



Article

Separating the Spectral Counterparts in NGC 1275/Perseus Cluster in X-Rays

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Abstract: We present a model-independent method for separating the spectral counterparts of the active galactic nucleus (AGN) NGC 1275 from the surrounding emission of the Perseus cluster, as observed by Suzaku/XIS cameras. The Perseus cluster emission extends to higher energies than typically observed in AGN environments, reaching up to 9–10 keV. This necessitates precise separation of AGN and cluster spectra. To circumvent the degeneracy arising from numerous spectral fitting parameters, including elemental abundances, thermal and Compton emissions from the nucleus, and spectral parameters of the jet synchrotron self-Compton/inverse Compton emissions, we avoid traditional spectral fitting methods. Instead, we leverage spatial resolution and employ a double background subtraction approach. We apply this procedure to the complete set of Suzaku/XIS observational data for NGC 1275, resulting in cleaned spectra and a light curve of the AGN emission in this system. To demonstrate the applicability of our method, we also utilize the available XMM-Newton/EPIC data.

Keywords: black hole physics; galaxies; active; X-rays; clusters



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1. Introduction

NGC 1275 (3C 84 or Perseus A) is a giant elliptical galaxy hosting the active nucleus of the Seyfert 1.5 type [1] classified as a Fanaroff–Riley type I radio-loud (RL) with a compact central source and extended jet [2,3]. It is situated at the center of the Perseus/Caldwell24 cluster of galaxies with the redshift $z = 0.01756$ [4]. The supermassive black hole (SMBH) mass in the AGN center is $\sim 3.4 \cdot 10^8 M_{\odot}$ [5].

NGC 1275 is surrounded by a massive network of cool gaseous filaments with a frozen-in magnetic field associated with a cooling flow [6,7]. These filaments emit an intensive network of spectral lines. Moreover, NGC 1275 contains a high-velocity system (HVS) of molecular gas moving in front of it towards its center [8,9], and hot radio-bright bubbles of relativistic plasma fed by the jets, heating the inner gas and preventing the radiative cooling-induced runaway [10]. The HVS system probably plays a significant role in the nucleus fueling [11].

The first detailed view of NGC 1275 and the Perseus Cluster in X-rays was obtained by RoSat (Roentgen Satellite)/HRI (High-Resolution Imager) [12]. It revealed the complicated substructure of the X-ray surface brightness within ≈ 5 arcminutes around the NGC 1275

center. They also found 30% surface brightness variations, presumably connected with the inflating of the relativistic plasma bubbles by the jets. Next, in 1996, NGC 1275 was detected by the Atmospheric Cherenkov Telescopic System, SHALON at TeV energies [13].

The SMBH nested in the nucleus of NGC 1275 was the first black hole “heard” by the Chandra X-ray Observatory [14]. These observations detected sound waves expanding in the warm gas surrounding the nucleus and heating it. They also revealed two vast bubbles in this gas, emanating from the NGC 1275 “central engine” [15].

Since then, NGC 1275 has been observed in X-rays quite intensively by several cosmic X-ray missions such as XMM-Newton, Suzaku, Swift, etc. A mutual analysis of the Suzaku/XIS (X-ray Imaging Spectrometer) and Fermi/LAT (large area telescope) data revealed the first evidence of correlated variability in X-rays and γ -rays during the period 2013–2015. The wide-band variability of NGC 1275 was investigated in [16,17] (γ -rays), [18] (X-rays to γ -rays), [19] (UV to soft γ -rays), and [20] (radio to the highest γ -rays). Short-term, rapid fluctuations in UV to X-ray emissions show a correlation with GeV γ -rays. The gradual correlated changes of the UV and soft/hard X-ray fluxes along with the GeV γ -rays were confirmed [19].

The γ -ray activity in 3C 84 can be split into short-term outbursts on top of a long-term, slowly increasing trend (also seen in the optical V band by Nesterov et al. [21]).

At the highest energies 90–1200 GeV, the spectrum follows the power-law with the photon index above 3, attributed to pure jet with no additional components due to diffuse medium [22]; the flares were observed in this energy range as well [23]. Such flares were interpreted in [24] as the result of the jet precession.

Long-term variations have been detected in the soft X-ray range, alongside variations in radio and GeV γ -ray emissions (as noted in Fabian et al. [25] and Fukazawa et al. [26]). These fluctuations likely suggest that we are witnessing the presence of X-ray emissions originating from the jet [19].

The highest spectral resolution in X-rays was achieved in the Hitomi observation of NGC 1275 [27]; despite the presence of the extremely bright emission line near 6.6 keV, the narrow F-K α 6.4 keV line with the EW $\approx$ 20–25 eV emitted either in the outer parts of the accretion disk or in the torus was resolved as well. However, the iron K α equivalent widths detected earlier by XMM-Newton were significantly higher: $\approx$ 70–80 eV in 2006 [28] and even $\approx$ 165 eV in 2001 [29]. The recent Swift data analyses [19] confirmed the presence of the Fe-K fluorescence line, indicating the presence of an accretion disk rather than the torus, but the low quality of the BAT (15–150 keV) spectrum did not allow them to detect high-energy exponential cut-off in the hard X-ray spectrum.

The deep Cycle-19 of the Chandra/HETG (high-energy transmission Grating) observations of NGC 1275 revealed several emission lines of highly ionized iron and mildly ionized Mg, S, and Si [30]). The 6.4 keV iron-K α line was detected by Chandra as well, with even lower EW at the 14 eV level.

The multiwavelength study of NGC 1275 in [31] revealed the four distinct activity phases in X-ray and γ with an increase in the baseline X-ray and UV fluxes during the first three phases, explained by the inverse Comptonization of the synchrotron photons by the jet electrons [31].

Absorption features were identified in the radio continuum emitted by the central parsec-scale jet [32]. Their blue shift in the range of 300–600 km/s indicates a rapid molecular outflow originating from the AGN with the column density $N_{\text{H}_2} \approx 2.3 \cdot 10^{22} \text{ cm}^{-2}$.

Due to the presence of the near year-long quasi-periodic oscillations at 1.3 mm wavelength, NGC 1275 is also considered a possible double BH candidate [33].

