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Intranight optical variability of γ-ray-loud narrow-line Seyfert 1 galaxies

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ABSTRACT

The Large Area Telescope (LAT) on-board the *Fermi Gamma-ray Space Telescope* has detected γ-ray emission in about half a dozen narrow-line Seyfert 1 (NLSy1) galaxies. This indicates the presence of relativistic jets in these sources similar to blazars and radio galaxies. In an attempt to have an idea of the intranight optical variability (INOV) characteristics of these γ-ray-loud NLSy1 galaxies, we have carried out optical flux monitoring observations of three NLSy1 galaxies detected by *Fermi*/LAT: 1H 0323+342, PMN J0948+0022 and PKS 1502+036. These optical monitoring observations in R_C band carried out during 2012 January–May showed the presence of rapid optical flux variations in these sources. The intranight differential light curves of these sources have revealed flux variations on time-scales of hours with amplitudes of variability >3 per cent for most of the time. However, for one source, PMN J0948+0022, we observed amplitude of variability as large as 52 per cent. On using the *F*-statistics to classify the variability nature of these sources, we obtained a duty cycle (DC) of INOV of ~85 per cent. Alternatively, the more commonly used *C*-statistics gave a DC of INOV of ~57 per cent. Such high DC of INOV is characteristics of the BL Lac class of active galactic nucleus. The results of our monitoring observations thus indicate that there is similarity in the INOV nature of γ-ray-loud NLSy1 galaxies and BL Lac objects, arguing strongly for the presence of relativistic jets aligned closely to the observers line of sight in γ-ray-loud NLSy1s. Moreover, our dense monitoring observations on some of the nights have led to the clear detection of some miniflares superimposed on the flux variations during the night over time-scales as short as 12 min. The detection of short time-scale flux variability in the sources studied here is clearly due to stronger time compression leading to the jets in these sources having large Doppler factors, similar to that of the inner jets of TeV blazars.

Key words: surveys – galaxies: active – quasars: general – gamma-rays: general.

1 INTRODUCTION

Flux variation across the electromagnetic spectrum is one of the defining characteristics of active galactic nuclei (AGN). They occur on a wide range of time-scales ranging from hours to days to months, making this particular property of AGN an efficient tool to understand the physics of these objects (Urry & Padovani 1995; Wagner & Witzel 1995). In AGN, where the flux is dominated by relativistic jets of non-thermal emission pointed towards the direction of the observer, the observed intensity variations will be rapid and of large amplitude (Begelman, Blandford & Rees 1984). Such rapid and large-amplitude variations, generally explained by invoking relativistic jets (Marscher & Gear 1985; Hughes, Aller & Aller 1992; Marscher, Gear & Travis 1992), have been observed in the blazar class of AGN (Miller, Carini & Goodrich 1989; Carini, Miller & Goodrich 1990) mostly on hour-like time-scales and recently on subhour time-scales as well (Rani et al. 2010; Impiombato et al. 2011).

Narrow-line Seyfert 1 (NLSy1) galaxies are an interesting class of AGN similar to Seyfert galaxies that came to be known about 25 yr ago by Osterbrock & Pogge (1985). Their optical spectra contain narrower than usual permitted lines from the broad-line region (BLR), having FWHM(H_β) < 2000 km s^{-1}. Normally, they have [O III]/H_β < 3; however, exceptions are possible if they have strong [Fe VII] and [Fe X] lines (see Pogge 2011, and references therein). Both BLR and narrow-line region (NLR) are present in NLSy1s, but the permitted lines from BLR are narrower than that of Seyfert 1 galaxies (Rodríguez-Ardila et al. 2000). NLSy1 galaxies were found to show rapid flux variability in the optical (Miller et al.

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Table 1. List of the γ-NLSy1 galaxies monitored in this work. Column information is as follows: (1) IAU name; (2) other name; (3) right ascension in the epoch 2000; (4) declination in the epoch 2000; (5) redshift; (6) absolute B magnitude; (7) apparent V magnitude; (8) observed optical polarization; (9) radio spectral index and (10) radio-loudness parameter $R = f_{1.4\,\mathrm{GHz}}/f_{440\,\mathrm{nm}}$(Foschini 2011).

IAU name (1)	Other name (2)	RA (2000)[a] (3)	Dec. (2000)[a] (4)	z[a] (5)	M_B[a] (mag) (6)	V[a] (mag) (7)	P_{opt} (per cent) (8)	α_R[d] (9)	R[e] (10)
J0324+3410	1H 0323+342	03:24:41.2	+34:10:45	0.063	−22.2	15.72	< 1[b]	−0.35	318
J0948+0022	PMN J0948+0022	09:48:57.3	+00:22:24	0.584	−23.8	18.64	18.8[c]	0.81	846
J1505+0326	PKS 1502+036	15:05:06.5	+03:26:31	0.409	−22.8	18.64	–	0.41	3364

[a] Véron-Cetty & Véron (2010).
[b] Eggen, Miller & Maune (2011).
[c] Ikejiri et al. (2011).
[d] Radio spectral index calculated using the 6 and 20-cm flux densities given in Véron-Cetty & Véron (2010) ($S_\nu \propto \nu^\alpha$).
[e] Foschini (2011).

2000; Klimek, Gaskell & Hedrick 2004). They also show the radio-loud/radio-quiet dichotomy (Laor 2000); however, the radio-loud fraction of NLSy1 is about 7 per cent (Zhou et al. 2003; Komossa et al. 2006), smaller than the fraction of 15 per cent known in the population of quasars (Urry & Padovani 1995). These radio-loud NLSy1 galaxies have flat radio spectrum and high brightness temperatures, suggesting the presence of relativistic jets in them (Zhou et al. 2003; Doi et al. 2006).

