Pauliny-Toth et al. 1978)
8.5	436 ± 4	Fassnacht & Taylor (2001)
8.4	521.7 ± 52.2	CRATES J114850.36+592456.4* (Healey et al. 2007)
8.1	520 ± 52	NRAO 300-f* (Wardle & Sramek 1974)
5.0	660 ± 20	Wrobel (1983)
4.9	606 ± 9	S4 1146+59 (Pauliny-Toth et al. 1978)
4.85	627 ± 62	87GB 114610.9+594135 (Gregory & Condon 1991)
2.7	440 ± 11	S4 1146+59 (Pauliny-Toth et al. 1978)
2.7	440 ± 44	NRAO 300-f* (Wardle & Sramek 1974)
1.4	471.6 ± 47.2	FIRST J114850.3+592456* (Becker et al. 1995)
1.4	481.4 ± 14.4	NVSS J114850+592457 (Condon et al. 1998)
0.365	327 ± 19	TXS 1146+596 (Douglas et al. 1996)
0.325	331 ± 33	WN B1146.1+5941* (Rengelink et al. 1997)
0.15	282.8 ± 28.6	TGSSADR J114850.2+592456 (Intema et al. 2017)
0.151	430 ± 43	7C 114610.00+594129.00* (Hales et al. 2007)
0.151	300 ± 30	6C 114613+594127* (Hales et al. 1990)
43.3	330 ± 33	VLA Calibrator Manual* (Perley & Taylor 2003)
22.5	280 ± 60	VLA Calibrator Manual* (Perley & Taylor 2003)
14.9	380 ± 60	VLA Calibrator Manual* (Perley & Taylor 2003)
8.4	630 ± 69	VLA Calibrator Manual* (Perley & Taylor 2003)
4.9	520 ± 78	VLA Calibrator Manual* (Perley & Taylor 2003)
1.4	480 ± 68	VLA Calibrator Manual* (Perley & Taylor 2003)

*Catalogs/Names indicated with asterisks did not quote uncertainties, and 10% was assumed here.

spectrum of NGC 3894, we repeat our analysis by choosing a smaller source extraction region of 5 px radius, and a close background from within 10 – 20 px, consistently with She et al. (2017). First we note, however, that for many realizations of the simulated 6.0–7.0 keV PSF for the target (see Section 4.2.1 above), the 5 px source extraction region encompasses less than 2σ of the count fraction, as visualized in Figure 4.8. Indeed, with the 5 px source extraction region, we measure 22 net counts for the target within the hard band, corresponding to about 85% of the net counts measured with the 10 px source extraction region.

We next fit the background-subtracted source spectrum, grouped with minimum 5 or 15 photons, assuming a simple model `zphabs*powerlaw+apec`. The results of the fitting are presented in Figure 4.9, and summarized in Table 4.5. As follows, for the small source extraction region the iron line can still be noted in the binned spectrum (or in the fitting residuals) but only for a small binning (min 5), while it seemingly disappears for a

Table 4.4.: Historical integrated IR-to-UV flux density measurements of NGC 3894.

ν [GHz]	S_ν [mJy]	$\pm\Delta S_\nu$ [mJy]
1.50E2	94.9	18.3
2.22E2	57.6	14.6
3.53E2	62.9	13.3
5.00E3	140	59
1.20E4	130	28
2.83E4	93	29
2.97E4	93	29
1.38E5	252	3.5
1.82E5	303	3.1
2.4E5	241	2.2
3.25E5	157	2.9E−1
3.79E5	168	15.5
3.89E5	119	1.1E−1
4.68E5	98.3	9.05
4.77E5	76.3	1.41E−1
5.42E5	81.1	11.2
5.42E5	66.2	4.27
6.17E5	33.9	6.24E−2
6.81E5	36.8	5.45
6.81E5	31.7	3.21
6.81E5	37.8	5.20
8.19E5	9.33	1.30
8.36E5	5.64	2.08E−2
9.52E5	6.25	1.91
1.20E6	3.66	0.78
1.29E6	0.419	5.87E−3

larger binning (min 15). This, in fact, should be expected keeping in mind the very limited photon statistics in the hard *Chandra* band. At the same time, with a small binning the fit returns unrealistic values of the model parameters, e.g. the photon power-law index $\Gamma \simeq 0$, or the unconstrained absorbing hydrogen column density N_{H} . The source spectrum and the model fit corresponding to grouping with minimum 15 photons, are in agreement with [She et al. \(2017\)](#).