The resolution of the Suzaku Point Spread Function (PSF) is insufficient to resolve the nucleus of NGC 1275 effectively. Therefore, we employed imaging spectroscopy to extract the emission from the AGN. The spectrum of NGC 1275 is heavily contaminated by the Intra-Cluster Medium (ICM) emission, contributing up to 80–90% within the soft to intermediate X-rays. In this work, we develop an algorithm of two-step background

subtraction, which could give us the possibility to subtract the cluster emission from the AGN spectrum without using the spectral modeling.

In Section 2, Data Processing, we describe the Suzaku/XIS data reduction and the recipe we propose to perform two-step background subtracting. We also demonstrate an example of the resulting cleaned spectrum of the nucleus and perform the simple preliminary fitting using the power-law model plus emission from hot diffuse gas with the neutral absorption $tbabs(N_{H,pl}) \cdot po(\Gamma) + tbabs(N_{H,KT}) \cdot mekal(kT)$. Furthermore, we present a monthly light curve spanning nearly a decade, providing a comprehensive overview in this section. In Section 3, Conclusions and Further Perspectives, we describe some further steps we are going to conduct using these results to obtain the physically motivated picture of the NGC 1275 nucleus and its high-energy spectrum and draw out our conclusions.

2. Data Processing

The primary objective of this study is to devise a model-independent method for isolating the source spectra from their surrounding spectra without resorting to spectral fitting. This task is performed in two steps. The first step involves standard data reduction to obtain the uncleaned spectra of the source (in our case, the AGN + cluster), its surroundings (i.e., the cluster), and the remote background. This first step is described in Section 2.1. In the second step, we describe the procedure and implement it on the Suzaku/XIS X-ray spectra of NGC 1275 to separate the AGN counterparts from those of the surrounding cluster. The analysis and discussion of our data treatment are described in Section 2.2. The method employed for the double background subtraction of the AGN spectra in NGC 1275 is described in detail in Appendix A.

2.1. Primary Suzaku/XIS Data Reduction

We processed the entire set of Suzaku/XIS observations of NGC 1275 AGN in the Perseus galaxy cluster. The basic parameters of these observations are presented in Table 1.

Table 1. Suzaku/XIS NGC 1275 observations LOG. The data events from various observations are shown in one cell; more than one observation during one month was merged to produce a common spectrum and marked as “total” below.

Obs. ID	Obs. Date	Active Cameras	Obs. Time ksec	Total Flux cts
800010010	2006-02-01	XIS0-XIS3	50.4	417,100 $\pm$ 2131
101012010	2006-08-29	XIS0-XIS3	150.9	13,396,000 $\pm$ 3940
101012020	2007-02-05	XIS0, XIS1, XIS3	43.8	2,884,200 $\pm$ 1778
102011010	2007-08-15	XIS0, XIS1, XIS3	42.3	2,889,000 $\pm$ 1777
102012010	2008-02-07	XIS0, XIS1, XIS3	61.7	4,560,200 $\pm$ 2235
103004010	2008-08-13	XIS0, XIS1, XIS3	40.6	2,431,000 $\pm$ 1635
103005010	2008-08-14	XIS0, XIS1, XIS3	21.5	517,280 $\pm$ 800
Total			61.6	2,948,280 $\pm$ 1790
103004020	2009-02-11	XIS0, XIS1, XIS3	50.0	3,265,086 $\pm$ 1886
103005020	2009-02-12	XIS0, XIS1, XIS3	28.8	1,833,000 $\pm$ 1481
Total			78.8	5,098,086 $\pm$ 2406
104018010	2009-08-26	XIS0, XIS1, XIS3	41.3	2,945,544 $\pm$ 1764
104020010	2009-08-27	XIS0, XIS1, XIS3	55.0	3,945,960 $\pm$ 2127
Total			96.3	6,891,504 $\pm$ 2780
104019010	2010-02-01	XIS0, XIS1, XIS3	38.6	2,428,740 $\pm$ 1646
104021010	2010-02-02	XIS1, XIS3	21.6	923,236 $\pm$ 1045
Total			60.2	3,351,976 $\pm$ 1922

Table 1. Cont.

Obs. ID	Obs. Date	Active Cameras	Obs. Time ksec	Total Flux cts
105009010	2010-08-09	XIS0, XIS1, XIS3	33.6	2,500,000 $\pm$ 1697
105010010	2010-08-10	XIS0, XIS1, XIS3	27.4	2,125,629 $\pm$ 1576
Total			61.0	4,623,629 $\pm$ 2232
105010020	2011-02-02	XIS0, XIS1, XIS3	21.1	1,414,400 $\pm$ 1191
105009020	2011-02-03	XIS0, XIS1, XIS3	40.5	2,686,704 $\pm$ 1807
105028010	2011-02-21	XIS0, XIS1, XIS3	20.6	1,414,872 $\pm$ 1234
105027010	2011-02-22	XIS0, XIS1, XIS3	45.3	2,884,020 $\pm$ 1704
Total			127.5	8,399,996 $\pm$ 2968
106006010	2011-07-26	XIS0, XIS1, XIS3	40.1	1,767,084 $\pm$ 1452
106005010	2011-07-27	XIS0, XIS1	40.8	1,739,514 $\pm$ 1497
Total			80.9	3,506,598 $\pm$ 2045
106008010	2011-08-22	XIS0, XIS1, XIS3	23.2	1,607,172 $\pm$ 1224
106007010	2011-08-23	XIS0, XIS1, XIS3	21.0	1,294,568 $\pm$ 1241
Total			44.2	2,901,740 $\pm$ 1712
106005020	2012-02-07	XIS0, XIS1, XIS3	46.8	3,168,472 $\pm$ 1923
106007020	2012-02-08	XIS0, XIS1, XIS3	20.9	1,348,127 $\pm$ 1277
Total			76.7	4,516,599 $\pm$ 2222
107006010	2012-08-20	XIS0, XIS1, XIS3	23.7	643,610 $\pm$ 870
107005010	2012-08-20	XIS0, XIS1, XIS3	41.1	2,855,320 $\pm$ 1808
Total			64.8	3,496,118 $\pm$ 2006
107005020	2013-02-11	XIS0, XIS1, XIS3	37.7	2,715,459 $\pm$ 1749
107006020	2013-02-12	XIS0, XIS1, XIS3	22.0	594,321 $\pm$ 826
Total			59.7	3,308,823 $\pm$ 1934
108005010	2013-08-15	XIS0, XIS1, XIS3	41.3	2,793,686 $\pm$ 1769
108006010	2013-08-16	XIS0, XIS1, XIS3	21.6	1,833,876 $\pm$ 1642
Total			62.9	4,627,562 $\pm$ 2369
108005020	2014-02-05	XIS0, XIS1, XIS3	38.0	2,544,166 $\pm$ 1691
108006020	2014-02-06	XIS0, XIS1, XIS3	19.0	1,302,468 $\pm$ 1213
Total			57.0	3,846,634 $\pm$ 2017
109005010	2014-08-27	XIS0, XIS1, XIS3	20.0	1,403,352 $\pm$ 1282
109005020	2015-03-03	XIS0, XIS1, XIS3	37.2	2,412,816 $\pm$ 2167
109006010	2015-03-04	XIS0, XIS1, XIS3	23.6	1,296,420 $\pm$ 1476
109007010	2015-03-05	XIS0, XIS1	30.7	3,560,711 $\pm$ 2017
Total			91.5	7,269,947 $\pm$ 3628

