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The first γ-ray detection of the narrow-line Seyfert 1 FBQS J1644+2619

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ABSTRACT

We report the discovery of γ-ray emission from the narrow-line Seyfert 1 (NLSy1) galaxy FBQS J1644+2619 by the Large Area Telescope on board the *Fermi* satellite. The Third Fermi LAT Source catalogue reports an unidentified γ-ray source, detected over the first four years of *Fermi* operation, $0\overset{\circ}{.}23$ from the radio position of the NLSy1. Analysing 76 months of γ-ray data (2008 August 4–2014 December 31) we are able to better constrain the localization of the γ-ray source. The new position of the γ-ray source is $0\overset{\circ}{.}05$ from FBQS J1644+2619, suggesting a spatial association with the NLSy1. This is the sixth NLSy1 detected at high significance by *Fermi*-LAT so far. Notably, a significant increase of activity was observed in γ-rays from FBQS J1644+2619 during 2012 July–October, and an increase of activity in the *V* band was detected by the Catalina Real-Time Sky Survey in the same period.

Key words: galaxies: active – galaxies: individual: FBQS J1644+2619 – galaxies: nuclei – galaxies: Seyfert – gamma-rays: general.

1 INTRODUCTION

The discovery of variable γ-ray emission from narrow-line Seyfert 1 (NLSy1) galaxies revealed the presence of a possible third class of active galactic nuclei (AGN) with relativistic jets (Abdo et al. 2009). Five NLSy1 have been detected at high significance in γ-rays by the Large Area Telescope (LAT) on board the *Fermi Gamma-ray Space Telescope* satellite so far (Abdo et al. 2009; D'Ammando et al. 2012). High brightness temperatures and radio-loudness parameters have been observed in the NLSy1 already detected by *Fermi*-LAT. Therefore, these properties may be a good proxy for the jet production efficiency, and thus for selecting the best candidates for a LAT γ-ray detection. However, in the radio-loud NLSy1 sample presented by Yuan et al. (2008), neither the source with the highest radio-loudness (B3 1044+476) nor the highest brightness temperature (TXS 1546+353) has yet been detected in γ-rays.

The NLSy1 detected in γ-rays so far have exhibited blazar-like behaviour, including strong γ-ray flux variability (D'Ammando et al. 2013a, 2014; Foschini et al. 2015). Due to this variability and their apparent rarity, identification of new γ-ray emitting NLSy1 will benefit enormously from frequent observations of a large number of candidates. The *Fermi*-LAT's nearly continuous surveying of the entire γ-ray sky provides a unique opportunity to carry out such monitoring, with great sensitivity. As the *Fermi* satellite continues to accumulate data, the discovery of new NLSy1 in γ-rays is expected.

The Third *Fermi* LAT source catalogue (3FGL; Acero et al. 2015) reports an unassociated γ-ray source, 3FGL J1644.4+2632 (RA=$251\overset{\circ}{.}123$, Dec.=$26\overset{\circ}{.}542$, with a 95 per cent error circle radius of $0\overset{\circ}{.}201$). The radio position of First Bright Quasar Survey (FBQS) J1644+2619 (RA=$251\overset{\circ}{.}177$, Dec.=$26\overset{\circ}{.}320$) lies $0\overset{\circ}{.}227$ from the γ-ray source, just outside its 95 per cent error circle radius. For this reason, 3FGL J1644.4+2632 was not associated with FBQS J1644+2619 in the 3FGL catalogue. FBQS J1644+2619 is an NLSy1 at redshift z = 0.145 (Bade et al. 1995), with a radio loudness[1] of R = 447, a full width at half-maximum (H β) = $(1507 \pm 42)\,\mathrm{km\,s^{-1}}$, and [O III]/H $\beta \sim 0.1$ (Yuan et al. 2008). In this paper we present results of the analysis of 76 months of *Fermi*-LAT data reporting the first detection in γ-rays of the NLSy1 FBQS J1644+2619.