Since the launch of the *Fermi Gamma-ray Space Telescope* in 2008, high-energy (E > 100 MeV) gamma rays were detected in a few radio-loud NLSy1 galaxies. We therefore refer to these sources as γ-ray-loud NLSy1 (γ-NLSy1) galaxies. These sources are found to have high-energy variable γ-ray radiation as detected by *Fermi*/Large Area Telescope (LAT). They are also found to have compact radio structure with a core–jet morphology (Doi et al. 2006; Zhou et al. 2007; Giroletti et al. 2011; Orienti et al. 2012), superluminal motion and high brightness temperatures (Doi et al. 2006; Orienti et al. 2012). All these characteristics give a distinctive proof of the presence of relativistic jets in them (Abdo et al. 2009a,b,c; Foschini et al. 2010). Another independent proof of the existence of relativistic jets oriented at small angles to the observer in these γ-NLSy1 sources is the detection of intranight optical variability (INOV) on hour to subhour (minute) time-scales. Liu et al. (2010) reported the first detection of INOV in the γ-NLSy1 galaxy PMN J0948+0022, wherein the authors detected INOV with amplitudes as large as 0.5 mag on time-scale of several hours. Recently, Maune, Miller & Eggen (2011) also found this source to show INOV. In this work, we aim to understand the INOV characteristics of this new class of γ-NLSy1 galaxies, in particular to detect rapid INOV on these sources on subhour (minute) time-scales and also to see if their INOV characteristics compare with that of the blazar class of AGN known to have relativistic jets.

We detail in Section 2 the sample of γ-NLSy1s selected for the intranight optical monitoring. Observations are described in Section 3. Section 4 is devoted to the results of this work followed by discussion and conclusion in the final Section 5.

2 SAMPLE

One of the discoveries by *Fermi*/LAT was the detection of γ-rays from the NLSy1 galaxy PMN J0948+0022 (Abdo et al. 2009a). An analysis of the publicly available LAT data during the period 2008 August–2011 February has led to the detection of γ-rays in a total of seven NLSy1 galaxies including the source PMN J0948+0022 (Foschini 2011). From this list of seven sources, we have selected for this work only sources having significant detections in *Fermi*/LAT with the test statistic (TS) larger than 100 and integrated γ-ray flux in the 0.1−100 GeV range greater than 5×10^{-8} photons cm^{-2} s^{-1}. A TS value of 10 roughly corresponds to 3σ (Mattox et al. 1996). This has led to the final selection of three sources for intranight optical monitoring, namely 1H 0323+342, PMN J0948+0022 and PKS 1502+036. The general properties of these sources are given in Table 1.

3 OBSERVATIONS AND REDUCTIONS

Our observations were carried out on the newly commissioned 130-cm telescope (Sagar et al. 2010) located at Devasthal and operated by the Aryabhatta Research Institute for Observational Sciences (ARIES), Nainital. This telescope is a modified Ritchey Chretein system with a *f*/4 beam (Sagar et al. 2010). We have used two detectors for our observations. One is a 2k × 2k conventional CCD having a gain of 1.39 e$^-$ ADU^{-1} and readout noise of 6.14 e$^-$. Each pixel in this CCD has a dimension of 13.5 µm. This corresponds to 0.54 arcsec pixel^{-1} on the sky thereby covering a field of 12 × 12 arcmin^2. The second detector used in our observation is the 512 × 512 electron multiplying charged coupled device (EMCCD). It has very low readout noise (0.02 e$^-$) and a variable gain which can be selected by the observer. The preliminary science results from observations of these CCDs are given by Sagar et al. (2012). For observations reported here, we used a gain of 225 e$^-$ ADU^{-1}. It is well known from optical monitoring observations of blazars that the probability of finding INOV can be enhanced by continuous monitoring of a source (Carini 1990; Noble 1995); thus, in this work we tried to monitor each source continuously for a minimum of 4 h during a night. However, due to weather constraints for some of the nights we were able to monitor sources for durations as low as 1 h. All of the observations were done in Cousins R (hereafter R_{C}) filter as the CCD response is maximum in this band. The exposure time was typically between 30 s and 15 min depending on the brightness of the source, the phase of the moon and the sky transparency on that night. The target γ-NLSy1 galaxies were also suitably placed in the field of view (FOV), so as to have at least three good comparison stars in the observed FOV.

Preliminary processing of the images, such as bias subtraction and flat fielding, was done through standard procedures in IRAF.[1]

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

Table 2. Positions and apparent magnitudes of the comparison stars from the USNO catalogue (Monet et al. 2003).

Source	Star	RA(J2000)	Dec.(J2000)	R (mag)	B (mag)
1H 0323+342	S1	03:24:44.26	+34:09:31.84	15.17	14.82
	S2	03:24:51.24	+34:12:26.53	15.06	14.91
	S3	03:24:35.01	+34:09:36.73	15.81	15.43
PMN J0948+0022	S1	09:49:00.44	+00:22:35.02	16.47	16.32
	S2	09:48:57.30	+00:24:18.53	16.15	16.35
	S3	09:48:53.69	+00:24:55.14	16.14	16.34
PKS 1502+036	S1	15:05:11.30	+03:22:25.57	15.24	16.20
	S2	15:05:15.90	+03:19:10.91	15.44	16.25
	S3	15:05:26.99	+03:24:37.25	15.71	16.95
	S4	15:05:15.37	+03:25:40.90	17.12	18.85
	S5	15:05:15.65	+03:25:27.62	16.55	17.92
	S6	15:05:14.53	+03:24:56.34	16.74	17.08

Table 3. Log of observations. Columns are listed as follows: (1) source name; (2) date of observations; (3) duration of monitoring in hour.; (4) number of data points in DLC; (5) exposure time in second; (6) CCD modes used; here 'normal' refers to the 2k × 2k pixel^2 CCD and 'EM' refers to the 512 × pixel^2 EMCCD.