Table 4.5:: Additional spectral modelling of the NGC 3894 nucleus

Model	N_{H} $\times 10^{22} \text{ cm}^{-2}$	kT keV	APEC norm. [†] $\times 10^{-6} \text{ XSPEC}$	Γ	PL norm. [†] $\times 10^{-6} \text{ XSPEC}$	χ^2/DOF
(1)	(2)	(3)	(4)	(5)	(6)	(7)
grouping min 5	1.68 ± 0.57	0.84 ± 0.07	2.16 ± 0.36	1.0 ± 0.33	15.14 ± 7.7	49.71/68
grouping min 15	1.62 ± 0.57	0.89 ± 0.08	2.23 ± 0.42	0.95 ± 0.34	15.20 ± 7.75	18.46/23

Col(1) — model fit; Col(2) — intrinsic hydrogen column density; Col(3–4) — temperature and normalization of the collisionally ionized thermal plasma; Col(5–6) — photon index and normalization of the power-law emission component; Col(7) — fitting statistics.

All the models include Galactic hydrogen column density $N_{\mathrm{H}, \text{Gal}} = 1.83 \times 10^{20} \text{ cm}^{-2}$; thermal component assumes solar abundance.

[†] The XSPEC normalizations are: (a) for the APEC component $10^{-14} (1+z)^2 n_e n_{\mathrm{H}} V / 4\pi d_L^2$, assuming uniform ionized plasma with electron and H number densities n_e and n_{H} , respectively, and volume V , all in cgs units; (b) for the power-law component photons/keV/cm²/s at 1 keV.

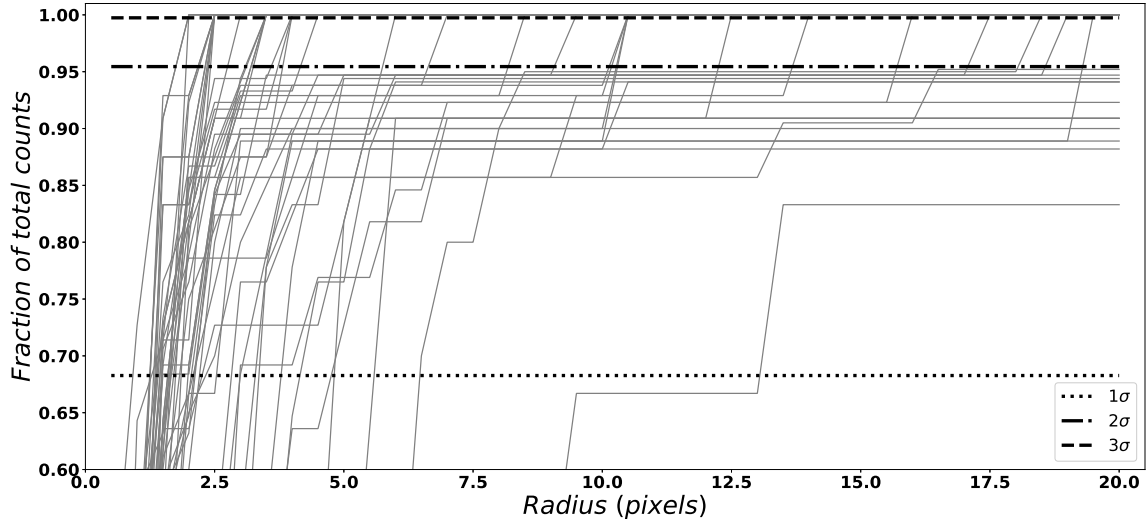


Figure 4.8: Enclosed count fraction for 50 simulated PSF images in the narrow range 6.0-7.0 keV; horizontal dotted lines from bottom to top correspond to 1σ , 2σ , and 3σ count fractions, respectively.