This paper is organized as follows. In Section 2, we report the *Fermi*-LAT data analysis and results. The data collected by the Catalina Real-time Transient Survey (CRTS[2]) in the *V* band, together with the X-ray, UV, and optical data collected by *Swift* are presented in Section 3. In Section 4, we discuss the properties of the source and draw our conclusions.

Throughout the paper, the quoted uncertainties are given at the 1σ level, unless otherwise stated, and the photon indices are parametrized as $\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma_\nu}$, where Γ_ν is the photon index in the different energy bands. We adopt a Λ cold dark matter cosmology with $H_0 = 71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.73$, and $\Omega_\mathrm{m} = 0.27$

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[1] The radio loudness R is defined as the ratio of radio at 1.4 GHz to B-band flux densities.

[2] http://crts.caltech.edu/

(Komatsu et al. 2011). The redshift of this source, $z = 0.145$, corresponds to a luminosity distance $d_{\rm L} = 690$ Mpc, where 1 arcsec corresponds to a projected size of 2.56 kpc.

2 *Fermi*-LAT DATA: SELECTION AND ANALYSIS

The *Fermi*-LAT is a pair-conversion telescope operating from 20 MeV to >300 GeV. Details about the *Fermi*-LAT are given in Atwood et al. (2009). The *Fermi*-LAT data reported in this paper were collected from 2008 August 4 (MJD 54682) to 2014 December 31 (MJD 57022). During this time the LAT instrument operated most of the time in survey mode, scanning the entire sky every 3 h. The analysis was performed with the SCIENCETOOLS software package version v9r34p03. Only events belonging to the 'Source' class were used. The time intervals when the rocking angle of the LAT was greater than 52° were rejected. In addition, a cut on the zenith angle (<100°) was applied to reduce contamination from the Earth limb γ-rays, which are produced by cosmic rays interacting with the upper atmosphere. The spectral analysis was performed with the instrument response functions `P7REP_SOURCE_V15` using an unbinned maximum likelihood method implemented in the Science tool `gtlike`. Isotropic ('iso_source_v05.txt') and Galactic diffuse emission ('gll_iem_v05_rev1.fit') components were used to model the background.[3] The normalization of both components was allowed to vary freely during the spectral fitting.

We analysed a region of interest of 10° radius centred at the location of FBQS J1644+2619. We evaluated the significance of the γ-ray signal from the source by means of a maximum-likelihood test statistic (TS) that results in TS $= 2\,(\log L_1 - \log L_0)$, where L is the likelihood of the data given the model with (L_1) or without (L_0) a point source at the position of FBQS J1644+2619 (e.g. Mattox et al. 1996). The source model used in `gtlike` includes all the point sources from the 3FGL catalogue that fall within 15° of FBQS J1644+2619. The spectra of these sources were parametrized by a power-law (PL), a log-parabola (LP), or a super exponential cut-off, as in the 3FGL catalogue.

We tested whether two distinct γ-ray sources (one at the radio position of FBQS J1644+2619 and one at the γ-ray position of 3FGL J1644.4+2632) are detected simultaneously by *Fermi*-LAT over 76 months of observations, including both sources in the model. In the fitting procedure, the normalization factors and the spectral parameters of the sources lying within 10° of FBQS J1644+2619 were left as free parameters. For the sources located between 10° and 15° from our target, we kept the normalization and the spectral parameters fixed to the values from the 3FGL catalogue. A first maximum likelihood analysis was performed yielding TS = 2 for 3FGL J1644.4+2632 and TS = 20 for FBQS J1644+2619. We concluded that only one γ-ray source at a position compatible with FBQS J1644+2619 is detected by *Fermi*-LAT over 76 months.

