X-ray Study of CSO NGC 3894

Karthik Balasubramaniam¹ (karthik@oa.uj.edu.pl)
PhD scholar

Collaborators: Ł. Stawarz¹, V. Marchenko¹, M. Sobolewska², A. Siemiginowska², C.C. Cheung³, D. Król¹

¹Astronomical observatory, Jagiellonian university-Krakow, Poland
²Harvard Smithsonian Center for Astrophysics, USA
³Space Science Division, Naval Research Laboratory, USA

6th CSSGPS workshop
An orientation/evolutionary-based unification of jetted active galactic nuclei.

Unification scheme of jetted-AGN with high accretion rate with respect to the Eddington limit and a high-density photon-rich environment. On the left side, young and smaller sources (NLS1s and CSS sources), compared to older and larger objects (FSRQs and FR HERG).

- Compact symmetric objects (CSOs) are jetted active galactic nuclei (AGNs) with a double-lobed radio structure confined to within 1 kpc.
- CSOs represent the earliest evolutionary phase of jetted AGNs. Some of them may eventually evolve into large-scale extended double sources, while others stall within the host galaxy and die out, depending on the longevity of nuclear activity, the jet power, and parameters of the surrounding galactic environment.
- Studying CSOs enables us to understand the evolution of galaxies and the interactions between relativistic jets and the interstellar medium of the hosts.
Bright nearby E/S0 galaxy discovered already by William Herschel

- Luminosity Distance = 50.1Mpc
- Scale = 0.24 kpc/arcsec
- Hubble Space Telescope observations of NGC 3894: see Perlman et al. 2001

RA: 11h 48m 50.3582s
Dec: +59d 24m 56.382s
1146+596 recognized as a compact radio source by Condon & Dressel (1978);

First VLBI imaging at 5 GHz (Wrobel et al. 1985) suggested the presence of three radio components, consistent with an asymmetric core-jet structure;

The VLBI 1981-1996 monitoring analyzed by Taylor et al. (1998) indicated that the twin jets were mildly relativistic with velocities $v \sim 0.3\ c$ and oriented at $\sim 50\deg$ from the line-of-sight.
Most recently, Principe et al. (2020) claimed that “VLBA results favor the youth scenario for the inner structure of this object, with an estimated dynamical age of 59 +/- 5 years, and the jet viewing angle 10-20deg”
“The 21 cm atomic hydrogen line is seen in absorption slightly redshifted with respect to the systemic velocity toward the core, jet, and counterjet of this source. There are four components in the gas that are spatially and/or spectrally distinct, two of which appear to be part of a single larger structure, possibly a circumnuclear torus.” (Peck & Taylor 1998, Gupta et al. 2006)
MIR studies (IRAS, Spitzer, WISE) indicate the low-luminosity LINER-type AGN, and low star formation rate ~0.5 M$_{\odot}$/yr in the host

(Willet et al. 2010, Kosmaczewski et al. 2020)
NGC 3894: a young radio galaxy seen by Fermi-LAT

G. Principe¹, G. Migliori¹,², T. J. Johnson³, F. D’Ammando¹, M. Giroletti¹, M. Orienti¹, C. Stanghellini¹, G. B. Taylor⁴, E. Torresi¹, and C. C. Cheung⁶

¹ INAF – Istituto di Radioastronomia, Bologna, Italy
e-mail: giancomo.principe@inaf.it
² Dip. di Fisica e Astronomia, Università di Bologna, Bologna, Italy
³ College of Science, George Mason University, Resident at Naval Research Laboratory, Washington DC, USA
⁴ University of New Mexico, Albuquerque, NM, USA
⁵ INAF – Osservatorio di Astrofisica e Scienze dello Spazio di Bologna, Bologna, Italy
⁶ Naval Research Laboratory, Space Science Division, Washington DC, USA

Received 4 November 2019 / Accepted 28 February 2020

ABSTRACT

Context. According to radiative models, radio galaxies may produce γ-ray emission from the first stages of their evolution. However, very few such galaxies have been detected by the Fermi Large Area Telescope (LAT) so far.

