PROCEEDINGS OF SCIENCE

Gamma-ray narrow-line Seyfert galaxies: first long-term optical, UV, and X-ray monitoring

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Gamma-ray narrow-line Seyfert 1 galaxies (γ-NLS1) are a well-established sub-class of jetted active galactic nuclei. Their number increased systematically since their discovery in 2009, but they were usually observed as a response to flares in the gamma-ray energy band. We performed, therefore, once-a-week, year-based *Swift* monitoring campaigns on four prominent γ-NLS1 which include the best candidates for detection by the Cherenkov Telescope Array Observatory, namely SBS 0846+513, PMN J0948+0022, PKS 1502+036, and FBQS J1644.9+2619, in order to investigate the long-term behaviour of such kind of sources. The novelty of these campaigns is that they are unbiased with respect to possible target-of-opportunity observations, which makes our study the first on γ-NLS1 objects based on this systematic approach, and it allows us to investigate their intrinsic variability properties. We present the long-term monitoring light-curves of our objects obtained following our unbiased data acquisition strategy. We also present the recent results on the radio loud γ-NLS1 SDSS J164100.10+345452.7 that we monitored for two years with *Swift* and which we caught in flare.

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1. Introduction

A new subclass of NLS1s, the γ-ray emitting NLS1 (γ-NLS1) galaxies, was defined after the detection of a NLS1 in γ-rays (E > 100 MeV) by *Fermi*-LAT [PMN J0948+0022, 1–3]. This class now consists of ~ 40 sources and candidates [e.g. 4–6] whose properties strongly resemble those of jetted sources [see, e.g. 7–9]. However, no detection in the very high energy (VHE, $E > 50$ GeV) regime has been obtained, yet, although some compelling upper limits were achieved (Whipple on 1H 0323+342, [10]; VERITAS on PMN J0948+0022, [11]; H.E.S.S. on PKS 2004−447, [12]). Typically, γ-NLS1 share the following properties [see 8, for a review]:

- relatively low black hole masses, $M_{\rm BH} \approx 10^6 - 10^8\,{\rm M}_\odot$,
- high accretion rate luminosity, $L \approx 0.01 - 0.5\,{\rm L}_{\rm Edd}$,
- low jet power, $P_{\rm jet} \approx 10^{42} - 10^{46}\,{\rm ergs}^{-1}$,
- super-luminal radio jets, $v \approx 10\,c$,
- photon-rich environments,
- disc-like galaxy hosts.

Moreover, as discussed in [13], the monochromatic radio luminosity function of γ-NLS1 appears to be an extension of that of flat-spectrum radio quasars (FSRQs) at luminosity $L_{1.4\,{\rm GHz}} \leq 3 \times 10^{42}$ erg s^{-1}, making them relatively young sources.

2. Monitoring of the "golden four" sample

Given the variability of these sources, especially in the *Fermi*-LAT energy band ($E > 100$ GeV), γ-NLS1 have often been observed by the Neil Gehrels *Swift* Observatory [hereafter *Swift*, 14], mainly as follow-up of flares at other wavelengths. This introduces a bias in the understanding of their variability behavior and duty-cycle because observations performed in response to external triggers favor high states. We started our project with a sample of four well-known γ-NLS1, reported in Table 1. We note that SBS 0846+513, PMN J0948+0022, and PKS 1502+036 were also selected

Table 1: Source Sample.

Source	RA (J2000) (deg)	DEC (J2000) (deg)	z
SBS 0846+710	132.51	51.14	0.584
PMN 0948+0022	147.24	0.37	0.585
PKS 1502+036	226.26	3.44	0.408
FBQS J1644+2619	251.24	26.31	0.145