We removed 3FGL J1644.4+2632 and all sources with TS < 5. A second maximum likelihood analysis was performed on the updated source model. Integrating over the period 2008 August 4–2014 December 31 using a PL model, $\mathrm{d}N/\mathrm{d}E \propto (E/E_0)^{-\Gamma}$, a TS of 26 ($\sim$4.4$\sigma$) was obtained for FBQS J1644+2619 in the 0.1–100 GeV energy range, with an average flux of $(5.9 \pm 1.9) \times 10^{-9}$ ph cm^{-2} s^{-1} and a photon index $\Gamma_\gamma = 2.5 \pm 0.2$. This flux corresponds to an apparent isotropic (rest-frame) γ-ray luminosity of 1.6×10^{44} erg s^{-1}. A γ-ray point source localization was performed using the `gtfindsrc` tool over the photons extracted during the entire period. The fit results in RA = 251.168°, Dec. = 26.372° with a 95 per cent error circle radius of $0\overset{\circ}{.}091$. The γ-ray source lies at an angular separation of $0\overset{\circ}{.}053$ from the radio position of FBQS J1644+2619, suggesting a spatial association between the γ-ray source and the NLSy1 FBQS J1644+2619.

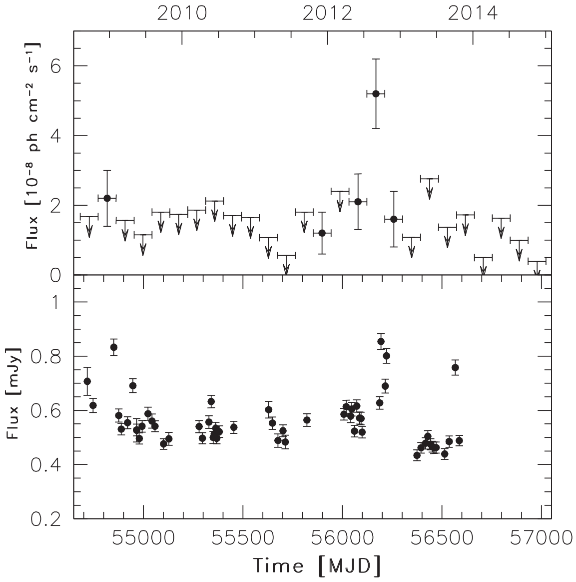

Figure 1. Upper panel: integrated flux light curve of FBQS J1644+2619 obtained by *Fermi*-LAT in the 0.1–100 GeV energy range during 2008 August 4–2014 December 31 (MJD 54682–57022) with 90-d time bins. Arrows refer to 2σ upper limits on the source flux. Upper limits are computed when TS < 5. Lower panel: light curve in the V band obtained by CRTS during 2008 October 8–2013 October 22.

Fig. 1 shows the γ-ray light curve for the first 76 months of *Fermi*-LAT observations of FBQS J1644+2619 using a PL model and 90-d time bins. For each time bin, the spectral parameters of FBQS J1644+2619 and of all sources within 10° of it were frozen to the values resulting from the likelihood analysis over the entire period. If TS < 5, the 2σ upper limits were calculated. The systematic uncertainty in the flux is dominated by the systematic uncertainty in the effective area (Ackermann et al. 2012), which amounts to 10 per cent below 100 MeV, decreasing linearly with the logarithm of energy to 5 per cent between 316 MeV and 10 GeV, and increasing linearly with the logarithm of energy up to 15 per cent at 1 TeV.[4]

FBQS J1644+2619 was detected sporadically by the *Fermi*-LAT, with an increase of activity during 2012 July 15–October 12. Running a γ-ray point source localization over the photons extracted during the period 2012 June–2013 January, in which the source was detected continuously, the fit results in RA = 251.156°, Dec. = 26.373° with a 95 per cent error circle radius of $0\overset{\circ}{.}096$. The γ-ray source lies at an angular separation of $0\overset{\circ}{.}056$ from the radio position of FBQS J1644+2619. The position estimated in the high-activity period lies at an angular separation of $0\overset{\circ}{.}011$ from the position estimated over 76 months of LAT observations.