The images and spectra for all observations were obtained using the standard multi-mission photon-collecting procedure *xselect*. After the image creation, the following regions were selected and stored as *.reg files using the SAOImageDS9 astronomical imaging and data visualization application by the Chandra X-ray Science Center (CXC), the High Energy Astrophysics Science Archive Center (HEASARC), and the JWST Mission office at Space Telescope Science Institute [34]: for the source (circular region with AGN in the center), the surrounding cluster (ring region centered on the AGN), and the remote background (empty circular region as far away as possible from the AGN).

Considering that the PSF half-brightness radius is approximately 1 arcmin [35], and thus the recommended radius of the source extraction region should not be smaller than 1.5 arcmin, we chose the following extraction areas: circles with radii of 1.74 arcmin for both the AGN and outer backgrounds (i.e., 100 ds9 physical units), and areas with an inner radius of 1.74 arcmin (100 ds9 physical units) and outer radii of 2.57 arcmin (i.e., 144 ds9 physical units). Examples of the images and regions are shown in Figure 1.

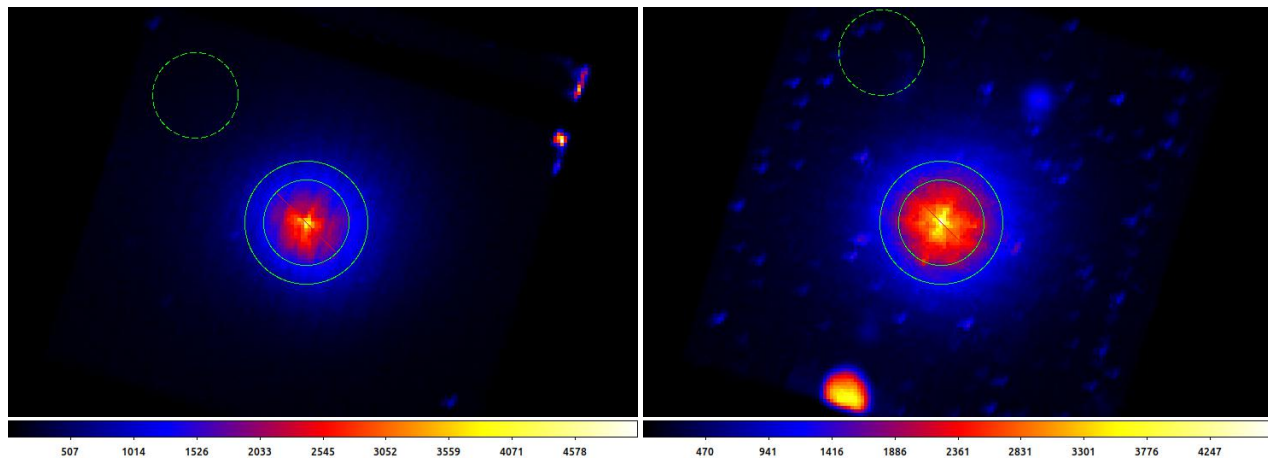


Figure 1. The 0.1–10 keV images of NGC 1275 by Suzaku/XIS for the observational window 101012010 (August 2006) with the regions from where the source, cluster, and background counts were extracted. Left: the image from the XIS0 camera, AGN circle, cluster ring, and remote background region (green circle); right: the XIS1 camera image, the AGN circle, cluster, and remote background region.

Some observations were conducted in partial window mode. For these, we selected square-shaped regions with a size of 2 arcmin for the AGN and the remote background (an empty square region positioned as far away as possible from the AGN), and a size of 2.88 arcmin for the outer square region with the inner AGN-centered region excluded for the cluster. Examples of the images and regions are displayed in Figure 2.