Source (1)	Date (2)	Duration (h) (3)	N (4)	Exp. time (s) (5)	CCD mode (6)
1H 0323+342	24.01.12	1.3	105	30	EM
	25.01.12	2.1	47	120	EM
	26.01.12	3.1	89	120	EM
	02.02.12	3.5	35	150	Normal
PMN J0948+0022	26.01.12	6.0	165	120	EM
	02.02.12	2.4	18	200	Normal
	11.03.12	4.9	40	150	Normal
	19.04.12	3.9	73	180	EM
PKS 1502+036	18.04.12	2.1	24	300	EM
	22.05.12	3.2	11	900	Normal
	23.05.12	3.8	13	900	Normal
	24.05.12	5.2	12	900	Normal

Aperture photometry on both the γ-NLSy1 and the comparison stars present on the cleaned image frames was carried out using the `phot` task available within the APPHOT package in IRAF. The optimum aperture radius for the photometry was determined using the procedure outlined in Stalin et al. (2004). First, star–star differential light curves (DLCs) were generated for a series of aperture radii starting from the median seeing full width at half-maximum (FWHM) of that night. The aperture that gave the minimum scatter for the different pairs of comparison stars was selected as the optimum aperture for the photometry of the target γ-NLSy1. Table 2 consists of the positions and apparent magnitudes (taken from USNO[2]) of the comparison stars used in the differential photometry. It should be noted that uncertainty in the magnitudes taken from this catalogue may be up to 0.25 mag. The log of observations is given in Table 3.

4 RESULTS

4.1 Intranight optical variability

From the derived instrumental magnitudes from photometry, DLCs were generated for the given γ-NLSy1 relative to steady comparison stars. The optimum aperture used here is close to the median FWHM of the images on any particular night most of the time. Also, as the central γ-NLSy1 dominates its host galaxy, it should have negligible effects on the contribution of the host galaxy to the photometry (Cellone, Romero & Combi 2000). In Figs 1–3 we present the DLCs for the objects 1H 0323+342, PMN J0948+0022 and PKS 1502+036 relative to two non-variable and steady comparison stars present in their observed frames. In order to judge the variability nature of the sources, we have tried to use more than two comparison stars. However, in Figs 1–3 we have shown the DLCs of γ-NLSy1 galaxies relative to only two comparison stars. These comparison stars were used later to characterize the variability of γ-NLSy1 galaxies. A γ-NLSy1 is considered to be variable only when it shows correlated variations both in amplitude and time relative to all the selected comparison stars. Great care is taken on the selection of comparison stars such that they are in close proximity to the source and also have similar brightness to the source. However, it is not easy to get such comparison stars, first due to the small FOV covered by the EMCCD used in some nights of the observations reported here and secondly due to the constraint of using the same standard stars irrespective of which CCD was used for the observations. We note here that the uncertainty of the magnitudes of the comparison stars given in Table 2 will have no effect on the DLCs as they involve the differential instrumental magnitudes between the γ-NLSy1 and the comparison stars. Also the typical error of each point in the DLCs is around 0.01 mag. To access the variability nature of the sources, we have employed the following two criteria.

4.1.1 C-statistics

To decide on the INOV nature of the sources on any given night of observations we have used the commonly used statistical criteria called the C parameter. Following Jang & Miller (1997), for any given DLC, it is defined as

$$C = \frac{\sigma_T}{\sigma}, \qquad (1)$$

where σ_T and σ are the standard deviations of the source and the comparison star DLCs. As we have used three comparison stars, we have three star–star DLCs. Of these, we consider that DLC where the standard deviation of the light curve is minimum, as this will involve the steadiest pair of comparison stars. The σ of this steadiest DLC is used in equation (1) to get two estimates of the C-statistics for the source–star DLC, corresponding to each of the comparison stars. A source is considered to be variable if $C \geq 2.576$, which corresponds to a 99 per cent confidence level (Jang & Miller 1997). Here, we get two values of C, corresponding to two DLCs of the source relative to each of the two comparison stars. Using C-statistics, we consider a source to be variable, when both the calculated C values exceed 2.576.

4.1.2 F-statistics

Recently, de Diego (2010) has argued that the C-statistics widely used in characterizing AGN variability is not a proper statistics and is wrongly established. An alternative to C-statistics according to

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[2] http://www.nofs.navy.mil/data/fchpix/