In the period 2012 July 15–October 12, the source reached a flux (0.1–100 GeV) of $(5.2 \pm 1.0) \times 10^{-8}$ ph cm^{-2} s^{-1}, a factor of 9 higher than its average γ-ray flux. Leaving the photon index of our

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[3] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

[4] http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

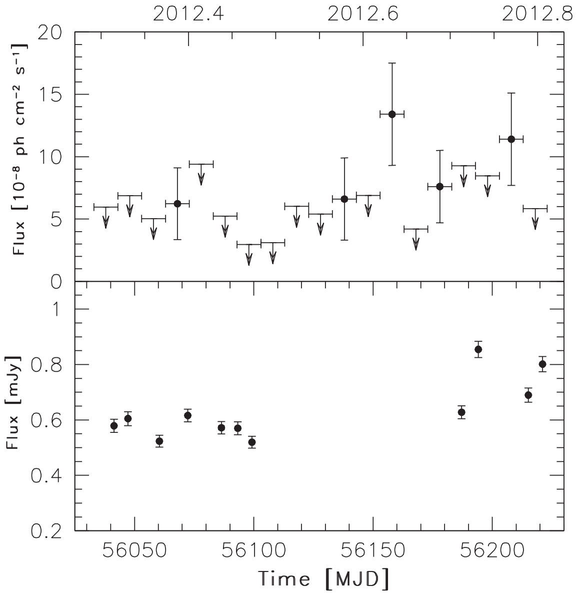

Figure 2. Upper panel: integrated flux light curve of FBQS J1644+2619 obtained by *Fermi*-LAT in the 0.1–100 GeV energy range during 2012 April 16–October 22 (MJD 56033–56222) with 10-d time bins. Arrows refer to 2σ upper limits on the source flux. Upper limits are computed when TS < 5. Lower panel: light curve in the *V* band obtained by CRTS in the same period of the *Fermi*-LAT light curve.

target (and of all sources within 10° of our target) free to vary, the fit for FBQS J1644+2619 results in a photon index $\Gamma_\gamma = 2.5 \pm 0.2$. Although limited by the statistics, no significant spectral change seems to be detected during the high state. A γ-ray light curve in the period 2012 April 16–October 22 with 10-d time bins is reported in Fig. 2. On daily time-scales peak activity was detected on 2012 August 18 (MJD 56157) and 2012 October 5 (MJD 56205), with fluxes of $(66 \pm 22)\times10^{-8}$ ph cm^{-2} s^{-1} and $(43 \pm 17)\times10^{-8}$ ph cm^{-2} s^{-1}, respectively. By means of the `gtsrcprob` tool, we estimated that the highest energy photon detected from FBQS J1644+2619 was observed on 2012 June 6 at a distance of $0.^{\circ}002$ from the γ-ray source with an energy of 25.7 GeV.

3 MULTIFREQUENCY DATA

3.1 Catalina Real-time Transient Survey data

The source has been monitored by the CRTS (Drake et al. 2009; Djorgovski et al. 2011), using the 0.68-m Schmidt telescope at Catalina Station, Arizona, and an unfiltered CCD. The typical cadence is four exposures separated by 10 min in a given night; this may be repeated up to four times per lunation, over a period of ∼6–7 months each year, while the field is observable. Photometry is obtained using the standard Source-Extractor package (Bertin & Arnouts 1996), and transformed from the unfiltered instrumental magnitude to Cousins V[5] by $V = V_{\rm CSS} + 0.31(B - V)^2 + 0.04$. We averaged the values obtained during the same observing night. During the CRTS monitoring the source showed a variability amplitude of ∼1 mag, changing between 17.78 and 16.72 mag. The CRTS flux densities, corrected for extinction using the $E(B - V)$ value of 0.073 from Schlafly & Finkbeiner (2011) and the extinction laws from Cardelli, Clayton & Mathis (1989), are reported in Figs 1 and 2.