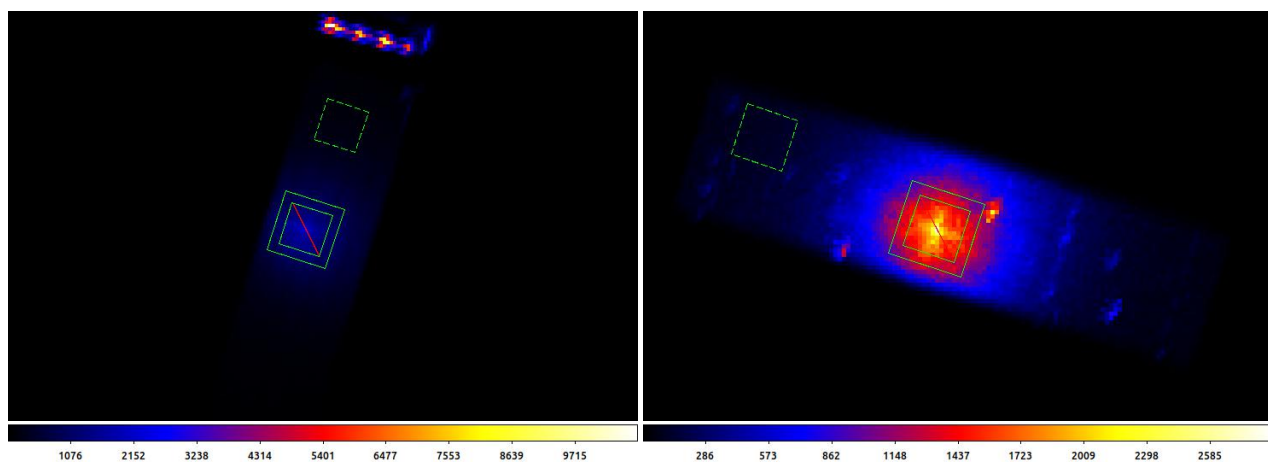


Figure 2. The 0.1–10 keV images of NGC 1275 by Suzaku/XIS for the observational window 107006010 (August 2012) with the regions from where the source, cluster, and background counts were extracted. Left: XIS0 camera, right: XIS1 camera.

After processing the images and creating the regions, we extracted the spectra of the source (AGN + cluster), cluster, and background for all available cameras. The spectra of the same object obtained from different cameras were merged into a single spectrum per observation. The resulting unified XIS spectra were obtained by merging the spectra for each camera into one using the *addascaspec* routine included in the HEASoft X-ray data analysis and processing offline software package, along with the corresponding response matrices and ancillary files. An example of the resulting spectra for the AGN circle region and the surrounding cluster (a ring region centered on the AGN) is depicted in Figure 3.

We also merged the spectra of the closely timed observations (i.e., within one month) in the same way and obtained the resulting 20 files for different observational periods. The observations that were merged are shown in Table 1 together in one cell.

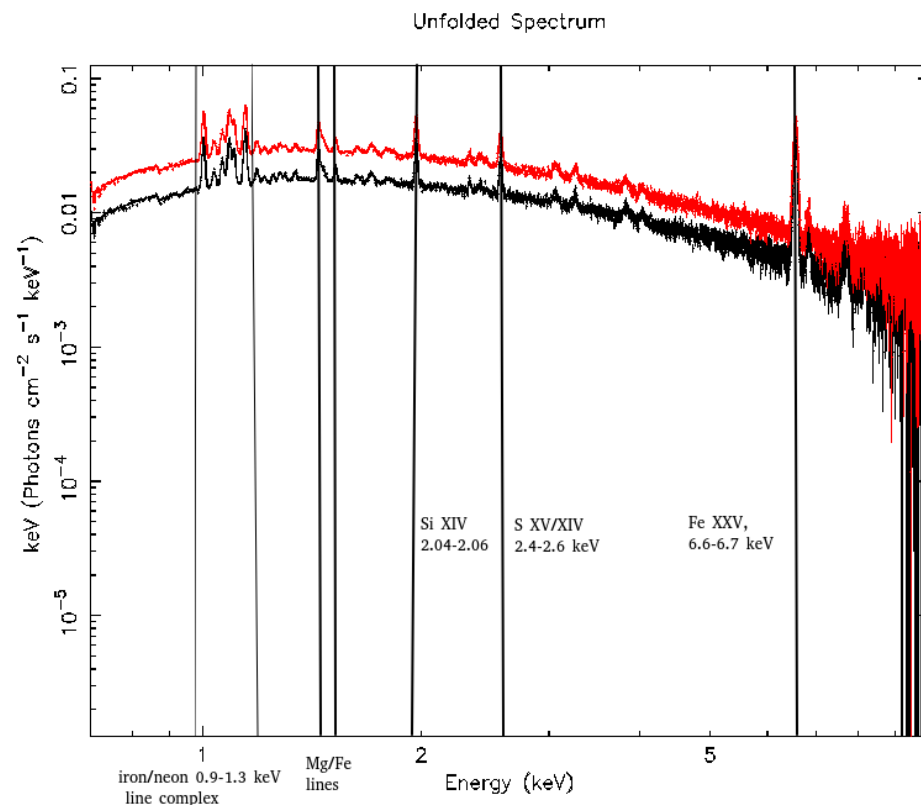


Figure 3. The example of the 0.5–10.0 keV spectra of the surroundings (cluster) and the source region (AGN + cluster) extracted in the standard way for the observational window 101012010. The AGN + cluster spectrum extracted from the circular central region around the AGN is shown in red, and the surrounding cluster spectrum extracted from the ring-shaped region is shown in black.

2.2. XMM-Newton/EPIC Data Processing

NGC 1275 was observed by the XMM-Newton mission three times (in 2001 and 2006), but only two of them were included in our consideration due to the poor quality of the second one. In Table 2, we show the log of these two observations.

Table 2. XMM-Newton/EPIC observations LOG.

Obs. ID	Obs. Date	Obs. Time ksec	Total EPIC Flux, cts
0085110101	2001-01-30	60.8	258,582
0305780101	2006-01-29	125.1	685,298

The data of the XMM-Newton/EPIC observations of NGC 1275 were processed to obtain two complex EPIC spectra. During both observation periods, all EPIC cameras were operated in full window mode. We reduced the EPIC data using the special software package XMM SAS (version 21.0) with its standard chains *epproc* and *emproc*. Only the single- and double-photon events were taken into account by applying the $PATTERN \leq 4$ option in *evselect* command. To exclude bad pixels or on-edge events, the filter $FLAG = 0$ was also added. The counts were extracted for the source/AGN (from the 30''-radii circular regions around the AGN center) and for the set of six concentric rings around it (excluding the counts from the inner circle of the radius of the previous one; the outer ring is matching exactly that of the Suzaku/XIS for the cluster). The inner cluster ring was used as a background for the cleaned source spectrum. The ancillary files and response matrices

were generated using the standard SAS chains *arfgen* and *rmfgen*. All the spectra (MOS1, MOS2, and PN) were merged into one spectral file using the *epicspeccombine* script.