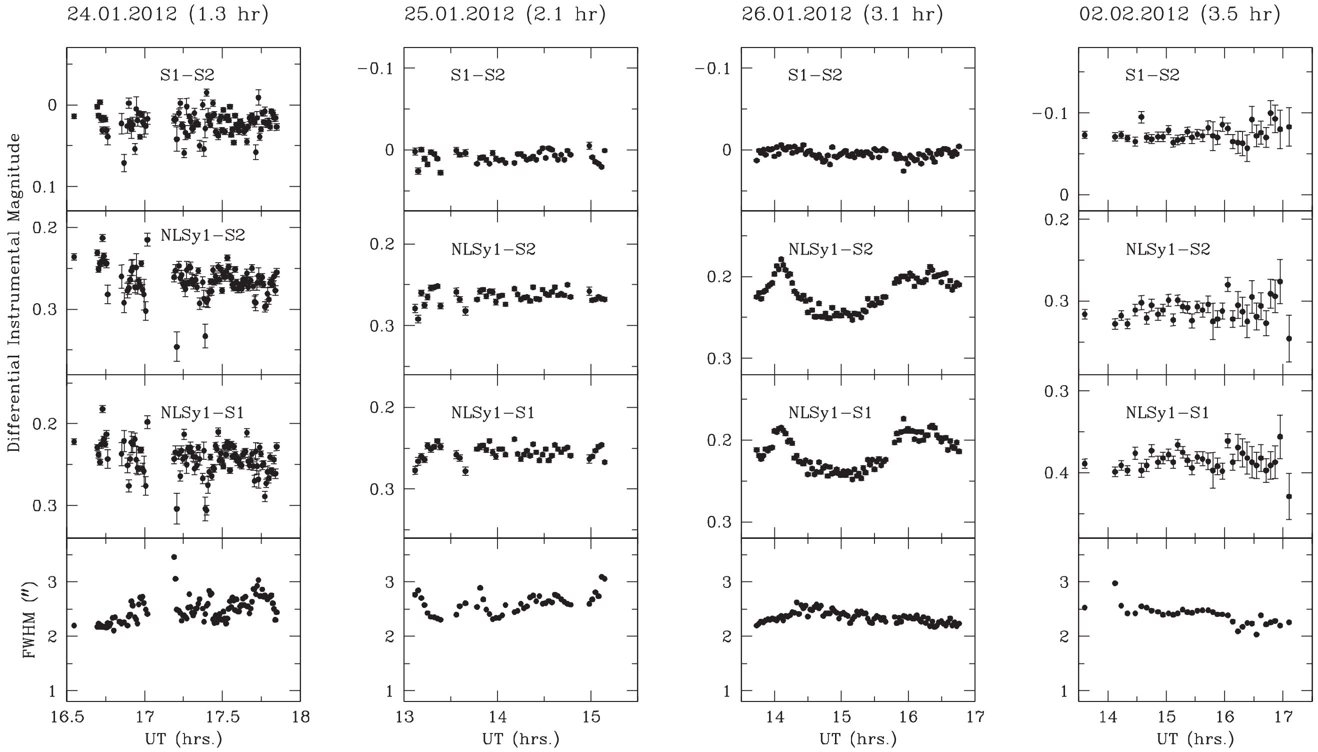

Figure 1. Intranight DLCs of the source 1H 0323+342. The date of observation and the duration of monitoring (within brackets) are given on the top of each panel. On the bottom panel of each night is given the variations of the FWHM of the stellar images during the monitoring period in the night.

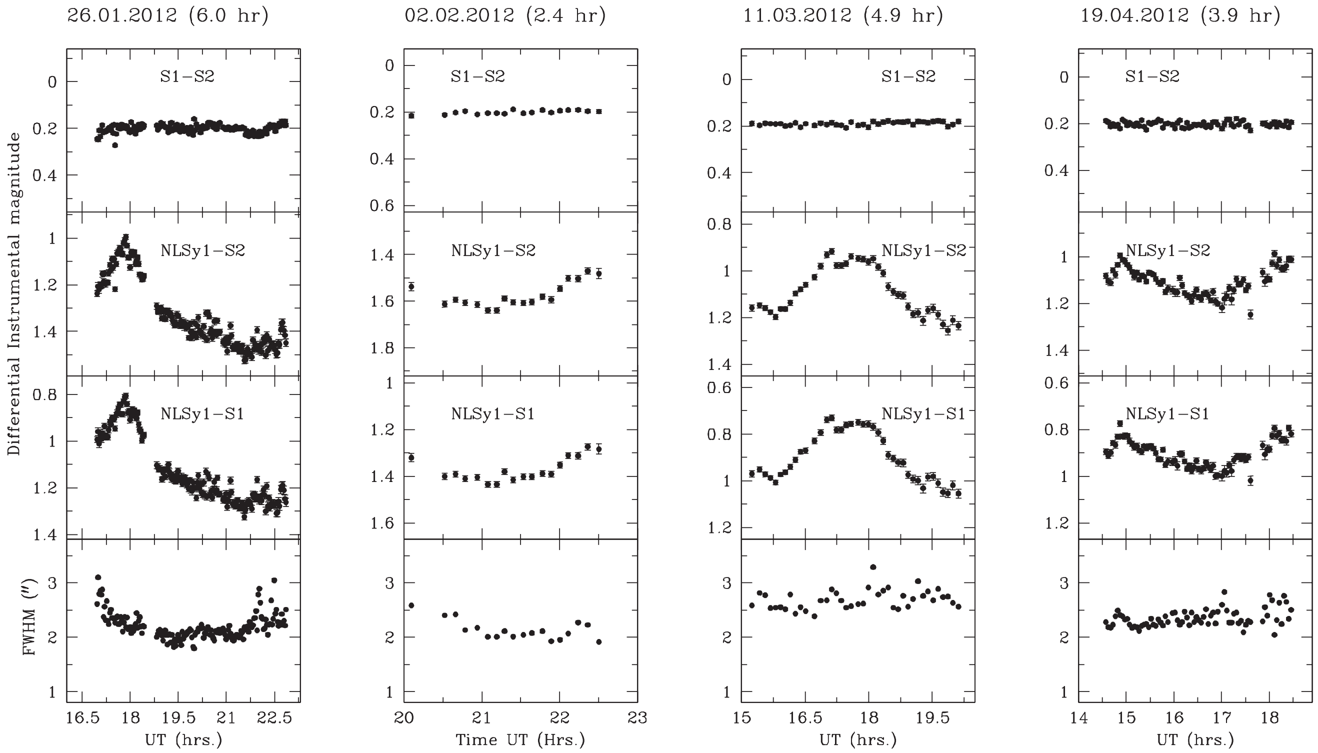

Figure 2. Intranight DLCs for the γ-NLSy1 galaxy PMN J0948+0022. The variation of FWHM over the course of the night is given in the bottom panel. Above the top panel, the date and duration of observations are given.