Aims. NGC 3894 is a nearby (z = 0.0108) object that belongs to the class of compact symmetric objects (CSOs, i.e., the most compact and youngest radio galaxies), which is associated with a γ-ray counterpart in the Fourth Fermi-LAT source catalog. Here we present a study of the source in the γ-ray and radio bands aimed at investigating its high-energy emission and assess its young nature.

Methods. We analyzed 10.8 years of Fermi-LAT data between 100 MeV and 300 GeV and determined the spectral and variability characteristics of the source. Multi-epoch very long baseline array (VLBA) observations between 5 and 15 GHz over a period of 35 years were used to study the radio morphology of NGC 3894 and its evolution.

Results. NGC 3894 is detected in γ-rays with a significance >9σ over the full period, and no significant variability has been observed in the γ-ray flux on a yearly time-scale. The spectrum is modeled with a flat power law (Γ = 2.6 ± 0.1) and a flux on the order of 2.2 × 10⁻⁸ ph cm⁻² s⁻¹. For the first time, the VLBA data allow us to constrain with high precision the apparent velocity of the jet and counter-jet side to be β_app, NW = 0.132 ± 0.004 and β_app, SE = 0.065 ± 0.003, respectively.

Conclusions. Fermi-LAT and VLBA results favor the youth scenario for the inner structure of this object, with an estimated dynamical age of 59 ± 5 years. The estimated range of viewing angle (10° < θ < 21°) does not exclude a possible jet-like origin of the γ-ray emission.

Key words. Galaxy: evolution – galaxies: nuclei – galaxies: general – galaxies: jets – radio continuum: galaxies – gamma-rays: galaxies
Table 6
Properties of Fermi-detected and Other Nearby CSO Galaxies

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$D_L$ (Mpc)</th>
<th>Host Galaxy</th>
<th>Morphology</th>
<th>LLGS (pc)</th>
<th>$\theta$ (deg)</th>
<th>$\beta_{lep}$ (c)</th>
<th>Age (yr)</th>
<th>$\nu_m$ (GHz)</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXS 0128+554</td>
<td>0.036</td>
<td>159</td>
<td>Elliptical</td>
<td>C</td>
<td>12</td>
<td>$\frac{52^2}{3}$</td>
<td>$0.32 \pm 0.07$</td>
<td>82 $\pm$ 17</td>
<td>0.66</td>
<td>0.48</td>
</tr>
<tr>
<td>NGC 3894</td>
<td>0.011</td>
<td>57</td>
<td>Elliptical</td>
<td>E</td>
<td>7</td>
<td>$10-21$</td>
<td>$\sim 0.1$</td>
<td>59 $\pm$ 5</td>
<td>0.5</td>
<td>0.18</td>
</tr>
<tr>
<td>PKS 1718-649</td>
<td>0.014</td>
<td>62</td>
<td>Elliptical</td>
<td>C</td>
<td>2</td>
<td>7</td>
<td>$0.06 \pm 0.03$</td>
<td>$70 \pm 30$</td>
<td>5.6</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PMN J1603-4904</td>
<td>0.232</td>
<td>1148</td>
<td>Unknown</td>
<td>E</td>
<td>56</td>
<td>7</td>
<td>$&lt;3$</td>
<td>$54 \pm 30$</td>
<td>0.39</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Fermi-detected CSOs

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$D_L$ (Mpc)</th>
<th>Host Galaxy</th>
<th>Morphology</th>
<th>LLGS (pc)</th>
<th>$\theta$ (deg)</th>
<th>$\beta_{lep}$ (c)</th>
<th>Age (yr)</th>
<th>$\nu_m$ (GHz)</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXS 0128+554</td>
<td>0.036</td>
<td>159</td>
<td>Elliptical</td>
<td>C</td>
<td>12</td>
<td>$\frac{52^2}{3}$</td>
<td>$0.32 \pm 0.07$</td>
<td>82 $\pm$ 17</td>
<td>0.66</td>
<td>0.48</td>
</tr>
<tr>
<td>NGC 3894</td>
<td>0.011</td>
<td>57</td>
<td>Elliptical</td>
<td>E</td>
<td>7</td>
<td>$10-21$</td>
<td>$\sim 0.1$</td>
<td>59 $\pm$ 5</td>
<td>0.5</td>
<td>0.18</td>
</tr>
<tr>
<td>PKS 1718-649</td>
<td>0.014</td>
<td>62</td>
<td>Elliptical</td>
<td>C</td>
<td>2</td>
<td>7</td>
<td>$0.06 \pm 0.03$</td>
<td>$70 \pm 30$</td>
<td>5.6</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PMN J1603-4904</td>
<td>0.232</td>
<td>1148</td>
<td>Unknown</td>
<td>E</td>
<td>56</td>
<td>7</td>
<td>$&lt;3$</td>
<td>$54 \pm 30$</td>
<td>0.39</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Redshift CSOs. Lacking Fermi-LAT Associations