2.3. Distinguishing Cluster and AGN Components: The Routine

After the first data reduction step, we obtained the source (AGN + cluster) spectra, surrounding cluster, and background for every period of observations. In the source and cluster spectra, the sets of emission lines typical for a collisionally ionized diffuse gas are clearly visible. Following the data and emission models *bapec* provided by atomdb (Atomic Data for Astrophysicists, <http://www.atomdb.org/>, accessed on 7 October 2024) and calculated by means of the HULLAC code by [36], these lines can be interpreted as follows:

- The set of iron and/or neon lines within the energy range 0.9–1.3 keV;
- Two lines of magnesium and iron near 1.5 keV;
- Si XIV line at 2.0 keV;
- S XV/XIV line near 2.5 keV;
- Fe XXV lines near 6.7 keV.

We can use these lines and relations between their amplitudes as clues to separate the spectral counterpart of the cluster from that of the active nucleus. Namely, we can choose several single lines easily distinguishable from others (in our case, these are: Si XIV near 2 keV, S XV/XIV at 2.4–2.6 keV, and Fe XXV near 6.7 keV) and calculate the relations between their amplitudes for the source and the cluster regions. The equivalence of these relations within the error bars tells us that the lines visible in the source and cluster area spectra are of the same origin and thus are emitted by the same medium (see Table 3). The radial temperature gradient in the cluster does not violate the relations between amplitudes of the lines in the considered series of observations. Otherwise, if some relation is higher for a source region, this can be considered as a sign of the presence of the line emission in the AGN spectrum as well (more often this concerns the case of the Fe XXV line as near it we can often observe the Fe-K α 6.4 keV line emitted from the AGN “central engine”). Additionally, from the results shown in Table 3, we can see that the relations between A3 and A1 or A2 are compatible with each other for AGN + cluster and cluster ring regions. A1 represents the amplitude of the Si XIV line at 2 keV, while A2 corresponds to the amplitude of the S XV/XVI lines between 2.4 and 2.6 keV. A3 denotes the amplitude of the Fe XXV line near 6.7 keV.

Using the mean values of the relations between the amplitudes of these lines emitted from the source (AGN + cluster) and cluster areas, we can now pass to the next step of cleaning the source (AGN + cluster) spectra from the contamination by the cluster counterpart. The presence of bright emission lines in the cluster spectra enables us to perform this with no continuum fitting. We can use the background-subtracted cluster spectrum as a correction file for the source spectrum with the correction coefficient set to the mean value of the three relations between emission line amplitudes for source and cluster areas. Together with the correction file, we add the systematic errors corresponding to those of the cluster spectrum with the factor of the correlation coefficient. A more detailed description of the recipe is shown in Appendix A.

The other possible concern could be the differences in the physical conditions in various spatial zones of the cluster (e.g., in the velocity dispersion, redshift, temperature differences, or spatial variations of the absorbing column). To trace the significance of these parameter changes, we collected the spectral counts from five concentric rings surrounding the AGN from the XMM-Newton observations. The outermost ring corresponds in its dimensions to the “cluster ring” when speaking about the Suzaku/XIS data. The rings and background areas are shown in Figure 4.

Table 3. Relations between amplitudes of the emission lines in the cluster spectra. A1 is the amplitude of the Si XIV 2 keV line, A2 is that of S XV/XVI within 2.4–2.6 keV, and A3 is that of the Fe XXV line near 6.7 keV.

Obs. Date	AGN + Cluster			Cluster		
	A ₁ /A ₂	A ₁ /A ₃	A ₃ /A ₂	A ₁ /A ₂	A ₁ /A ₃	A ₃ /A ₂
2006-02	2.11 ± 0.2	1.38 ± 0.12	1.53 ± 0.15	2.07 ± 0.21	1.27 ± 0.14	1.62 ± 0.17
2006-08	2.0 ± 0.2	1.48 ± 0.08	1.36 ± 0.05	1.9 ± 0.2	1.45 ± 0.08	1.31 ± 0.05
2007-02	2.3 ± 0.25	1.66 ± 0.2	1.4 ± 0.1	2.25 ± 0.27	1.56 ± 0.21	1.44 ± 0.11
2007-08	2.0 ± 0.2	1.11 ± 0.13	1.81 ± 0.19	2.09 ± 0.24	1.16 ± 0.14	1.80 ± 0.20
2008-02	2.0 ± 0.1	1.48 ± 0.05	1.36 ± 0.04	1.9 ± 0.13	1.45 ± 0.06	1.31 ± 0.06
2008-08	1.5 ± 0.25	1.24 ± 0.16	1.21 ± 0.15	1.54 ± 0.27	1.13 ± 0.17	1.36 ± 0.19
2009-02	1.64 ± 0.23	1.33 ± 0.15	1.23 ± 0.14	1.57 ± 0.3	1.34 ± 0.16	1.17 ± 0.15
2009-08	2.09 ± 0.2	1.25 ± 0.1	1.67 ± 0.15	2.12 ± 0.2	1.28 ± 0.1	1.65 ± 0.15
2010-02	1.83 ± 0.28	1.33 ± 0.20	1.38 ± 0.21	1.64 ± 0.29	1.28 ± 0.2	1.28 ± 0.21
2010-08	1.66 ± 0.25	1.21 ± 0.16	1.35 ± 0.16	1.79 ± 0.26	1.38 ± 0.19	1.32 ± 0.16
2011-02	2.06 ± 0.15	1.23 ± 0.09	1.68 ± 0.10	2.19 ± 0.16	1.31 ± 0.10	1.68 ± 0.11
2011-07	1.47 ± 0.17	1.19 ± 0.14	1.24 ± 0.15	1.62 ± 0.2	1.21 ± 0.15	1.33 ± 0.19
2011-08	2.0 ± 0.3	1.3 ± 0.3	1.5 ± 0.3	1.8 ± 0.3	1.1 ± 0.3	1.7 ± 0.3
2012-02	2.13 ± 0.25	1.57 ± 0.23	1.36 ± 0.21	2.18 ± 0.31	1.62 ± 0.24	1.35 ± 0.22
2012-08	1.83 ± 0.24	1.26 ± 0.16	1.27 ± 0.15	1.77 ± 0.25	1.2 ± 0.17	1.28 ± 0.17
2013-02	2.26 ± 0.18	1.41 ± 0.15	1.61 ± 0.16	2.25 ± 0.2	1.33 ± 0.16	1.69 ± 0.18
2013-08	1.95 ± 0.23	1.45 ± 0.19	1.35 ± 0.18	1.89 ± 0.28	1.60 ± 0.20	1.20 ± 0.19
2014-02	1.94 ± 0.23	1.35 ± 0.22	1.44 ± 0.22	1.85 ± 0.3	1.22 ± 0.25	1.5 ± 0.2
2014-08	1.9 ± 0.34	1.55 ± 0.3	1.23 ± 0.28	1.84 ± 0.42	1.1 ± 0.29	1.67 ± 0.37
2015-03	1.75 ± 0.23	1.17 ± 0.10	1.2 ± 0.11	1.62 ± 0.25	1.27 ± 0.12	1.28 ± 0.13

