X-Ray Emission of the γ-ray-loud Young Radio Galaxy NGC 3894

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Abstract

The radio source 1146+596 is hosted by the elliptical/S0 galaxy NGC 3894, with a low-luminosity active nucleus. The radio structure is compact, suggesting a very young age for 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 Fermi Large Area Telescope 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 ks long exposure. We have found that the core spectrum is best fitted by a combination of an ionized thermal plasma with a temperature of ≳0.8 keV, and a moderately absorbed power-law component (photon index Γ = 1.4 ± 0.4, hydrogen column density N_H/10^{22} cm$^{-2}$ = 2.4 ± 0.7). We have also detected the iron Kα line at 6.5 ± 0.1 keV, with a large equivalent width of 1.0$^{+0.3}_{-0.2}$ keV. Based on the simulations of Chandra’s point-spread function, 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 kiloparsec 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 Kα line.

Unified Astronomy Thesaurus concepts: X-ray active galactic nuclei (2035); Low-luminosity active galactic nuclei (2033); Active galaxies (17); Relativistic jets (1390); Radio galaxies (1343); Gamma-ray sources (633)

1. Introduction

The elliptical/lenticular galaxy NGC 3894, a member of a noninteracting pair located at R.A.(J2000) = 11h48m50s36 and decl.(J2000) = +59°24′56″43 (Nilson 1973; 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 and 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 subrelativistic expansion, and oriented at a rather large ∼50° 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 galaxies.

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

Redshifted H I absorption has been detected toward 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 have been estimated as N_H ≳ 4 × 10^{20} cm$^{-2}$ on average, with the (2–14) × 10^{20} cm$^{-2}$ range found for distinct components of the radio structure (see also Perlman et al. 2001; Emonts et al. 2010).

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

At optical frequencies, the high-resolution imaging performed with the telescopes of the 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 circumnuclear 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 Large Area Telescope (LAT) 8 yr Source Catalog (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. 2014; Migliori et al. 2014, 2016; D’Ammando et al. 2016; Lister et al. 2020).

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 ks exposure with the Advanced CCD Imaging Spectrometer (ACIS) detector. Along with presenting the results of the Chandra data analysis, we also update the spectral energy distribution (SED) of the source.

Throughout the paper we assume modern ΛCDM 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 \( 0.238 \text{ kpc arcsec}^{-1} \).

2. Chandra Data Analysis

The Chandra ACIS-S observation of the galaxy NGC 3894 was conducted in 2009 July, during Observing Cycle 10 (PI: E. Perlman), with the exposure totaling 38.4 ks. 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 a total number of net counts of 457 within a 10 px radius from the core in the full photon energy range of 0.5–7.0 keV utilized in our analysis. Figure 1 presents the resulting Chandra images of NGC 3894, smoothed with a 3 σ 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 a 10 px 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 inner and outer radii of 10\(^5\) and 20\(^5\), 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).

The Chandra data analysis was performed with the CIAO v4.13 software (Fruscione et al. 2006) using CALDB v4.8.5. We processed the data by running the CIAO tool chandra_repro. Spectral modeling was done in XSPEC v12.11.1 (Arnaud 1996), using the chi-square fitting statistics and the Nelder–Mead optimization method, and also with Sherpa (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. In Section 2.1 we present the detailed point-spread function (PSF) simulations and the surface brightness profile analysis in the narrow energy ranges (soft, medium, and hard bands), due to the fact that the source spectrum appears relatively hard, and also due to the presence of a strong iron fluorescence; in Section 2.2 we present spectral modeling.

2.1. Surface Brightness Profiles

In order to correct for Chandra’s dithering motion, the limited size of detector pixels, and detector effects, we performed the High Resolution Mirror Assembly PSF simulations for the NGC 3894 nucleus, using the Chandra Ray Tracer (ChaRT) online tool (Carter et al. 2003).\(^7\) For these, the source spectrum file was uploaded to ChaRT, obtaining a set of rays, which were then projected onto the detector plane with MARX software (Davis et al. 2012).\(^8\) The resulting PSF files were normalized to the observed count rate, and filtered with the source region at bin factor 1.