3.2 *Swift* data: analysis and results

The *Swift* satellite (Gehrels et al. 2004) observed FBQS J1644+2619 on 2011 December 26 with the X-ray Telescope (XRT; Burrows et al. 2005, 0.2–10.0 keV) and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005, 170–600 nm). The XRT data were processed by using the `xrtpipeline v0.13.1` of the HEASOFT package (v6.16) with standard procedures, filtering, and screening criteria. The data were collected in photon counting mode for a net exposure of about 1.3 ks. Considering the low number of photons collected (<200 counts) the spectra were rebinned with a minimum of 1 count per bin and we performed the fit with the Cash statistic (Cash 1979). Source events were extracted from a circular region with a radius of 20 pixels (1 pixel ∼2.36 arcsec), while background events were extracted from a circular region with radius of 50 pixels far away from bright sources. Ancillary response files were generated with `xrtmkarf`, and account for different extraction regions, vignetting, and point spread function corrections. We used the spectral redistribution matrices in the Calibration data base maintained by HEASARC. The X-ray spectrum can be fitted in the 0.3–10 keV energy range with an absorbed power-law using the photoelectric absorption model `tbabs` (Wilms, Allen & McCray 2000), with a neutral hydrogen column density fixed to its Galactic value (5.14×10^{20} cm^{-2}; Kalberla et al. 2005) and a photon index of $\Gamma_{\rm X} = 2.0 \pm 0.3$ (χ^2/d.o.f = 80/59). The corresponding unabsorbed 0.3–10 keV flux is $(2.3\pm0.5) \times 10^{-12}$ erg cm^{-2} s^{-1}. Adding a thermal component (i.e. a blackbody model), as in Yuan et al. (2008), yields a temperature kT $= 0.06^{+0.05}_{-0.04}$ keV and a photon index $\Gamma_{\rm X} = 1.7^{+0.4}_{-0.5}$ with a comparable quality of fit (χ^2/d.o.f = 78/57). The low number of counts does not allow a detailed comparison between the two models.

UVOT data in the v, b, u, $w1$, $m2$, and $w2$ filters were analysed with the `uvotsource` task included in the HEASOFT package (v6.16) and the 20130118 CALDB-UVOTA release. Source counts were extracted from a circular region of 5 arcsec radius centred on the source, while background counts were derived from a circular region with 10 arcsec radius in a nearby source-free region. The observed magnitudes are: $v = 17.71 \pm 0.24$, $b = 18.09 \pm 0.14$, $u = 16.81 \pm 0.08$, $w1 = 16.96 \pm 0.08$, $m2 = 16.91 \pm 0.09$, $w2 = 16.88 \pm 0.05$. Compared to the CRTS observations, UVOT detected the source in the *V* band during a low activity state.

4 DISCUSSION AND CONCLUSIONS

The confirmation of the existence of relativistic jets in NLSy1 opened a new research path for improving our knowledge of the AGN phenomenon, but brought new challenging questions. After the five objects detected by *Fermi*-LAT (Abdo et al. 2009; D'Ammando et al. 2012), no new NLSy1 were reported in the 3FGL catalogue that covers the first 48 months of *Fermi* operation (2008 August 4–2012 July 31). The NLSy1 FBQS J1644+2619 lies $0.^{\circ}23$ from the γ-ray source 3FGL J1644.4+2632, just outside its 95 per cent error circle of $0.^{\circ}20$. 3FGL J1644.4+2632 is a new γ-ray source detected at 4.5σ, not reported in the previous *Fermi*-LAT catalogues (Abdo et al. 2010; Nolan et al. 2012), with a photon index of $\Gamma_\gamma = 2.8 \pm 0.2$ and without an associated low-energy counterpart in the 3FGL catalogue. Analysing 76 months of *Fermi*-LAT observations we were able to better constrain the position of the

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[5] http://nessi.cacr.caltech.edu/DataRelease/FAQ2.html#improve

γ-ray source and thus to have a spatial association between the γ-ray source and the NLSy1 FBQS J1644+2619.