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$D_L$ (Mpc)</th>
<th>Host Galaxy</th>
<th>Morphology</th>
<th>LLGS (pc)</th>
<th>$\theta$ (deg)</th>
<th>$\beta_{lep}$ (c)</th>
<th>Age (yr)</th>
<th>$\nu_m$ (GHz)</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C 31.04</td>
<td>0.060</td>
<td>266</td>
<td>Elliptical</td>
<td>C</td>
<td>100</td>
<td>$75-80$</td>
<td>0.34</td>
<td>550</td>
<td>0.4</td>
<td>0.016</td>
</tr>
<tr>
<td>PMN J1511+0518</td>
<td>0.084</td>
<td>378</td>
<td>Elliptical</td>
<td>C</td>
<td>11</td>
<td>7</td>
<td>$0.28$</td>
<td>55</td>
<td>10</td>
<td>0.03</td>
</tr>
<tr>
<td>B2 0035+22</td>
<td>0.096</td>
<td>435</td>
<td>Elliptical</td>
<td>C</td>
<td>22</td>
<td>7</td>
<td>0.5</td>
<td>450</td>
<td>0.4-1.4</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Notes. Columns are as follows: (1) source name, (2) redshift, (3) luminosity distance in Mpc, (4) host galaxy type, (5) kiloparsec-scale radio morphology, where $E$ = extended, and $C$ = compact, (6) largest projected linear size of inner jet structure as measured from hotspot to hotspot in parsecs, (7) jet viewing angle in degrees, (8) apparent expansion speed in units of the speed of light, (9) dynamical age of the radio source in years, (10) radio spectral turnover frequency in GHz, (11) ratio of core flux density to total flux density at 8 GHz.

NGC 3894. This low-luminosity CSO is located in an elliptical galaxy at $z = 0.01075$, and was found to be γ-ray loud by Principe et al. (2020) after stacking 10.8 yr of Pass 8 Fermi-LAT data. The 5 GHz VLA image of Taylor et al. (1998) shows a bright core flanked by radio lobes separated by ~800 pc. On milliarcsecond scales, the flat-spectrum core is flanked by two bright, continuous jets with projected lengths of ~2 pc (Tremblay et al. 2016). Fainter diffuse emission is visible in both jets farther from the core in low-frequency VLBI images (Taylor et al. 1998). The inner radio source has a high core fraction ($f = 0.18$). Principe et al. (2020) find expansion speeds of ~0.1 c and a viewing angle of $10^\circ < \theta < 21^\circ$ for the inner jets. These measurements imply a young kinematic age of $59 \pm 5$ yr.

Table 7
Spectral Properties of Fermi-detected and Other Nearby CSO Galaxies

<table>
<thead>
<tr>
<th>Source</th>
<th>$log I_{\nu}$ (1.4 GHz)</th>
<th>$log I_{\nu}$ (0.5-2 keV)</th>
<th>$log I_{\nu}$ (2-10 keV)</th>
<th>$log I_{\nu}$ (0.1-100 GeV)</th>
<th>$\Gamma$</th>
<th>$log I_{\nu}$ (10-1000 GeV)</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXS 0128+554</td>
<td>23.7</td>
<td>42.5</td>
<td>42.3</td>
<td>43.2</td>
<td>$2.10 \pm 0.09$</td>
<td>42.5</td>
<td>$3.4 \pm 0.9$</td>
</tr>
<tr>
<td>NGC 3894</td>
<td>23.1</td>
<td>40.4</td>
<td>40.8</td>
<td>41.8</td>
<td>$2.06 \pm 0.12$</td>
<td>42.4</td>
<td>$2.49 \pm 0.18$</td>
</tr>
<tr>
<td>PKS 1718-649</td>
<td>23.3</td>
<td>40.9</td>
<td>41.2</td>
<td>42.1</td>
<td>$2.02 \pm 0.03$</td>
<td>45.6</td>
<td>$2.2 \pm 0.10$</td>
</tr>
<tr>
<td>PMN J1603-4904</td>
<td>26.3</td>
<td>43.5</td>
<td>43.6</td>
<td>45.9</td>
<td>$2.02 \pm 0.03$</td>
<td>45.6</td>
<td>$2.2 \pm 0.10$</td>
</tr>
</tbody>
</table>