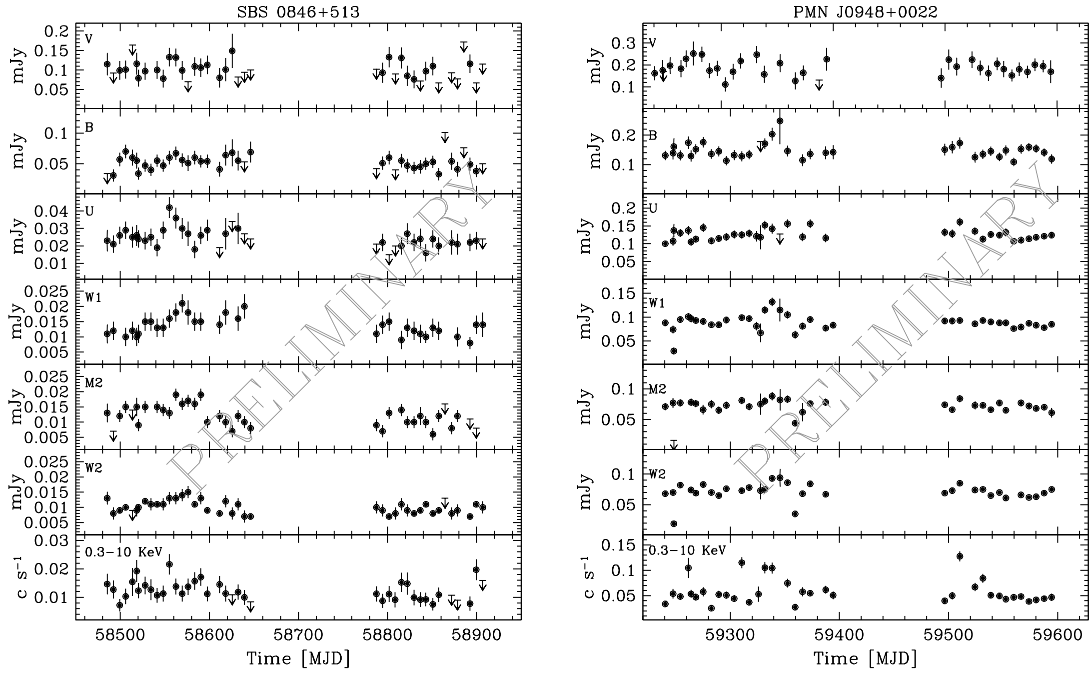

Figure 1: Multi-wavelength observations of SBS 0846+513 (left) and PMN J0948+0022 (right).