In Fig. 1 we compare the *Fermi*-LAT light curve over the period 2008 August–2014 December with the light curve obtained by CRTS in the *V* band for FBQS J1644+2619. It is worth noting that both the *Fermi*-LAT detections in 2008 November–2009 January and in 2012 July–October correspond to periods of high optical activity of the NLSy1. This is another indication in favour of an association between the γ-ray source and FBQS J1644+2619. Unfortunately, as shown in Fig. 2, no optical observations simultaneous to the γ-ray peaks observed in 2012 August and October are available. The average apparent isotropic (rest-frame) γ-ray luminosity of the source is 1.6×10^{44} erg s^{-1}, comparable to the value estimated for the NLSy1 1H 0323+342 over the first 4 years of *Fermi* science operation (D'Ammando et al. 2013d), but smaller than the other γ-ray NLSy1 by one to two orders of magnitude. The average photon index of FBQS J1644+2619 ($\Gamma_\gamma = 2.5 \pm 0.2$) is similar to those observed in flat spectrum radio quasars as well as γ-ray-loud NLSy1. No significant spectral evolution was observed during the high γ-ray activity state in 2012 July–October, when the source reached an average flux of $(5.2 \pm 1.0) \times 10^{-8}$ ph cm^{-2} s^{-1}, and a daily peak of $(66 \pm 22) \times 10^{-8}$ ph cm^{-2} s^{-1}, corresponding to an apparent isotropic (rest-frame) γ-ray luminosity of 1.9×10^{46} erg s^{-1}.

In the radio band, the source has an inverted spectrum ($\alpha_r = 0.4 \pm 0.2$, where $S \propto \nu^{\alpha_r}$) between 1.7 and 8.4 GHz (Doi, Asada & Nagai 2011) and a very high core dominance[6] ($r = 3.19$; Doi et al. 2012), suggesting the presence of a relativistic jet. Its brightness temperature of 7×10^9 K, derived from the 1.7 GHz VLBI flux density of its unresolved core, is too high for free–free emission, indicating that non-thermal processes dominate the radio emission. However, this value is lower than the limiting value predicted by the inverse Compton catastrophe (e.g. Readhead 1994), and in contrast to what was observed in the γ-ray emitting NLSy1 SBS 0846+513 (D'Ammando et al. 2013a) and PKS 1502+036 (D'Ammando et al. 2013b), where the variability brightness temperature exceeds 10^{13} K.

On parsec scales the source has a one-sided core–jet structure (Doi et al. 2011), suggesting the presence of Doppler beaming effects. From the core dominance, Doi et al. (2012) estimated a jet speed of $\beta > 0.983$ and a viewing angle of $\theta < 5^\circ$, corresponding to a Lorentz factor $\Gamma > 5$. In the same way, a Lorentz factor $\Gamma > 6.5$ and $\Gamma > 2.2$ has been estimated for the γ-ray emitting NLSy1 PMN J0948+0022 and 1H 0323+342, respectively. On kpc scale the source shows a two-sided structure with extended lobes each dominated by a hotspot near its outer edge (Doi et al. 2012), reminiscent of a Fanaroff–Riley type II radio galaxy.

FBQS J1644+2619 is included in the *ROSAT* All Sky Survey Bright Source Catalogue with a 0.1–2.4 keV flux of 2.6×10^{-12} erg cm^{-2} s^{-1} and a photon index $\Gamma_X = 2.03^{+0.25}_{-0.28}$ (Yuan et al. 2008). On 2003 June 3 the source was observed by the *Chandra* ACIS-S for 3 ks. The 0.3–5.0 keV spectrum was fitted with a power law with $\Gamma_X = 2.19 \pm 0.17$. A fit of comparable quality was obtained adding a soft component (e.g. a blackbody) and the resulting photon index was $\Gamma_X = 1.8^{+0.6}_{-0.3}$ (Yuan et al. 2008). As noted in Section 3.2, a flat photon index ($\Gamma_X \sim 2$) was observed by *Swift*/XRT in 2011 December 26. In contrast, a relatively hard spectrum ($\Gamma_X < 2$) was observed in the other γ-ray-loud NLSy1, SBS 0846+513 (D'Ammando et al. 2013a), PMN J0948+0022 (e.g. Foschini et al. 2011; D'Ammando et al. 2015), 1H 0323+342 (D'Ammando et al. 2013c), and PKS 1502+036 (D'Ammando et al. 2013b). The relatively hard spectrum has been interpreted as an indication for a significant contribution of a relativistic jet in X-rays. In the case of PMN J0948+0022 the contribution of a soft X-ray excess was evident below 2 keV (D'Ammando et al. 2014).