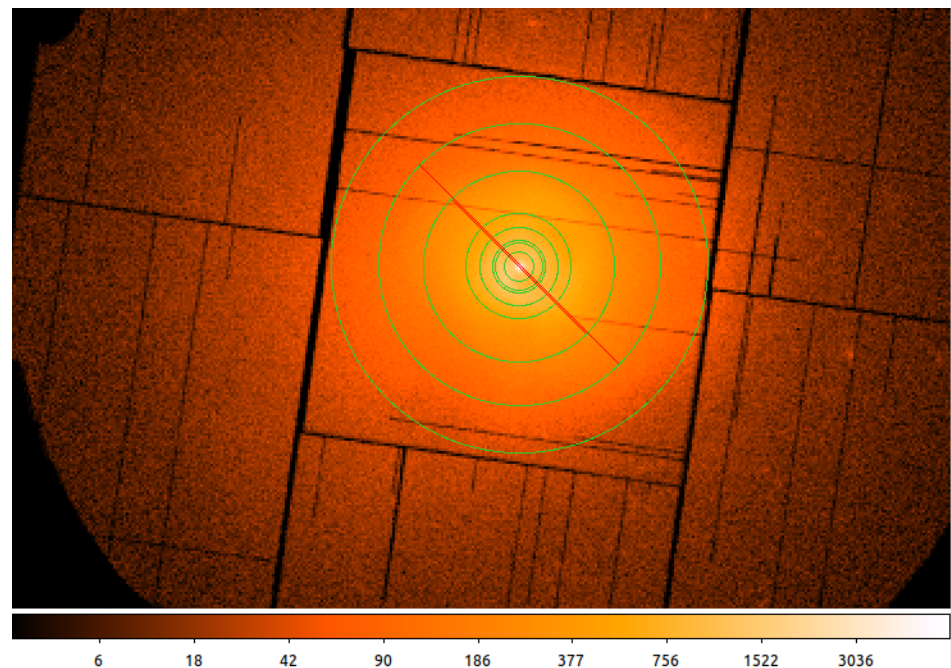


Figure 4. Concentric rings around the source and background area for XMM-Newton/EPIC spectra of different cluster zones (MOS1 camera).

The spectra obtained from these rings were fitted with the collisionally ionized diffuse gas *bvapec* model with the same (but unfrozen) elementary abundances, untied temperatures, redshifts, and velocity dispersions. The absorbing columns fitted with the *tbabs* model were untied as well. The results are shown in Table 4.

Table 4. Spectral parameters to the XMM-Newton/EPIC spectra of the cluster zones surrounding the central AGN. Number 1 corresponds to the innermost ring, 5 to the outermost one.

Ring Number	kT keV	V km/s	z	N_H 10^{20} cm^{-2}
1	3.16 ± 0.04	<160	0.0155 ± 0.0003	4 ± 1
2	3.09 ± 0.04	<210	0.0156 ± 0.0003	6 ± 1
3	3.06 ± 0.05	<211	0.0154 ± 0.0002	7 ± 1
4	3.10 ± 0.04	<421	0.0144 ± 0.0003	9 ± 1
5	2.93 ± 0.10	<1544	0.0137 ± 0.0002	15 ± 2

As one can see from Table 4, the temperature difference between these rings is relatively small and just a little higher than the error bars. The same can be observed for the velocity dispersion, which is zero-compatible in all cases. The differences in the absorbing columns are quite significant, but at the same time, the absorption level is quite low and affects the spectral shape below 1 keV of energy, and thus ignoring the energy range below 1 keV resolves this obstacle. The only parameter in which changes are quite prominent is the redshift, and this can possibly demand a compensatory spectral energy/channel shift of the cluster spectrum relative to the source/AGN one to achieve better quality of cleaned spectra.

2.4. Fitting the Spectra

To test the method and its application, we performed spectral fitting for the Suzaku/XIS cleaned observations of AGN in NGC 1275.

The data are effectively characterized by a spectral model: $tbabs(N_{H,pl}) * po(\Gamma) + tbabs(N_{H,kT}) * mekal(kT)$, aligning well with findings from other studies [26,30]. Spectral fitting was executed using the Xspec v.12.10.1f package within the HEASoft software, version 6.26. Best-fit parameters are shown in Table 5. An example of a folded spectrum with the model is shown in Figure 5.

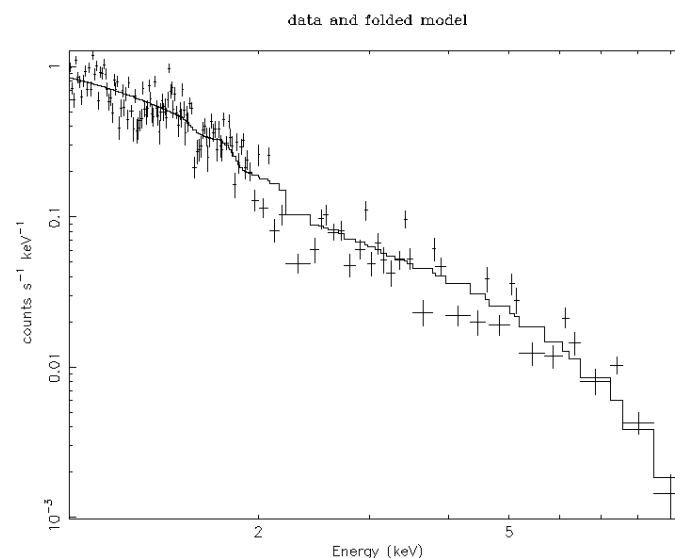


Figure 5. The 1–10 keV range folded spectrum of NGC 1275 by Suzaku/XIS for the observation performed on August 2007 with the model.