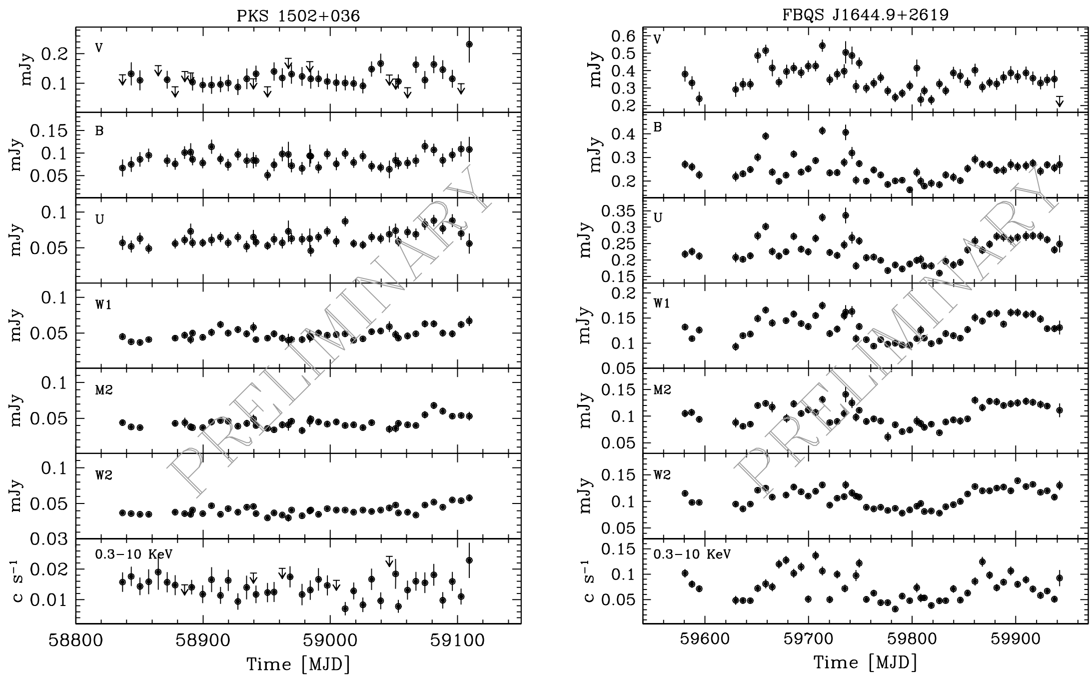

Figure 2: Multi-wavelength observations of PKS 1502+036 (left) and FBQS J1644.9+2619 (right).

in [15, 16] as potential candidates for a detection by the next generation Čerenkov telescope array observatory [(CTAO), 17] at energies above a few tens of GeV.

In order to achieve our goal, we performed long-term monitoring observations with *Swift*/XRT and *Swift*/UVOT (all filters) with a pace of one observation per week, 3 ks each observation, and one-year baseline for each source. Figures 1 and 2 show the multi-wavelength light-curves for our four sources. Time-gaps mark the periods when a source cannot be observed by *Swift*. Our strategy allows us to preliminary evaluate that we have, in the X-ray energy band, a number of high-states of the order of a few [Romano et al., in preparation].

3. Absorbed jet in SDSS J164100.10+345452.7

SDSS J164100.10+345452.7 is a nearby [z = 0.16409 ± 0.00002, 18] γ-NLS1, hosted in a spiral galaxy [19] that was initially classified as radio quiet. It was recently detected at 37 GHz with the 13.7 m radio telescope at Aalto University Metsähovi Radio Observatory [20] with an average flux of 0.37 Jy, and reaching a flux of 0.46 Jy. The authors also reported a detection in the Fermi-LAT data, with a flux of $F_{\rm E>100\,MeV} = (12.5 \pm 2.18) \times 10^{-9}$ ph cm^{-2} s^{-1}. This latter detection was interpreted as a clear indication of the presence of a relativistic jet. So, in order to investigate this possibility we commenced a *Swift* monitoring campaign simultaneous with the ongoing Metsähovi one. The optical, UV, and X-ray light curves were collected by *Swift* from 2019-12-09 to 2020-08-17 (first year campaign), and from 2021-01-31 to 2021-07-28 (second year), with a pace of one $\sim$ 2–3 ks observation per week. The seasonal gaps were due to observational constraints.