Fermi-detected CSOs

<table>
<thead>
<tr>
<th>Source</th>
<th>$log I_{\nu}$ (1.4 GHz)</th>
<th>$log I_{\nu}$ (0.5-2 keV)</th>
<th>$log I_{\nu}$ (2-10 keV)</th>
<th>$log I_{\nu}$ (0.1-100 GeV)</th>
<th>$\Gamma$</th>
<th>$log I_{\nu}$ (10-1000 GeV)</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXS 0128+554</td>
<td>23.7</td>
<td>42.5</td>
<td>42.3</td>
<td>43.2</td>
<td>$2.10 \pm 0.09$</td>
<td>42.5</td>
<td>$3.4 \pm 0.9$</td>
</tr>
<tr>
<td>NGC 3894</td>
<td>23.1</td>
<td>40.4</td>
<td>40.8</td>
<td>41.8</td>
<td>$2.06 \pm 0.12$</td>
<td>42.4</td>
<td>$2.49 \pm 0.18$</td>
</tr>
<tr>
<td>PKS 1718-649</td>
<td>23.3</td>
<td>40.9</td>
<td>41.2</td>
<td>42.1</td>
<td>$2.02 \pm 0.03$</td>
<td>45.6</td>
<td>$2.2 \pm 0.10$</td>
</tr>
<tr>
<td>PMN J1603-4904</td>
<td>26.3</td>
<td>43.5</td>
<td>43.6</td>
<td>45.9</td>
<td>$2.02 \pm 0.03$</td>
<td>45.6</td>
<td>$2.2 \pm 0.10$</td>
</tr>
</tbody>
</table>

Low-redshift CSOs. Lacking Fermi-LAT Associations

<table>
<thead>
<tr>
<th>Source</th>
<th>$log I_{\nu}$ (1.4 GHz)</th>
<th>$log I_{\nu}$ (0.5-2 keV)</th>
<th>$log I_{\nu}$ (2-10 keV)</th>
<th>$log I_{\nu}$ (0.1-100 GeV)</th>
<th>$\Gamma$</th>
<th>$log I_{\nu}$ (10-1000 GeV)</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C 31.04</td>
<td>25.3</td>
<td>&lt;40.6</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>PMN J1511+0518</td>
<td>25.2</td>
<td>42.0</td>
<td>42.7</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>B2 0035+22</td>
<td>25.1</td>
<td>41.6</td>
<td>41.9</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. Columns are as follows: (1) source name, (2) log of 1.4 GHz luminosity ($I_{\nu}$) in W Hz$^{-1}$, (3) log of 0.5-2 keV x-ray luminosity in erg s$^{-1}$, (4) log of 2-10 keV x-ray luminosity ($I_{\nu}$) in erg s$^{-1}$, (5) log of 0.1-100 GeV γ-ray luminosity from 4FGL in erg s$^{-1}$, (6) 4FGL power-law photon index between 0.1 and 100 GeV, (7) log of 10-1000 GeV γ-ray luminosity from 3FHL in erg s$^{-1}$, (8) 3FHL power-law photon index between 10 and 1000 GeV.