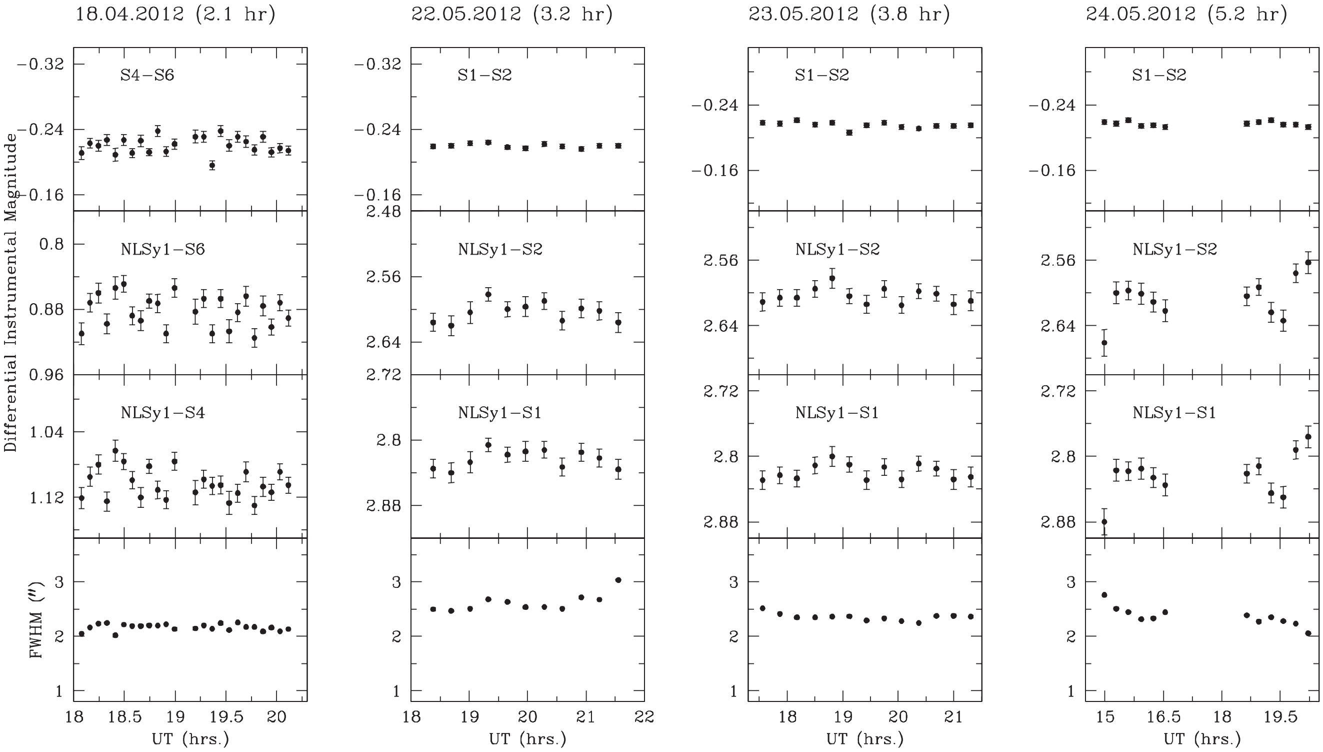

Figure 3. Intranight DLCs for the γ-NLSy1 galaxy PKS 1502+036. The FWHM variation during the night is given in the bottom panel. The dates of observations and the duration of monitoring are given on the top of each panel.

de Diego (2010), which can better access the variations in AGN light curves, is the F-statistics. This statistics takes into account the ratio of two variances given as

$$F = \frac{\sigma_T^2}{\sigma^2}, \tag{2}$$

where σ_T^2 is the variance of the source-comparison star DLC and σ^2 is the variance of the comparison stars DLC. Thus, in computing the F-statistics, of the three comparison star DLCs, similar to the calculation of C-statistics, we have selected the comparison stars DLC that involves the steadiest pair of comparison stars.

Using equation (2), for each source, two values of the F-statistics were computed for the source–star DLCs corresponding to each of these two comparison stars. This calculated F-statistics is then compared with the critical F value, F_ν^α, where α is the significance level and ν ($= N_p - 1$) is the degree of freedom for the DLC. We have used a significance level of $\alpha = 0.01$, corresponding to a confidence levels of $p > 99$ per cent. Thus, if both the computed F values, corresponding to the DLCs of the source to each of the two comparison stars, are above the critical F value corresponding to $p > 0.99$, we consider the source to be variable. However, we point out that the C-statistics might be a more compelling measure of the presence of variability, particularly when the comparison star light curves are clearly not steady. Also, the variations in the FWHM of the point sources in the observed CCD frames during the course of the night might give rise to fictitious variations in the target NLSy1 galaxies. However, the variations of the NLSy1s detected in the observations reported here do not have any correlation with the FWHM variations and are thus genuine variations of the NLSy1s.

4.1.3 *Amplitude of variability (ψ)*

The actual variation displayed by the γ-NLSy1 galaxies on any given night is quantified using the INOV variability amplitude after correcting for the error in the measurements. This amplitude, ψ, is determined using the definition of Romero, Cellone & Combi (1999):

$$\psi = 100\sqrt{D_{\max} - D_{\min})^2 - 2\sigma^2}\ \text{per cent}, \tag{3}$$

with
$D_{\max}$ = maximum in γ-NLSy1 DLC,
$D_{\min}$ = minimum in γ-NLSy1 DLC and
σ^2 = variance in the star–star DLC involving the steadiest pair of comparison stars.

The amplitude of variability calculated using equation (3) for the nights when INOV was observed is given in Table 4. The results of INOV are also given in Table 4. Also, we mention that, given the random variability nature of the sources with occasional short time-scale and large-amplitude flares, it is possible to detect large-amplitude variability in these NLSy1s, if they are monitored for a longer duration of time.

4.1.4 *Duty cycle*

Definition of duty cycle (DC) from Romero et al. (1999) was used to calculate it in our observations. It is very well known that objects may not show flux variations on all the nights they were monitored. Therefore, it is appropriate if DC is evaluated by taking the ratio of the time over which the object shows variations to the total observing

Table 4. Log of INOV and LTOV observations. Columns are listed as follows: (1) source name; (2) date of observation; (3) INOV amplitude in per cent; (4) and (5) F-values computed for the γ-NLSy1 galaxy DLCs relative to the steadiest pair of comparison stars on any night; (6) variability status according to F-statistics; (7) and (8) values of C for the two γ-NLSy1 galaxy DLCs relative to the two comparison stars; (9) variability status as per C-statistics and (10) magnitude difference for LTOV relative to the first epoch of observation.