Because of the limited photon statistics we are dealing with here, one should expect possibly quite substantial differences in each particular realization of the PSF, due to random photon fluctuations. For this reason, we have repeated the PSF simulations 50 times, and then averaged them, in this way obtaining 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 extremely low photon statistics in the last-mentioned case, amounting to only 26 net photons within the <10 px radius 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 centered on the galactic nucleus up to ~60 px (without removing any point sources), and fitted 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 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 ~30 px ~3.5 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 <3σ). In the hard band, finally, no source extension—either due to a diffuse component, or due to the identified point sources—is present beyond the central PSF (effectively the central <5′′ ~1.2 kpc radius), although the very limited photon statistics in this band should be kept in mind.

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\(^7\) http://cxc.harvard.edu/ciao/PSFs/chart2/runchart.html

\(^8\) https://space.mit.edu/cxc/marx
Figure 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 gray 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.
Likewise, no prominent extended structures can be seen on the hardness ratio \( HR = (H - M)/(H + M) \) map presented in Figure 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 data set, the target is unresolved down to a few tens of parsecs, which is the scale of the extension in the Fe Kα emission observed in several nearby Compton-thick sources (Marinucci et al. 2013, 2017; Fabbiano et al. 2018a, 2018b).

### 2.2. Spectral Modeling

Based on the analysis of the X-ray surface brightness profiles in NGC 3894 presented in Section 2.1 (see Figure 2), for the spectral modeling of the active nucleus in the system, we have selected a circular region with the radius of 10 px centered on the core. For this source extraction region, the background was chosen as an annulus with an inner radius of 20 px and an outer radius of 40 px (with the prominent point sources removed—see Figure 1).

#### 2.2.1. 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 specextract. 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 \( N_{H,Gal} = 1.83 \times 10^{20} \) cm\(^{-2}\); a thermal component assumes solar abundance. The 0.5–7.0 keV unabsorbed flux of the power-law component reads as \( F_{0.5-7.0 \text{ keV}} \approx 2 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). The 6.5 keV line equivalent width (EW, 1σ range) reads as \( EW = 0.6(0.4 - 1.1) \) keV for the fit with frozen \( \sigma_f = 0.01 \) keV, and \( EW = 1.0(0.5 - 1.9) \) keV for \( \sigma_f \) set free. The XSPEC normalizations in columns (4), (7), and (10) are: (a) for the APEC component \( 10^{-14} (1 + z)^2 n_e n_H V/(4\pi d_L^2) \), assuming a 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 cm\(^{-2}\) s\(^{-1}\) in the line; (c) for the power-law component photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.

### Table 1

Spectral Modeling of the Binned Nuclear Spectrum of NGC 3894

| Model | \( N_{H} \) \( \times 10^{22} \) cm\(^{-2}\) | \( kT \) (keV) | APEC Norm. \( \times 10^{-6} \) XSPEC | \( E_f \) (keV) | \( \sigma_f \) (keV) | Line Norm. \( \times 10^{-6} \) XSPEC | \( \Gamma \) | PL Norm. \( \times 10^{-6} \) XSPEC | \( \chi^2/DOF \) |
|-------|----------------|------|-----------------|------|------|-----------------|------|-----------------|----------------|
| (i)   | 2.0 ± 0.6      | 0.8 ± 0.1 | 3.4 ± 0.4       | ... | ... | ...             | 1.1 ± 0.4 | 20 ± 11         | 64.27/72       |
| (ii)  | 2.2 ± 0.7      | 0.8 ± 0.1 | 3.5 ± 0.4       | 6.5 ± 0.1 | 0.01 (frozen) | 1.3 ± 0.6     | 1.3 ± 0.4 | 24 ± 14         | 59.21/70       |
| (iii) | 2.4 ± 0.7      | 0.8 ± 0.1 | 3.5 ± 0.4       | 6.5 ± 0.1 | 0.12 ± 0.08   | 2.0 ± 0.9     | 1.4 ± 0.4 | 29 ± 17         | 57.90/69       |