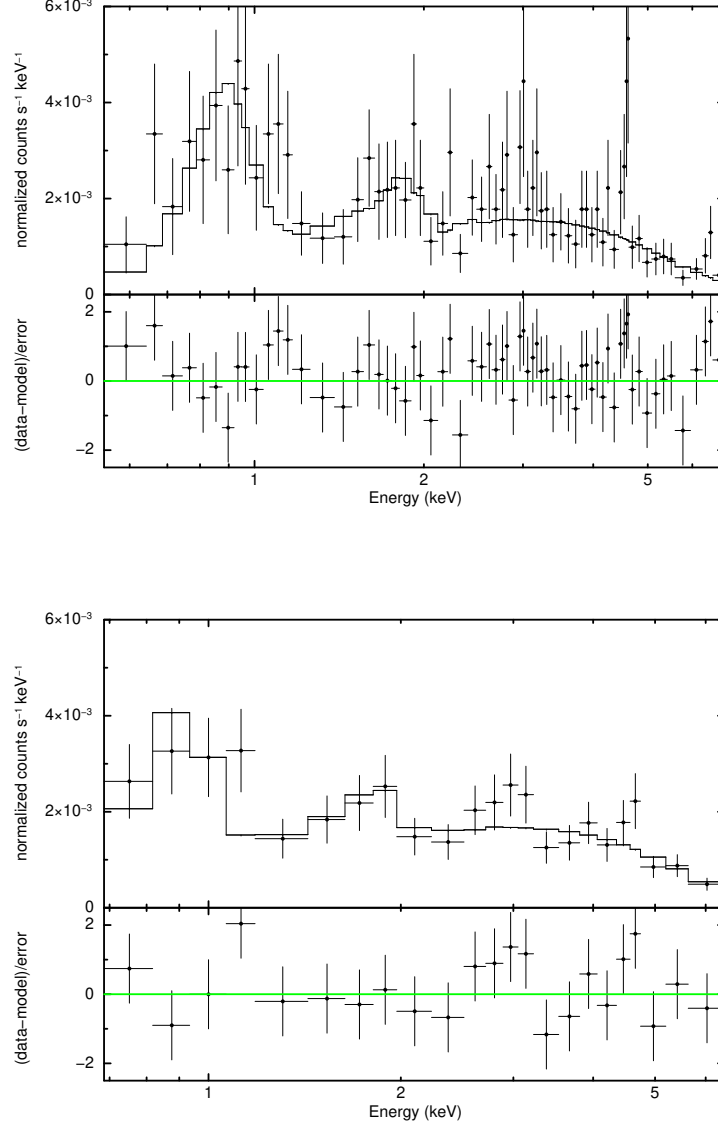


Figure 4.9: Background-subtracted 0.5 – 7 keV *Chandra* spectrum of the unresolved X-ray core in NGC 3894 corresponding to the small source extraction region (radius = 5 px) and a close background (annulus with radii = 10 – 20 px), fitted with emission model `zphabs*powerlaw+apec`, with the applied grouping minimum 5 photons (upper panel) and 15 photons (lower panel). See Table 4.5 for the resulting best-fit model parameters.

Chapter 5

Conclusions and Final Remarks

Active galactic nuclei (AGN) are the systems powered by a matter falling onto a super-massive black hole (SMBH) residing in a center of a galaxy. The X-ray radiation emitted by the accreting matter is particularly intriguing, since it may originate very close to the SMBH event horizon, and as such it is expected to bear the hallmark of the intense gravitational field. Typically, this X-ray radiation is composed of several distinct spectral components. First, when optical/UV disc photons are inverse-Compton scattered by a corona of hot electrons around the SMBH, the main X-ray continuum emission takes on a power-law shape. Second, a fraction of this radiation is reflected and reprocessed by the accretion flow itself, and next by the absorbing gas and dust located further away from the center (within ionized disk outflows and circumnuclear dusty tori). And third, X-ray emission spectra of AGN are often contributed by a thermal emission of a hot gas (collisionally ionized and/or photoionized plasma), as well as — in the case of radio-loud (jetted) systems — by a non-thermal emission of relativistic jets. A robust identification and modelling of all such components, requires high-quality (i.e., high energy-resolution) X-ray spectra with sufficient photon statistics in a broader range of frequencies, obtained in addition with high angular-resolution telescopes.

The reprocessing of the X-ray (disk corona) continuum by the surrounding gas and dust, includes photoelectric absorption, followed by fluorescent line emission: when the direct X-ray continuum shines on elements, it produces X-ray emission lines to glow. Out of all fluorescence features, the iron feature is the most prominent; this is due to the combination of the high relative abundance of iron, and its high fluorescence yield. The $K\alpha$ line from a cold neutral iron is positioned at ~ 6.4 keV; for ionized iron, the lines' energies are increased. Moreover, when produced around the innermost orbits of the

CHAPTER 5. CONCLUSIONS AND FINAL REMARKS

accretion disks, the iron features are relativistic broadened and gravitationally redshifted, depending on the disk structure, as well as the black hole spin.

In my research, summarized in this thesis, I have analyzed in detail the X-ray radiative output of the three radio-loud AGN of various types, focusing in particular on their Fe fluorescence emission.