The rather flat X-ray spectrum we have found in FBQS J1644+2619 may be due to the fact that the *Swift* observation was performed when the source was in a low γ-ray state, and the jet contribution to the X-ray spectrum could not hide the Seyfert component (e.g. the accretion disc and hot corona). Alternatively, the X-ray energy range observed by *Swift*/XRT may cover the part of the spectrum including the tail of the synchrotron emission and the initial rise of the inverse Compton emission, as in the intermediate-synchrotron-peaked BL Lac objects. A deep X-ray observation of FBQS J1644+2619 with *XMM–Newton* will allow us to determine if the X-ray spectrum is completely dominated by the jet emission or if there is some contribution from the accretion flow (e.g. the soft excess, inverse Compton emission from the hot corona above the disc or other reflection features such as the Fe K α line).

Since NLSy1 are thought to be hosted in spiral galaxies (e.g. Deo, Crenshaw & Kraemer 2006) the presence of a relativistic jet in these sources seems to conflict with the paradigm that such structures could be produced only in elliptical galaxies (e.g. Marscher et al. 2009). The most powerful jets are found in luminous elliptical galaxies with very massive central black holes (BH) and low accretion rates (e.g. McLure et al. 2004; Sikora, Stawarz & Lasota 2007). This has been interpreted as indirect evidence that a high spin is required for the jet formation, since at least one major merger seems to be necessary to spin up the supermassive BH. At the same time, low accretion rates, which are usually associated with geometrically thick advection dominated accretion flows, may be important in jet formation by creating large-scale poloidal magnetic fields (Sikora & Begelman 2013). Using the relation between BH mass and broad line width, Yuan et al. (2008) estimated a BH mass of 8×10^6 M$_\odot$ for this source, one of the smallest values among the 23 sources in the sample. However, Calderone et al. (2013) pointed out that BH masses estimated for NLSy1 by modelling optical/UV data with a Shakura and Sunyaev disc spectrum could be significantly higher than those derived on the basis of single epoch virial methods (see also Decarli et al. 2008; Marconi et al. 2008). In particular, for FBQS J1644+2619 they found a value of 10^8 M$_\odot$. Even adopting this higher mass, FBQS J1644+2619 lies in the low tail of the blazar mass distribution, challenging the theoretical scenarios proposed for the production of relativistic jets. This object has the second lowest redshift of the γ-ray NLSy1 (the most nearby object being 1H 0323+342), which makes it a good candidate for detailed studies of the host galaxy (e.g. Leon Tavares et al. 2014). While the Sloan Digital Sky Survey image suggests a disc-like galaxy, observations with higher resolution are needed in order to establish the morphology of the host and thus to obtain important insights into jet formation and development.

FBQS J1644+2619 was detected only sporadically in γ-rays during 2008 August–2014 December. This clearly demonstrates the importance of *Fermi*-LAT's continuous survey coverage for identifying variable γ-ray emitting AGN like the NLSy1. Detections of new NLSy1 like FBQS J1644+2619 by *Fermi*-LAT are important to better characterize this new class of γ-ray-emitting AGN and to understand the nature of these objects. Further multifrequency observations of this source from radio to γ-rays are needed to

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[6] The core dominance, *r*, is defined as the flux ratio of the core to extended emissions.

investigate in detail its characteristics over the entire electromagnetic spectrum.

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