Source (1)	Date (dd.mm.yy) (2)	ψ (per cent) (3)	*F1* (4)	*F2* (5)	Status (6)	*C1* (7)	*C2* (8)	Status (9)	LTOV (Δm) (10)
1H 0323+342	24.01.12	12.69	1.903	1.736	V	1.380	1.318	NV	
	25.01.12	–	1.414	1.357	NV	1.189	1.165	NV	−0.01
	26.01.12	7.35	12.445	12.406	V	3.528	3.522	V	0.04
	02.02.12	–	1.766	2.153	NV	1.329	1.467	NV	−0.17
PMN J0948+0022	26.01.12	51.92	114.427	107.992	V	10.697	10.392	V	
	02.02.12	17.12	54.448	56.270	V	7.411	7.501	V	−0.24
	11.03.12	33.13	168.340	161.495	V	12.975	12.708	V	0.47
	19.04.12	25.25	24.071	25.500	V	4.906	5.050	V	−0.01
PKS 1502+036	18.04.12	6.49	3.263	3.913	V	1.806	1.978	NV	
	22.05.12	3.58	21.744	23.753	V	4.663	4.874	V	
	23.05.12	3.16	8.429	10.186	V	2.903	3.192	V	
	24.05.12	10.09	93.043	86.512	V	9.646	9.301	V	

time, instead of considering the fraction of variable objects. Thus, it can be written as

$$\mathrm{DC} = 100\frac{\sum_{i=1}^{n} N_i(1/\Delta t_i)}{\sum_{i=1}^{n}(1/\Delta t_i)} \text{ per cent,} \tag{4}$$

where $\Delta t_i = \Delta t_{i,\mathrm{obs}}(1+z)^{-1}$ is the duration of the monitoring session of a source on the ith night, corrected for its cosmological redshift z. N_i was set equal to 1 if INOV was detected, otherwise $N_i = 0$. Using only the C-statistics to judge the presence of INOV, on any particular night, we find a DC of 57 per cent for INOV of these γ-ray NLSy1 galaxies. However, using the F-statistics, we find an increased DC of INOV of 85 per cent.

4.2 Long-term optical variability

Since the total time span covered for observations ranges from days to months, this allowed us to search for the long-term optical variability (LTOV) of the sources. The LTOV results are summarized in the last column of Table 4. Here, the values indicate the difference of the mean γ-NLSy1 DLC with respect to the previous epoch of observation.

5 NOTES ON THE INDIVIDUAL SOURCES

5.1 1H 0323+342

This source was found to be a γ-ray emitter by *Fermi*/LAT (Abdo et al. 2010). Eggen et al. (2011) found optical polarization <1 per cent on 2011 February 7 and 10. *Hubble Space Telescope* (*HST*) images were well decomposed using a central point-source component above a Sérsic profile (Zhou et al. 2007). Very long baseline interferometry (VLBI) observations give clear evidence of a core–jet structure for this source (Zhou et al. 2007). Using the 6- and 20-cm flux densities given in the Véron-Cetty & Véron (2010) catalogue, the source is found to have an flat radio spectrum with $\alpha_{\mathrm{R}} = -0.35$ ($S_\nu \propto \nu^\alpha$). This source has not been studied for INOV prior to this work. Observations with good time resolution was obtained for a total of four nights. To judge the variability of 1H 0323+342, we have selected three comparison stars, namely S1, S2 and S3. However, as S3 was clearly non-steady, it was not used for generating the DLCs of 1H 0323+342. On 2012 January 24, the comparison stars were not found to be stable. On this night, the observations have an average time resolution of 30 s. From F-statistics we find the γ-NLSy1 DLCs to be variable. However, from C-statistics, the γ-NLSy1 galaxy has a $C < 2.576$, making it to be non-variable on that night. One day later, on 2012 January 25, the source was again observed for a total duration of 2.1 h with a typical sampling of one data point every 2 min. The source was non-variable on this night using both the C- and F-statistics. On 2012 January 26, about 3.5 h of data were gathered on the source with a temporal resolution of 2 min, and the source was found to show clear variations on that night. It was also found to be non-variable over the 5 h of monitoring done on 2012 February 2. On this night we have on average one data point around every 5 min. Thus, the source was found to show unambiguous evidence of INOV on one of the four nights of monitoring. However, on 2012 January 24, according to F-statistics, the source is variable, while it is not so, when C-statistics was used. Considering the LTOV of the source, the total time baseline covered for this source is 8 d. Over the course of 8 d, the source was found to show variations. It faded by 0.01 mag in the first 24 h, however brightened by 0.04 mag in another 24 h and again became fainter by 0.17 mag over 6 d between 2012 January 26 and 2012 February 2 (Fig. 4).

5.2 PMN J0948+0022

This was the first NLSy1 galaxy detected in the γ-ray band during the initial months of operation of *Fermi* (Abdo et al. 2009b). It was found to have high optical polarization of 18.8 per cent when observed during 2009 March–April, by Ikejiri et al. (2011). However, it showed low optical polarization of about 1.85 per cent when observed again on 2011 February 10 (Eggen et al. 2011). Such polarization variations are not uncommon in blazars. It has an inverted radio spectrum with $\alpha_{\mathrm{R}} = 0.81$ evaluated using the 6- and 20-cm flux densities given in Véron-Cetty & Véron (2010) catalogue. VLBI observations revealed high brightness temperature and a compact structure (Doi et al. 2006), with a possible core–jet morphology (Giroletti et al. 2011). Previous INOV observations showed the source to show violent variations with amplitudes of