Note. Column (1)—model fit; column (2)—intrinsic hydrogen column density; columns (3), (4)—temperature and normalization of the collisionally ionized thermal plasma; columns (5)–(7)—Gaussian line energy, width, and normalization; columns (8), (9)—photon index and normalization of the power-law emission component; column (10)—\( \chi^2 \) fitting statistics/DOF. All the models include Galactic hydrogen column density \( N_{H,Gal} = 1.83 \times 10^{20} \) cm\(^{-2}\); a thermal component assumes solar abundance. The 0.5–7.0 keV unabsorbed flux of the power-law component reads as \( F_{0.5-7.0 \text{ keV}} \approx 2 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). The 6.5 keV line equivalent width (EW, 1σ range) reads as \( EW = 0.6(0.4 - 1.1) \) keV for the fit with frozen \( \sigma_f = 0.01 \) keV, and \( EW = 1.0(0.5 - 1.9) \) keV for \( \sigma_f \) set free. The XSPEC normalizations in columns (4), (7), and (10) are: (a) for the APEC component \( 10^{-14} (1 + z)^2 n_e n_H V/(4\pi d_L^2) \), assuming a 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 cm\(^{-2}\) s\(^{-1}\) in the line; (c) for the power-law component photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV.
detected in HE $\gamma$-rays, PKS 1718-649 (see the discussion in Beuchert et al. 2018). 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 nonthermal 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 $N_H = (2.4 \pm 0.7) \times 10^{22}$ cm$^{-2}$. The 0.5–7.0 keV unabsorbed flux of the power-law component reads as $F_{0.5–7.0 \text{ keV}} \simeq 2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, corresponding to the isotropic luminosity of $L_X \simeq 6 \times 10^{40}$ erg s$^{-1}$.

In order to compare models (i)-(iii), we apply the F-test, obtaining the $p$-value 0.05669 for models (i) and (ii), 0.21572 for models (ii) and (iii), and finally 0.06425 for models (i) and (iii). Hence, we conclude that the zphabs*(powerlaw+zgauss) +apec models (ii) and (iii), which in addition include the redshifted iron line with the width $\sigma$ 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 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, $\Gamma$, 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 1$\sigma$ uncertainty range for the EW of the iron line in the model,

$$\text{EW} = \frac{F_l}{F_{PL}(E_l)} = \frac{\text{Line norm.}}{\text{PL norm.} \times (E_l/\text{keV})^{-\Gamma}},$$

where $F_l$ is the total photon flux in the line, and $F_{PL}(E_l)$ is the photon flux density of the power-law component at the position of the line, could be estimated as $\sim (0.5–1.9)$ keV using 200 trials, while for the model (ii) it would read as 0.4–1.1 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 any precise characterization of a Compton hump component.

Finally, we note that the same Chandra data set 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 differs from ours with respect to the source and background extraction regions; the analysis results were comparable however, except there was no iron line detected in the analysis by She et al. (2017).

In Appendix B 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 indeed be overlooked.
2.2.2. Fitting the Unbinned Data

In the case of low-count spectra, such as the one we are dealing with here, spectral fittings performed on the binned data with the $\chi^2$ 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 unbinned data using the Cash statistics (and the Nelder–Mead optimization method as before), simultaneously fitting the source and the background regions. The problem we encountered, however, was that the background spectrum—in particular its lower-energy segment below 1 keV—could not be fitted well in this approach using any of several models selected. For this reason, the unbinned data fitting was performed exclusively within the 1.5–7.0 keV photon energy range, where all the interstellar-medium-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 assumed either (a) an absorbed single power-law model $zphabs-powerlaw$, (b) an absorbed single power-law model with a redshifted Gaussian line, $zphabs*(powerlaw+zgauss)$, or (c) an absorbed single power-law with a redshifted Gaussian line plus 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 2, and for model (c) also presented in Figure 6.

As follows, the results of the modeling are in very good agreement with the ones presented in the previous section ($\chi^2$ fitting of the binned spectrum), in particular returning the equivalent width of the iron line with the best-fit position $6.5 \pm 0.8 (0.5–1.6)$ keV for model (b), and even $1.1 (0.6–1.7)$ keV for 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) and (b), 0.00301 for models (b) and (c), and finally 0.00098 for models (a) and (c). This implies that model (c), despite being the most complex one, best describes the data, and should be selected over models (a) and (b) with high significance.

2.3. Broadband SED

The background-subtracted 0.5–7.0 keV Chandra spectrum of the central parts of NGC 3894 (5″ ≈ 1.2 kpc source extraction...
Table 2
Spectral Modeling of the Unbinned Nuclear Spectrum of NGC 3894 Together with the Background