Table 5. Fitting parameters to the AGN 1–10 keV Suzaku/XIS and XMM-Newton spectra in NGC 1275 observations.

Obs. Date	Γ	$N_{\text{H,pl}}^1$	kT, keV	$N_{\text{H,kT}}^1$	$\chi^2/\text{d.o.f.}$	F_{2-10}^2	F_{5-10}^2
2001-01	1.88 ± 0.04	1.1 ± 0.3	$1.43^{+0.31}_{-0.26}$	99^{+53}_{-35}	1374.6/1346	$8.2^{+0.1}_{-0.3}$	3.7 ± 0.1
2006-01	1.81 ± 0.02	2.6 ± 0.3	0.65 ± 0.06	<1.0	2001.7/1662	10.7 ± 0.1	5.1 ± 0.1
2006-02	2.7 ± 0.2	16 ± 4	0.5 ± 0.2	3^{+6}_{-1}	3994.1/2456	13.3 ± 0.2	4.7 ± 0.1
2006-08	1.98 ± 0.13	<8.2	2.3 ± 0.2	3.3 ± 1.4	281/210	9.6 ± 0.2	3.6 ± 0.1
2007-02	2.1 ± 0.2	<2	<0.6	<4	13/44	8.5 ± 1.2	3.2 ± 0.9
2007-08	1.7 ± 0.8	<5.5	2.0 ± 0.3	<16	231.9/108	6.7 ± 0.2	3.1 ± 0.1
2008-02	1.9 ± 0.3	6 ± 2	1.8 ± 0.6	<6	117.8/93	7.0 ± 0.4	2.6 ± 0.3
2008-08	2.9 ± 0.4	9 ± 4	1.8 ± 0.3	<4.5	127.6/93	6.3 ± 0.8	1.7 ± 0.2
2009-02	$1.65^{+0.34}_{-0.23}$	<4	1.6 ± 0.3	7 ± 2	131.0/126	12 ± 3	4.9 ± 1.3
2009-08	2.4 ± 0.2	<1.2	2.0 ± 0.4	19 ± 2	217.3/150	10.0 ± 1.0	3.4 ± 0.4
2010-02	2.1 ± 0.3	<5	1.7 ± 0.3	5 ± 4	133.5/96	7.5 ± 1.0	2.6 ± 0.5
2010-08	2.2 ± 0.3	<8	1.4 ± 0.3	5 ± 2	186.5/109	7.2 ± 2.0	3.3 ± 1.2
2011-02	1.7 ± 0.3	<8	1.6 ± 0.3	7 ± 2	193.6/152	13.7 ± 0.5	5.6 ± 0.3
2011-07	1.7 ± 0.3	<6.1	1.9 ± 0.4	5.2 ± 3.5	125.0/94	13.9 ± 2.6	5.6 ± 1.3
2011-08	2.0 ± 0.4	<8	2.2 ± 0.7	8 ± 3	80.2/70	17.8 ± 0.8	6.5 ± 0.5
2012-02	1.9 ± 0.2	<3.3	1.8 ± 0.2	6 ± 3	164.4/160	12.8 ± 0.7	5.0 ± 0.4
2012-08	2.0 ± 0.3	4.5 ± 4.1	1.9 ± 0.5	<6.2	173.6/152	10.9 ± 1.0	4.2 ± 0.4
2013-02	1.7 ± 0.2	<8.2	2.1 ± 0.5	4 ± 2	166.3/151	15.1 ± 0.5	6.4 ± 0.3
2013-08	2.2 ± 0.2	5 ± 2	2.1 ± 0.3	<4.5	198.4/147	17.6 ± 0.6	6.7 ± 0.4
2014-02	2.1 ± 0.2	<5.1	1.1 ± 0.5	3.4 ± 2.5	71.2/74	13.5 ± 1.1	5.1 ± 0.5
2014-08	1.9 ± 0.3	<1	$1.1^{+0.8}_{-0.5}$	34 ± 25	71.2/74	15.0 ± 1.5	6.1 ± 0.6
2015-03	1.8 ± 0.2	<2.7	2.1 ± 0.7	4.8 ± 4.1	140.6/132	13.9 ± 0.8	5.8 ± 0.5

¹ 10^{21} cm^{-2} ; ² $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$.

Based on this spectral model, using the *flux* Xspec command, we calculated the AGN fluxes within the 2–10 keV energy range for all Suzaku/XIS NGC 1275 observations (see Table 5) and plotted the light curve (see Figure 6).

Previous data analysis has revealed that the X-ray emission from the nucleus of NGC 1275 exhibits variability over both long-term (spanning several years) and short-term (occurring over several days) timescales [25,26]. When examining the light curves in X-ray spectra in the period from 2010 to 2015, a consistent increase in flux density is observed. This matches the radio light curve, demonstrating similar growth during the same period shown by Zhang et al. [33] and Paraschos et al. [37]. Notably, the X-ray emissions show good synchronization with emissions at lower frequencies, specifically at 15, 37, and 91.5 GHz. This suggests that radio and X-ray emissions likely originate from spatially proximate regions, potentially the base of the jet. However, this tie becomes less pronounced at higher frequencies, such as 230 and 345 GHz. There is no obvious correlation between X-ray and γ -ray activity when only considering light curves, but there is a general tendency towards an increase in flux density [26]. In the work by Paraschos et al. [37], it was found that the γ -rays either precede the 230 GHz flux (345 GHz flux) by $\tau_{\gamma-230 \text{ GHz}} = 1.56 \pm 0.27$ years ($\tau_{\gamma-345 \text{ GHz}} = 1.57 \pm 0.49$ years) or trail the 230 GHz flux (345 GHz flux) by $\tau_{\gamma-230 \text{ GHz}} = 1.43 \pm 0.30$ years ($\tau_{\gamma-345 \text{ GHz}} = 1.58 \pm 0.64$ years). The authors' conclusion leans toward the γ -ray source being situated within the parsec-scale jet, positioned downstream of the core

region of 3C 84. Also, Tanada et al. [38] reported the flaring activity of NGC 1275 during the same period based on the Fermi observations.