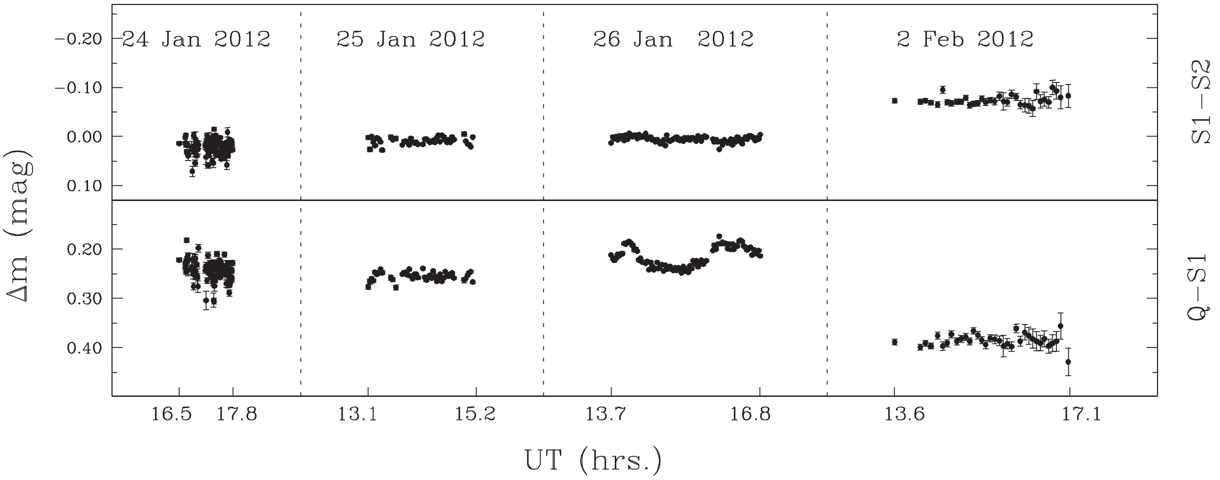

Figure 4. Long-term light curves of 1H 0323+342.

variability as large as 0.5 mag in time-scale of hours (Liu et al. 2010). Recently, Maune et al. (2011) have also detected INOV in PMN J0948+0022. This source has been monitored by us for four nights with durations ranging from 2 to 6 h between 2012 January and April. To characterize the variability of PMN J0948+0022 during the nights it was monitored, we have selected three comparison stars, S1, S2 and S3, all of which were found to be non-variable. However, for all variability analysis we have considered only the DLCs of PMN J0948+0022 relative to S1 and S2. On 2012 January 26, it was monitored for a total duration of 7 h, with a good time resolution of about 2 min. Clear evidence of variability was found on this night with amplitudes of variability as large as 52 per cent. A fast increase in brightness to 0.1 mag and slow declining flare with peak at ∼17.9 UT was found. The source then displayed a gradual decrease in brightness during the course of the night. Superimposed on this brightness change of the source, we found several miniflares with time-scales as short as 12 min. One such miniflare is towards the end of the night. Between 22.6 and 22.9 UT, the source increased in brightness by 0.12 mag, reaching maximum brightness at 22.76 UT and then gradually decreased in brightness. These miniflares are in fact real and cannot be attributed to seeing fluctuations during the course of the night, as we do not see any correlation between the occurrence of the miniflares and fluctuations in the FWHM variations. The FWHM after 22.5 UT was nearly steady, whereas a brightness change of 0.12 mag was noticed in the γ-NLSy1. On the observations done on 2012 February 2 for a duration of 2.4 h with a temporal resolution of about 7 min, the source showed a gradual brightness change of about 0.2 mag during the course of our observations. A large flare over a period of 3 h was found during the 4.9 h of observations on 2012 March 11. On this night, the average time resolution of the observations is about 7 min. Again on this night, superimposed on the large flare we noticed two miniflares one at 17 UT and the other at 19.5 UT. The miniflare at 19.5 UT showed a fast increase in brightness by 0.05 mag between 19.28 and 19.52 UT and then gradually reached the original brightness level at 19.87 UT. The total flare duration is ∼35 min with a rise time of ∼14 min and a decay time of ∼21 min. During 17 UT the FWHM has become poorer by 0.2 arcsec, whereas the γ-NLSy1 galaxy increased in brightness by 0.05 mag. The increase in brightness of the NLSy1 at 19.5 UT is not associated with the FHWM becoming poorer by 0.2 arcsec, as we might expect the source to become fainter due to FWHM degradation. Thus, the two miniflares observed on this night are also real and they are not due to any changes in the seeing variations during those times. INOV was also detected on the observations done on 2012 April 19. On this night, the light curve is densely sampled wherein we have on average one data point every 3 min. Thus, the source has shown variations on all the four nights monitored by us. The LTOV of this source can be noticed from the four epochs of monitoring over a duration of 4 months. Between the first two epochs, separated by six days, the source has decreased in brightness by about 0.2 mag. It then brightened by ∼0.5 mag between 2012 February 2 and 2012 March 11, and again became fainter by about 0.01 mag when observed on 2012 April 19 (Fig. 5).

5.3 PKS 1502+036

This source was found to be emitting in γ-ray band by *Fermi*/LAT (Abdo et al. 2010) and is the faintest γ-NLSy1 known in the Northern hemisphere as of now. It was found to have a core–jet structure from Very Long Baseline Array imaging (Orienti et al. 2012). Its radio spectrum is inverted with $\alpha_{\rm R} = 0.41$. PKS 1502+036 was monitored by us on four nights for INOV. We have used six comparison stars which are brighter than the source PKS 1502+036, to detect the presence of variability in it mainly due to the non-availability of suitable comparison stars of brightness similar to PKS 1502+036 in the observed field. For characterization of variability either using the *C*-statistics or *F*-statistics, we have used the stars S4 and S6 for the observations of 2012 April 18, whereas, for the other three nights, we have used the stars S1 and S2. The three nights of observations carried out in May have an average time resolution of 19 min, whereas on 2012 April 18, we have a better sampling of one data point every 5 min. On the observations done on 2012 April 18, INOV could not be detected. Clear INOV was also detected when the source was monitored on 2012 May 22 for a duration of 3.2 h, though the order of fluctuations in magnitude was found to be very small. A gradual increase in brightness of 0.03 mag over a period of 2 h and then a decrease by 0.035 mag in the next one and half hour's were found. Source showed the largest variability on 2012 May 24, with amplitude of variability as large as ∼10 per cent. The observations made on this source cover a total time baseline of about a month. As the comparison stars used during the April and May observations were different, the LTOV during this period could not be ascertained. However, from the observations done in May, the source brightness remained the same both