M.L. Lister et al 2020
Motivation

- Well characterized at radio, IR, & optical frequencies
- Archival Chandra Data (~40 ks) not analyzed (published) before!
- One of the youngest nearby radio galaxies; one of a few CSOs detected in gamma-rays by Fermi-LAT!
- A need for a proper X-ray spectroscopy and a broad-band SED
Archival Chandra Observation ~ 40 ks (PI: Perlman), not analyzed/published before

ACIS-I observations in 2001

Net count rate: $1.134 \times 10^{-2}$ cts/s

~450 photons within the source extraction region 5"
Chandra view of the active nucleus in NGC 3894

- source extraction region: 5” radius circle (white solid)
- background: annulus with 10” and 20” radii (white dashed)

- excluding the two 2.5” radii circles corresponding to bright point sources (solid)
- Chandra images of NGC 3894, smoothed with 3 sigma; as shown, the 6-7 keV emission is restricted to the unresolved core
Indeed, no extension in the 6-7 keV emission beyond the PSF (simulated for the 6-7 keV range)
X-ray hardness ratio analysis

- Hardness ratio map
  \[ HR = \frac{(H-M)}{(H+M)} \]
  between the Hard (6-7keV) and Medium (2-6keV) bands.
- Note the map is reliable with no prominent artefacts because the PSFs for both M and H bands are rather similar.

K.Balasubramaniam et al. to be submitted
A simple model \texttt{phabs.gal * (zphabs*powerlaw + zapec)} applied to the background-subtracted source spectrum, returns a very flat, moderately absorbed power-law (N_{H} \sim 2 \times 10^{22} \text{cm}^{-2}, \Gamma \sim 1.3), contributed by a thermal component (kT \sim 0.8 \text{ keV}; assumed solar metallicity). The residuals indicate however a presence of the emission lines, including:

- A line around 6.4 keV, consistent with the neutral iron K-shell line;
- A line around 4.6 keV, which most likely is the instrumental artefact (Si escape peak, following the Fe 6.4 keV emission (see Grimm et al. 2009, ApJ, 690, 128)
- Positive residuals in the soft range (\textgreater; see next slides!)

Adding a simple redshifted Gaussian line component to the model:
\texttt{phabs.gal *(zphabs*(powerlaw+zgauss) + zapec)}

improves the fitting, and confirmed the presence of a neutral iron K-shell line with the EW \sim 0.6 \text{ keV}. 

---

**Chandra spectral modelling**
Best fit parameters

- $N_H^{(\text{Gal})} \text{ [cm}^{-2}\text{]}$ (frozen!): $0.0183 \times 10^{22}$
- $kT \text{ [keV]}$: $0.789 \pm 0.0579$
- $N_H^{(\text{int})} \text{ [cm}^{-2}\text{]}$: $(2.21 \pm 0.66) \times 10^{22}$
- $\Gamma_{\text{src}}$: $1.28 \pm 0.37$
- Line E [keV]: $6.47 \pm 0.05$
- EW [keV]: $0.6$
- Unabsorbed flux of the PL component (0.5-7.0) [erg/cm$^2$/s]: $1.987 \times 10^{-13}$

K. Balasubramaniam et al. to be submitted
We considered more sophisticated emission models as well, however due to a rather limited photon statistics, those did not improve the fitting, or actually made it worse.
Positive residuals we see in the core spectrum of NGC 3894 in the soft range (<~ 1keV), may indicate the presence of the photoionized plasma component in addition to the collisionally ionized 0.8 keV plasma modeled here by apec, similarly as seen in PKS 1718−649.

PKS 1718−649 - another very compact CSO with LINER-type nucleus, detected in gamma-rays

X-ray data analysis: Beuchert et al. 2018

Model:
- photoionized plasma (xstar)
- collisionally ionized plasma (apec)
- absorbed PL (variable!)

XMM-Newton
+ Multiple Chandra pointings
Multiwavelength SED of NGC 3894

Chandra X-ray (from our modelling)

Principe et al 2020 (Fermi-LAT)
Summary

- One of the youngest nearby radio galaxies; one of a few CSOs detected in gamma-rays by Fermi-LAT.
- Here we present the first attempt for detailed X-ray spectroscopy.
- Very flat PL with Gamma 1.3+/−0.3, and total luminosity $L_X \sim 6\times10^{40}$ erg/s.
- Neutral iron line at 6.4keV with relatively large EW $\sim 0.6$keV !!!
- Poor photon statistics makes fitting quite challenging although we believe that our findings regarding a very flat PL component and neutral iron line with relatively large EW, are robust!

6th CSSGPS workshop