In the first system analyzed, the broad-line quasar 4C +74.26 with giant large-scale radio morphology, by means of modeling the relativistically broadened iron line, I have provided constraints on the structure of the innermost portions of the accretion disk, which enabled in turn an in-depth investigation of the disk-jet coupling in the system, using our multi-wavelength monitoring data at radio, optical, and X-ray frequencies. The analysis I have performed on a photon-rich *NuSTAR* spectrum of the source, relied on a combination of the relativistic reflection model RELXILL with the warm ionized absorber model WARMABS, and implied in particular a truncated disk in 4C +74.26, with the inner disk radius of the order of tens of gravitational radii (assuming a maximum spin of the black hole).

The second system I have analyzed based on the originally acquired ~ 100 ksec *Chandra* observations, was the intriguing LINER-type AGN CGCG 292–057 hosted by a post-merger disk galaxy, with a multi-scale and multi-component radio morphology reflecting intermittent jet activity of the central SMBH. In our analysis, we detected the excess X-ray emission on the scale of the host galaxy bulge, resulting from compression and heating of the hot diffuse fraction of the interstellar medium displaced by the expanding inner radio lobes. The nuclear X-ray spectrum of the target revealed also an ionized iron line at ~ 6.7 keV. We demonstrated that the observed equivalent width of Fe XXV $K\alpha$ (of order 0.3 keV) could be explained in a scenario involving a Compton-thin gas located at the scale of the broad-lined region in this source and photoionized by nuclear (disk and disk corona) illumination. By comparing the spectral properties of CGCG 292–057 with those of other nearby AGN, we argued that the system appears under-luminous in X-rays for its bolometric disk luminosity, and at the same time over-luminous in radio. As such, the post-merger AGN CGCG 292–057 appears to be located almost exactly in between the populations of X-ray-luminous Seyfert galaxies, which are typically hosted by spiral/disk galaxies, and Radio Galaxies, which are typically hosted by ellipticals.

The third analyzed radio source, 1146+596 hosted by an elliptical galaxy NGC 3894, with a low-luminosity active nucleus, is one of the youngest radio galaxies known (kinematic age of the jets of only ~ 60 yrs), which recently has been also confirmed as a high-energy γ -ray emitter. Despite a very limited photon statistics in the archival *Chandra* data (corresponding to a single ACIS-S 40 ksec-long exposure), we have managed to find that the X-ray spectrum of the target is best fitted by a combination of an ion-

CHAPTER 5. CONCLUSIONS AND FINAL REMARKS

ized thermal plasma, and a moderately absorbed power-law component, with a prominent iron $K\alpha$ line at $\simeq 6.4$ keV. We argued that the line, with the estimated equivalent width of $EW \simeq 1$ keV, is indicative of the X-ray reflection from a cold neutral gas in the central regions of NGC 3894, consistently with the “X-ray Baldwin effect” (or the “Iwasawa-Taniguchi effect”), given the mid-infrared luminosity of the AGN. However, we also noted that the large EW of the fluorescence feature stands at odds with only a moderate absorption inferred from the modelling, suggesting that the true absorbing column density, may be seriously under-estimated in our analysis, due to the complex structure of the circumnuclear cold neutral gas and dust in the system.

All in all, my research reveals a prevalent fluorescent iron line emission in various types of radio-loud AGN, including both low- and high-luminosity objects (i.e., SMBHs accreting at low and high rates, respectively), hosting radio structures ranging from the smallest ones (and therefore the youngest, $\lesssim 100$ yr-old), up to the giant ones (and hence the oldest, ~ 100 Myr-old). There is a variety in the iron features in the population of jetted AGN, including relativistically broadened lines, ionized lines, and neutral lines with a larger range of equivalent widths. Detailed modelling of such lines, provides in general crucial information regarding the structure of AGN, including the innermost segments of accretion disks and disk coronae in the closest vicinity of SMBHs, ionized disk outflows, and circumnuclear dusty tori. A robust modeling, on the other hand, is often hampered by either a limited photon statistics, or a limited angular resolution, of the currently operating X-ray telescopes. This, on the other hand, is expected to change dramatically in the near future, with the launch of the XRISM and Athena missions. Together with my supervisor, we hope that the research I have carried out during my PhD program, does provide a notable contribution in this respect, prompting in particular on the importance of the iron fluorescence studies for radio-loud AGN, for which the constraints regarding AGN innermost structure enabled exclusively by the X-ray spectroscopy, can be complemented uniquely by the constraints on the energetic and duty cycle of the systems, following from the analysis of their radio (jet) emission.

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