All data from the 2-yr campaign are shown in Figure 3. In particular, grey bands mark the Metsähovi detection. In response to the 37 GHz flare observed on 2020-05-24 to 2020-05-26, we intensified the pace of the *Swift* monitoring. This strategy allowed us to study the X-ray spectrum around (Figure 4) and during the radio flare, discovering that, generally, the X-ray spectrum can be fit with an absorbed power law model with a photon index $\Gamma = 1.93 \pm 0.12$, modified by a partially covering neutral absorber with a covering fraction $f = 0.91^{+0.02}_{-0.03}$. However, during the flare, the extra absorbing component is not required and the spectrum becomes much harder ($\Gamma_{\rm flare} \sim 0.7 \pm 0.4$), thus implying the emergence of a further, harder spectral component. We consider these findings as the jet emission emerging from a gap in the absorber and to unambiguously link the jetted radio emission of SDSS J164100.10+345452.7. In order to investigate the physical properties of this source in the framework of γ-NLS1, from the H_β luminosity we calculated the broad-line region (BLR) luminosity $L_{\rm BLR}$ and, subsequently, the disc luminosity, $L_{\rm disc} = 6.8 \times 10^{43}$ erg s^{-1}, following the usual relationship described in [21]. Moreover, assuming a black-hole mass $M_{\rm BH} = 1.41 \times 10^7 M_\odot$, we obtained $L_{\rm Edd} = 1.8 \times 10^{45}$ erg s^{-1}. When reporting these values in the $L_{\rm disc}/L_{\rm Edd}$–$M_{\rm BH}/M_\odot$ plane [see Figure 4 in 8], we note that SDSS J164100.10+345452.7 fits in the region of the γ-NLS1 galaxies well. When computing the jet power, $P^{\rm tot}_{\rm jet}$, we obtain $P^{\rm tot}_{\rm jet} \approx 3.5 \times 10^{42}$ erg s^{-1}, similar to the lowest value in Table 3 of [8]. Given the relatively good data availability, we also computed the spectral energy distribution (SED, Figure 5), including both strictly simultaneous data (light blue and green points), and archival ones (open symbols). The synchrotron component peaks below $\nu_{\rm peak} \approx 10^{13}$ Hz, and a host galaxy component peaks at a few $\times 10^{14}$ Hz. The X-ray data can be representative for a synchrotron self-Compton component, which undergoes a remarkable spectrum change during and out-of the flare.