| Model | $N_H$ (× 10$^{22}$ cm$^{-2}$) | $\Gamma$ | PL Norm. (× 10$^{-6}$) | $E_L$ (keV) | Line Norm. (× 10$^{-6}$) | 4.6 keV Line Norm. (× 10$^{-6}$) | $\Gamma_{bc}$ | Back PL Norm. (× 10$^{-6}$) | C-stat/DOF |
|-------|------------------|--------|---------------------|--------|---------------------|---------------------|--------|---------------------|----------|
| (a)   | 1.2 ± 0.6        | 0.7 ± 0.3 | 13.2 ± 2         | ...   | ...                | ...                | 0.7 ± 0.2 | 3.1 ± 0.8         | 689.21/751 |
| (b)   | 1.9 ± 0.7        | 0.6 ± 0.4 | 25.2 ± 1          | 6.5 ± 0.1 | 2.0 ± 0.9         | ...                | 0.7 ± 0.2 | 3.1 ± 0.8         | 681.665/749 |
| (c)   | 2.1 ± 0.7        | 0.5 ± 0.3 | 33 ± 1           | 6.5 ± 0.1 | 2.3 ± 0.8         | 1.1 ± 0.5          | 0.7 ± 0.2 | 3.4 ± 0.7         | 672.87/748  |

Note. Column (1)—model fit; column (2)—intrinsic hydrogen column density; columns (3), (4)—photon index and normalization of the power-law emission component; columns (5), (6)—Gaussian line energy and normalization; column (7)—4.6 keV Gaussian line normalization; columns (8), (9)—photon index and normalization of the power-law emission representing the background; column (10)—Cash fitting statistics/DOF. The iron line equivalent width (1σ range) reads as EW $\approx$ 0.8(0.5–1.6) keV for the fit (b) with no 4.6 keV line, and EW $\approx$ 1.1(0.6–1.7) keV for the fit (c) including the 4.6 keV line.

3. Discussion

3.1. The Iron Line Fluorescence

The best-fit line energy for the iron fluorescence detected in the Chandra data for NGC 3894, $E_L = 6.5 \pm 0.1$ keV (see Section 2.2), is consistent with the position of a neutral Kα line, 6.4 keV, within the errors, although a slight blueshift could suggest a blend with ionized iron features with much lower intensity. Iron fluorescence seems restricted to the unresolved core, which corresponds in our case to the inner kiloparsec radius around the galactic nucleus (see Section 2.1).

Until now, neutral iron Kα lines have 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. 2019b), and 2021+614 (Sobolewska et al. 2019a), none of which, 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, a claim based on the Beppo-SAX or first XMM-Newton observations (Risaliti et al. 2003; Tengstrand et al. 2009); this has not been confirmed with Chandra or following XMM-Newton data (Siemiginowska et al. 2016; Sobolewska et al. 2019a). On the other hand, yet another CSO, 0710+439, has been found to display a very strong ionized iron line at $E_L \approx$ 6.6 keV, with a large EW $\approx$ 1 keV (Siemiginowska et al. 2016). An ionized iron line at $\approx$ 6.7 keV with EW $\approx$ 0.3 keV has been also found in two other radio galaxies with young inner structures (although not strictly of the CSO morphological type), namely PMN J1603-4904 (Müller et al. 2015; 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 $\approx$ 4 pc, $\approx$ 10 pc, and $\approx$ 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 density $N_H \sim 10^{24}$ cm$^{-2}$, which is about two orders of magnitude larger than $N_H$ inferred in our analysis for NGC 3894. At the same time, the EWs of the iron Kα lines in 1404+286 and 2021+614 are lower, $\approx$ 0.6 keV and $\approx$ 0.2 keV, respectively.

It may therefore be that in our relatively simple modeling of the Chandra spectrum with a limited energy range and limited photon statistics, we seriously underestimate 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 EWs of the order of 1 keV are expected rather for Compton-thick AGN, while for the objects with $N_H < 10^{23}$ cm$^{-2}$ the iron Kα EWs are typically of the order of 100 eV only (e.g., Fukazawa et al. 2011). Investigating this
possibility in more detail awaits deeper X-ray exposures of our target with instruments such as XMM-Newton and NuSTAR (but see also the discussion in the following subsection).

In this context, we note that the result of our analysis regarding the EW values are in 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 that there is an anticorrelation between the EW of the Fe K\alpha emission line at 6.4 keV and the X-ray continuum luminosity (see, e.g., Page et al. 2004; Fukazawa et al. 2011; Ricci et al. 2014; Boorman et al. 2018, and references therein).