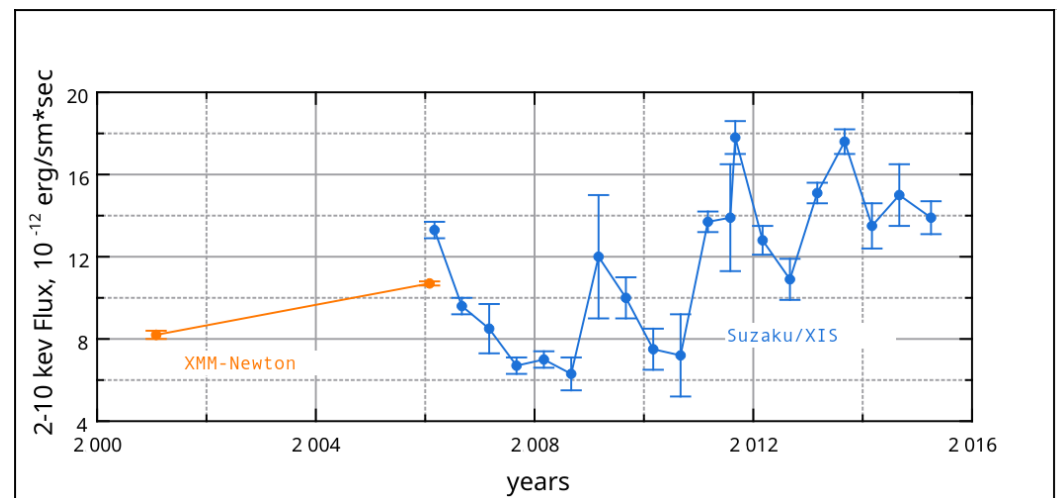


Figure 6. The 2–10 keV lightcurve of NGC 1275 derived from the XMM-Newton/EPIC (orange circles) and Suzaku/XIS (blue circles) observations.

3. Conclusions and Further Perspectives

We have developed and tested a new algorithm to separate the cluster emission from active galactic nucleus emission for all available observational data for NGC 1275 by Suzaku/XIS within the energy of 1–10 keV in a model-independent way. No spectral fitting models were applied to perform this spectral separation. As a result, we obtained individual spectra for 20 periods of observations (the observations performed within a month were merged together). Spectral fitting with the power-law plus emission from the hot, diffuse gas with the neutral absorption model was performed.

Although this model is rough, it allows us to estimate the AGN 2–10 keV flux levels at different time intervals. It can be used as a cross-check tool for common spectral fitting, as it does not have the main difficulty of the latter caused by the possibility of parameter degeneracy. As a result, we found that the flux from the AGN nucleus in NGC 1275 increased significantly during the period from 2011 to 2015.

Similar flux growth was detected within the same period in the radio range [33] and in the highest γ -ray energies [38]. This suggests that the observed increase in flux may be driven more by processes in the jet rather than by those in the “corona-accretion disk” system. Our conclusions align well with those of previous studies by [26].

Fabian et al. showed decade-long fluctuations in X-ray flux, with increases in the 1980s and 2000s, and a dip in the 1990s [25]. Our flux values align closely with prior investigations, particularly those by Churazov et al. [29] and Balmaverde et al. [39], albeit slightly higher than fluxes obtained in studies utilizing the same Suzaku/XIS instrument but focusing on an energy range of 5–10 keV [26,40]. When adjusting for energy range in our analysis, the fluxes exhibit good agreement, affirming the efficacy of our method in distinguishing between contributions from the AGN and the cluster. This underscores the significant, if not predominant, role in the NGC 1275 nucleus X-ray emission, primarily from the accretion disc and corona, while the remaining contribution originates from the jet [30].

The next step of interest is to separate the spectral signatures of the jet and corona/disk components. Such an approach could involve applying the method outlined in [41,42] to analyze the Suzaku/XIS spectra alongside the simultaneous spectra obtained at higher energies, such as those from Suzaku/HXD (Hard X-ray Detector).

This will provide us with the opportunity to trace the jet power in NGC 1275 and its temporal evolution during the observational periods. Alternatively, we can explore

the structure of the “central engine” of the NGC 1275 nucleus, considering the potential presence of a double black hole [24,43].

The method itself and the scripts created for its realization can be used as well for another similar point-like object (AGN) surrounded by a dense bright medium (cluster), under the condition that in the X-ray spectrum of the surroundings, there are some bright features present (such as emission or in some case absorption lines) that are not associated with the source of our interest (i.e., AGN).

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Appendix A. Double Background-Subtracting

The materials for the algorithm used here to perform the double background-subtracting of the spectra of the AGN in NGC 1275 are available on GitHub (<https://github.com/AnatoliyTugay/Separating-the-spectral-counterparts-in-NGC-1275-Perseus-cluster-in-X-rays/tree/main>, accessed on 7 October 2024). This algorithm includes the following steps:

- Regular reduction of the observational data to collect the remote background, cluster, and AGN+cluster spectral counts;
- Creating and rebinning of the remote background, cluster, and AGN+cluster spectra;
- Extraction of the remote background from the cluster spectrum using our python script `back_corr.py`, applying the following console command to launch it:

```
python3 back_corr.py -c clus_raw.pha -b back.pha -c 1.0 clus_clean.pha
```

 (here `clus_raw.pha` is an input uncleaned cluster spectrum, `back.pha` is a remote background spectrum, 1.0 in our case is the ratio between the areas of the cluster and background regions $S_{cluster}/S_{bkg}$, and `clus_clean.pha` is an output file);
- Use the resulting AGN+cluster spectrum with the cleaned cluster spectrum as a correction file in Xspec:

```
data source.grp
corfile clus_clean.pha
cornorm 1.5
```
- Set the “cornorm” coefficient to the value obtained from the relations between the amplitudes of the emission lines from AGN+cluster and cluster regions;

- Add the systematic errors to the resulting spectra. As we have subtracted the remote background from the cluster spectrum, the additional errors are equivalent to the cluster + remote background errors. Depending on the observation, in our case, it is on the level of 0.07–0.15.

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