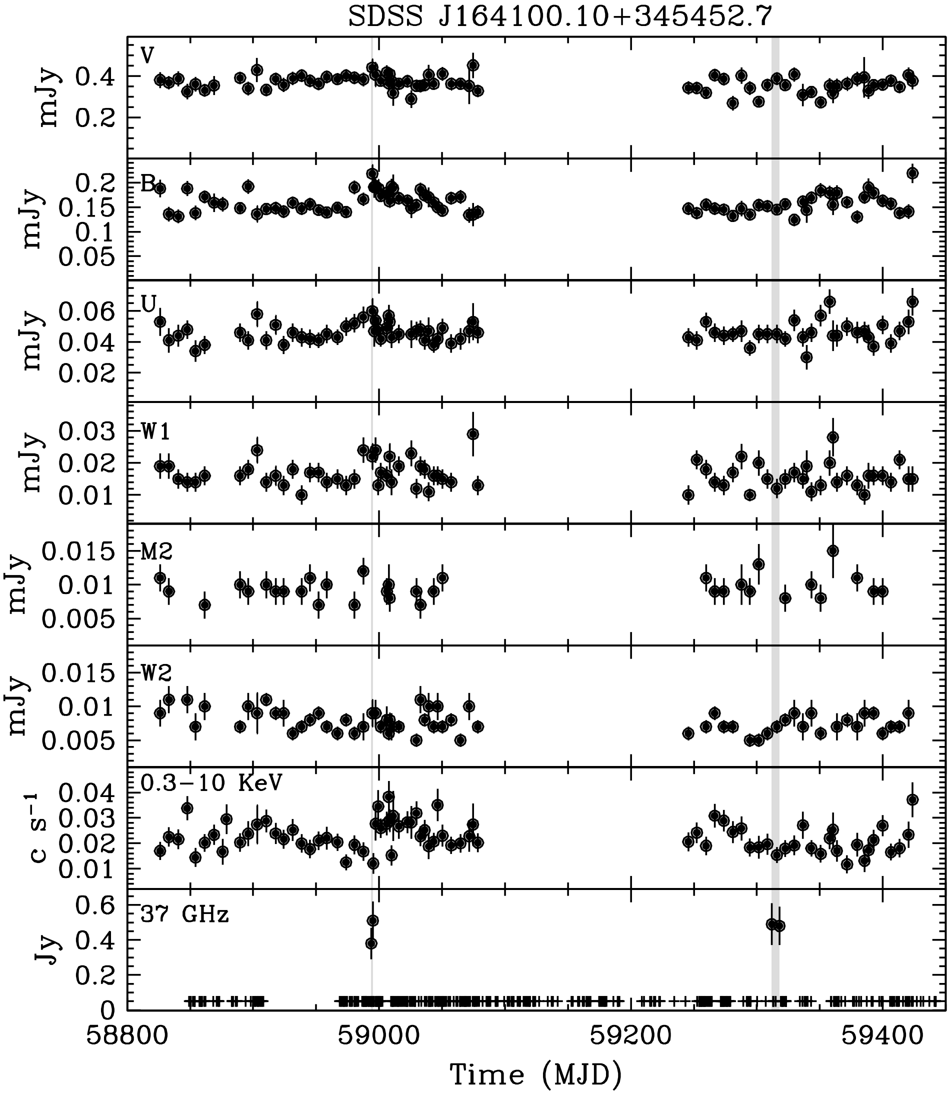

Figure 3: Multi-wavelength light curves of SDSS J164100.10+345452.7. The *Swift* optical, UV, and X-ray light curves collected are shown with 1 σ errorbars. The data at 37 GHz were collected at Metsähovi (<4 σ non-detections represented by crosses). The grey bands mark the Metsähovi detections. Adapted from [21].

4. Conclusions

γ-NLS1 galaxies are a relatively young (established in 2008) and small (about 40 objects) sub-class of extra-galactic jetted sources. Because of their properties, they are excellent targets for long-term multi-wavelength monitoring, especially with flexible and panchromatic facilities such as *Swift*. These unbiased programs allow us to investigate their on-flare and off-flare behaviours, as well as study the recurrence of flares in different bands. As SDSS J164100.10+345452.7 demonstrates, the simultaneous monitoring in the radio band, combined with the *Swift* one, may provide important information on both the jet and the environment surrounding it. Last but not least, these sources could represent a new class of VHE emitters.