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

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

(2)

For the WISE 12 \mu m luminosity of NGC 3894, $L_{12 \mu m} \approx 1.0 \times 10^{42} \text{ erg s}^{-1}$ (Kosmaczewski et al. 2020), this correlation would therefore imply EW =1.07^{+0.37}_{-0.28} keV, which is in (surprisingly) very good agreement with the best-fit value following from our spectral analysis.

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 $N_{\text{HI}} \approx 2.5 \times 10^{22} \text{ cm}^{-2}$. This best-fit value turns out about $\sim 2$ dex larger than the average value for the neutral hydrogen column density $N_{\text{HI}}$ inferred from the H I absorption features, assuming a spin temperature of the H I 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 their Section 6.1, sample D’ therein), namely

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

(3)

with the intrinsic spread $\epsilon_{\text{HI}} = 0.92^{+0.30}_{-0.20}$, which—for our best-fit value $N_{\text{HI}}$—implies that $N_{\text{HI}}$ should fall (with 68% probability) within a factor of about 8 from $\sim 6.5 \times 10^{20} \text{ cm}^{-2}$. This agreement reinforces the main conclusions by Ostorero et al. (2017) 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 underestimated in our Chandra spectral modeling, as speculated in the previous subsection, the average $N_{\text{HI}}$ value according to the Ostorero et al. (2017) correlation should be larger than observed. For example, assuming a Compton-thick limit of $N_{\text{HI}} = 1.5 \times 10^{24} \text{ cm}^{-2}$, from Equation (3) we obtain the expected $N_{\text{HI}} \approx 8.5 \times 10^{21} \text{ cm}^{-2}$. Still, we emphasize a rather large intrinsic spread in Equation (3) (a factor of about 8), interpreted as due to a spread in the H I gas spin temperature (which may vary substantially from the typically assumed “universal” value of 100 K; see the discussion in Ostorero et al. 2017).

3.3. The Overall Energetics of the Active Nucleus

The optical velocity dispersion of the central 3\,\prime\,5 of the galaxy was measured by van den Bosch et al. (2015), with the 10 m Hobby–Eberly Telescope at the McDonald Observatory, as $\sigma = 326.0 \pm 10.1 \text{ km s}^{-1}$. Van den Bosch et al. (2015) also provided the best-fit relation between the velocity dispersion.
and the black hole mass:

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

(4)

with $\alpha = 8.24 \pm 0.06$, $\beta = 5.28 \pm 0.37$, and the intrinsic scatter $\epsilon_M = 0.40 \pm 0.21$, consistent with McConnell & Ma (2013).

With this, for NGC 3894 we obtain $M_{\text{BH}} \sim 2 \times 10^9 M_{\odot}$ within a factor of 2.5, which is in very good agreement with the value obtained by Willett et al. (2010) based on the [O IV] 25.8 $\mu$m transition line. The estimate does not change if the $M_{\text{BH}} \sim \sigma$ 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 returns a black hole mass that is lower by one order of magnitude (see Willett et al. 2010).

With $M_{\text{BH}} \sim 2 \times 10^9 M_{\odot}$, 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 Eddington units, as $L_X/L_{\text{Edd}} \sim 2 \times 10^{-7}$. Likewise, the jet/lobe-related HE $\gamma$-ray emission of the source, as estimated by Principe et al. (2020), turns out to be one order of magnitude larger, namely $L_\gamma/L_{\text{Edd}} \sim 2 \times 10^{-6}$.

Unfortunately, the bolometric accretion-related luminosity in the target, $L_{\text{bol}}$, 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 $L_X/L_{\text{bol}}$ is known to vary widely among the youngest radio galaxies of the CSO type, from $\gtrsim 0.1$ down to $< 10^{-3}$ (see Wójciowicz 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. As such, the integrated 8–1000 $\mu$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 $L_{\text{Edd}} \equiv L_{\text{bol}}/L_{\text{Edd}} \sim 10^{-2}$. We stress, however, that the above estimate is highly uncertain, because of the uncertain value of the radiative efficiency factor $\eta_{\text{DT}}$, 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, $L \approx 4$ pc and kinematic age of the radio structure $t_\gamma \sim 60$ yr (Principe et al. 2020), as well as the VLBA 5 GHz flux of 387.6 mJy (Helmholtz et al. 2007), corresponding to the monochromatic radio power $L_{\text{GHz}} \sim 0.6 \times 10^{40}$ erg s$^{-1}$ from Equation (4) in Wójciowicz et al. (2020), we obtain $P_j \sim 2 \times 10^{42}$ 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 $\gamma$-ray emission, on the other hand, if it is 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 a rather lower limit for a true jet kinetic power in the source.