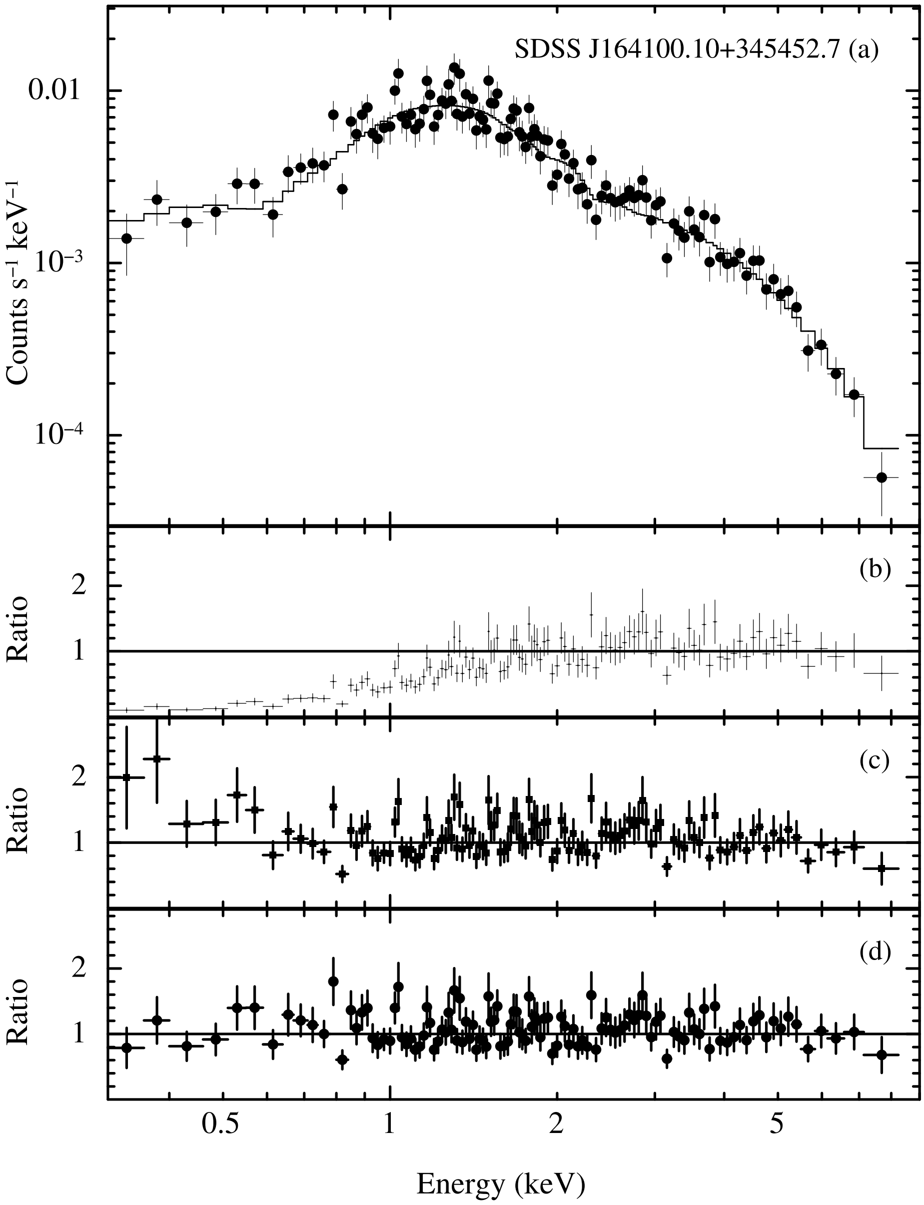

Figure 4: *Swift*/XRT average spectrum of SDSS J164100.10+345452.7. Data are drawn from the whole 2 yr observing campaign: (a) best fit obtained by adopting the model TBABS * ZPCFABS * ZPOWERLW; (b): data/model ratio from the fit with TBABS * ZPOWERLW in the 2–10 keV band; (c) data/model ratio from the fit with TBABS * ZTBABS * ZPOWERLW (0.3–10 keV); (d) data/model ratio from the fit with TBABS * ZPCFABS * ZPOWERLW (0.3–10 keV). Adapted from [21].

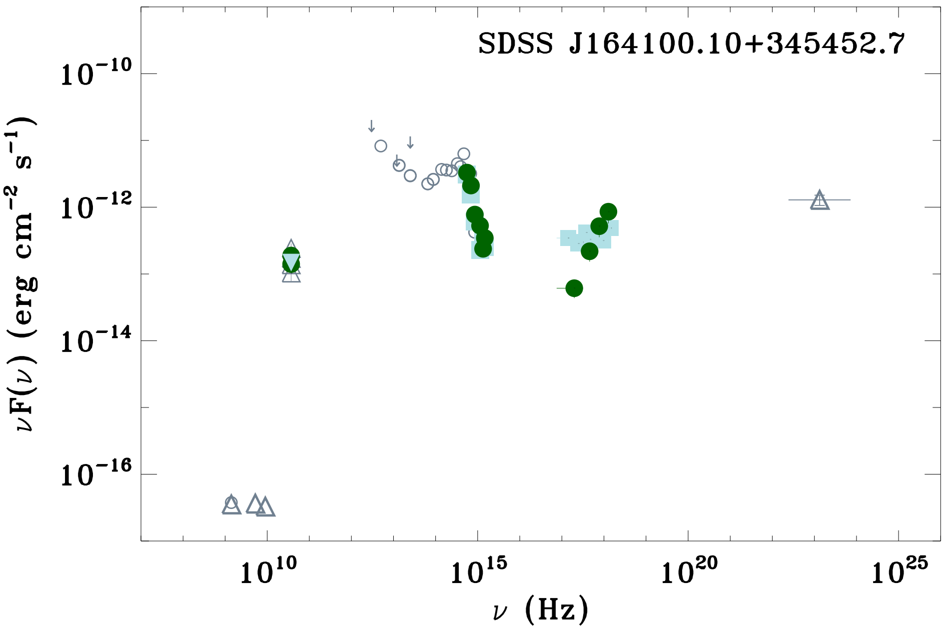

Figure 5: SED of SDSS J164100.10+345452.7. The grey points are historical data. The light blue filled square points are the *Swift* data obtained during the 2-yr campaign; the light blue filled triangle is the Metsähovi upper limit 0.40 Jy, while the green filled circles are those, strictly simultaneous, obtained during the flare of May 2020 (*Swift* and Metsähovi). Adapted from [21].

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