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 the “nonblazar” type) detected at HE $\gamma$-rays with Fermi-LAT. The analyzed data consist of a single 40 ks long ACIS exposure. We have found that the core spectrum is best fitted by a combination of a collisionally ionized thermal plasma with a temperature of $\sim 0.8$ keV, and a moderately absorbed power-law component (photon index $\Gamma = 1.4 \pm 0.4$, hydrogen column density $N_{\text{H}}/10^{22}$cm$^{-2} = 2.4 \pm 0.7$). We have also detected the iron Kα line at $6.5 \pm 0.1$ keV, with a relatively large EW of $10.6^{+0.5}_{-0.4}$ 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 kiloparsec radius around the galactic nucleus. The results summarized above, following from fitting the binned data, were supported by the additional analysis performed on the unbinned 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 the moderate obscuration implied by our spectral analysis. For this reason, we speculate that in our relatively simple modeling of the Chandra data with a limited energy range and limited photon statistics, we could seriously underestimate the true absorbing column density in the source. This speculation seems to be supported by the agreement of our best-fit EW Fe Kα value with the $\text{EW}_{\text{FeKα}} \sim L_{12.2 \mu m}^{-0.08}$ correlation 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 $\mu$m luminosity of the target as measured with WISE.

A moderate X-ray obscuration in the NGC 3894 nucleus seems, on the other hand, to be supported by the agreement of our best-fit $N_{\text{H}}$ value and the average neutral hydrogen column density $N_{\text{H}}$ inferred from the redshifted H1 absorption seen against the continuum emission of the central compact radio structure, with the $N_{\text{H}} \propto N_{\text{HI}}^{0.63}$ correlation claimed by Ostorero et al. (2017).

We also update on the broadband 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 $M_{\text{BH}} \sim 2 \times 10^9 M_{\odot}$ within a factor of 2.5. We also attempt to roughly estimate 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 $L_{\text{Edd}} \sim 10^{-4}$. 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 $P_j \sim 2 \times 10^{42}$ erg s$^{-1}$.

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Facility: Chandra (ACIS).

Software: CIAO (Fruscione et al. 2006), XSPEC (Arnaud 1996), Sherpa (Freeman et al. 2001), ChaRT (Carter et al. 2003), and MARX (Davis et al. 2012).

Appendix A
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. 2011), the 15 GHz flux densities vary from ~100 to 500 mJy. The few integrated measurements at 8 GHz indicate similar variations from 436 to 520 mJy (see Table 3). From available images in the RFC database, this level of change can be attributed to changes in the VLBI core, with observed 8 GHz flux densities of 66 mJy in 1994 August, and 155 to 183 mJy in 2017 April and August, respectively. The VLBI-scale jet knots appear variable as well, but with typical 5–8 GHz flux densities observed at levels of only about tens of millijansky (Principe et al. 2020).

Historical IR–optical–UV flux-density measurements of NGC 3894 collected from the literature, with no extinction correction applied, are summarized in Table 4.

### Table 4
Historical Integrated IR–Optical–UV Flux-density Measurements of NGC 3894

| $\nu$ [GHz] | $S_\nu$ [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                     |
| 8.19E5     | 37.8          | 5.20                     |
| 8.36E5     | 9.33          | 1.30                     |
| 9.52E5     | 6.25          | 1.91                     |
| 1.20E6     | 3.66          | 0.78                     |
| 1.29E6     | 0.419         | 5.87E–3                  |

Note. The catalogs/names indicated did not quote uncertainties, and 10% was assumed here.
Figure 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 the $1\sigma$, $2\sigma$, and $3\sigma$ count fractions, respectively.
Figure 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 \texttt{zphabs*powerlaw+apec}, with the applied grouping minimum 5 photons (upper panel) and 15 photons (lower panel). See Table 5 for the resulting best-fit model parameters.
5 px radius, and a close background from within 10–20 px, consistent 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 2.1), the 5 px source extraction region encompasses less than 2σ of the count fraction, as visualized in Figure 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 9, and summarized in Table 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 (minimum 5), while it seemingly disappears for a larger binning (minimum 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 $\Gamma \approx 0$, or the unconstrained absorbing hydrogen column density $N_H$. The source spectrum and the model fit corresponding to the grouping with minimum 15 photons are in agreement with She et al. (2017).

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