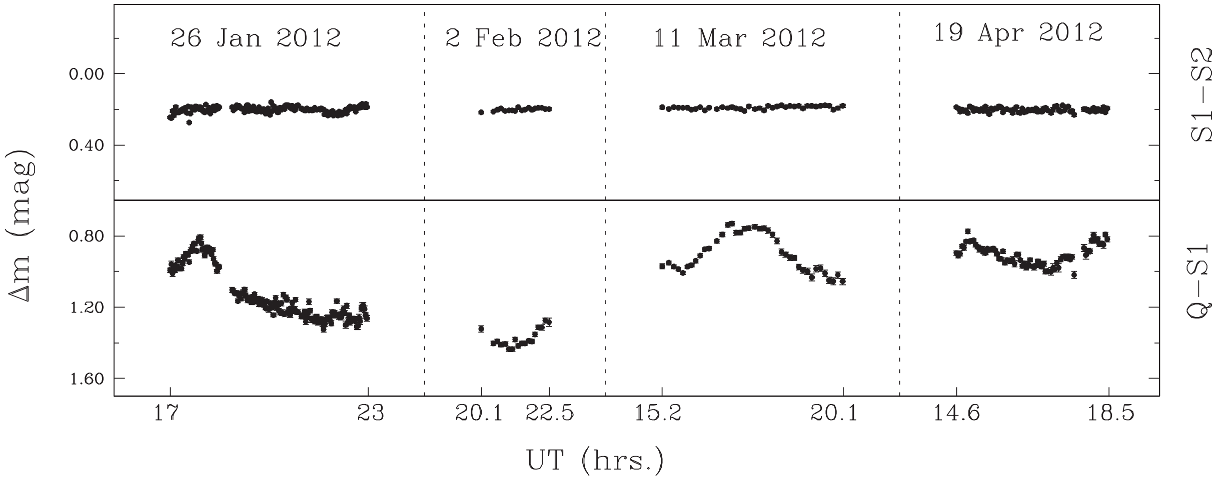

Figure 5. Long-term light curves of PMN J0948+0022.

on May 22 and 23, but faded by 0.045 mag when last observed on 2012 May 24. The large error bars in the DLCs of PKS 1502+036 are mainly due to its faintness. Though from visual examination it is difficult to unambiguously identify the variations, using the conservative *C*-statistics we classify the source to be variable on three of the four nights it was monitored.

6 CONCLUSIONS AND DISCUSSION

All the three sources of this present study have flat/inverted radio spectra, and also show γ-ray flux variability (Zhou et al. 2003; Abdo et al. 2009a,b). The source PMN J0948+0022 showed a large polarization of 18.8 per cent in 2009 (Ikejiri et al. 2011); however, it was found to be in a low polarized state with $P_{\rm opt}$ of 1.85 per cent in 2011 (Eggen et al. 2011). Optical polarization of <1 per cent was also observed for the source 1H 0323+342 (Eggen et al. 2011). High-resolution radio observations of these γ-NLSy1 galaxies point to the presence of core–jet structure, superluminal motion and high brightness temperatures (Doi et al. 2006; Zhou et al. 2007; Giroletti et al. 2011; Orienti et al. 2012). All these observations clearly point to the presence of relativistically beamed jets in these sources, closely aligned to the observers line of sight. It is known that γ-ray-detected blazars show more INOV, compared to non-γ-ray-detected blazars pointing to an association between INOV and relativistic jets that are more aligned to the observers line of sight (Gopal-Krishna et al. 2011). Earlier studies have shown that large amplitude $\psi >$ 3 per cent and high DC of around 70 per cent is exhibited by the BL Lac class of AGN (Sagar et al. 2004; Stalin et al. 2004).

The spectral energy distribution (SED) of γ-NLSy1 galaxies is found to be similar to that of blazars (Abdo et al. 2009b; Foschini et al. 2011; D'Ammando et al. 2012). This non-thermal continuum spectrum consists of distinct low-energy (due to synchrotron emission mechanism) and high-energy (due to inverse Compton emission mechanism) components. The polarized optical flux seen in γ-NLSy1 galaxies (Eggen et al. 2011; Ikejiri et al. 2011) is therefore a manifestation of relativistically beamed synchrotron emission which also accounts for the low-energy component of their SED, similar to the blazar class of AGN. From high-resolution VLBI observations and optical monitoring data of AGN, optical flare rise is always associated with the emergence of new superluminal blobs of synchrotron plasma (knots) in the relativistic jet (Arshakian et al. 2010; León-Tavares et al. 2010). Correlations between flux and polarization variations were observed in blazars such as Mrk 421 (Tosti et al. 1998) and AO 0235+164 (Hagen-Thorn et al. 2008). Similar to blazars, the flux variations in γ-NLSy1 galaxies can be explained by the shock-in-jet model (Marscher & Gear 1985). The turbulent jet plasma when it passes through the shocks in the jet downstream could give rise to increased multiband synchrotron emission and polarization (Goyal et al. 2012, and references therein). Recently, it has been found by Goyal et al. (2012) that sources with strong optical polarization also show high INOV.

Though there are ample observational evidence for the presence of closely aligned relativistic jets in these γ-NLSy1 galaxies, an independent way to test their presence is to look for INOV in them. The prime motivation for this work is therefore to understand the INOV characteristics of this new class of γ-NLSy1 galaxies and also to see for similarities/differences with respect to the γ-ray-emitting blazar population of AGN. The observations presented here report the INOV characteristics of the sample of three γ-NLSy1 galaxies. The sample of sources in the present study consists of three out of the seven known γ-NLSy1 galaxies, and therefore the INOV results found here might be representative of the INOV characteristics of the new population of γ-NLSy1 galaxies. Our high temporal sampling observation carried out on some of the nights using the EMCCD have enabled us to detect ultra rapid continuum flux variations in the source PMN J0948+0022. Such rapid flux variations are possible as it is known that the jet in γ-ray bright AGN has large bulk flow Lorentz factor, thereby oriented at small angles to the line of sight leading to stronger relativistic beaming (Pushkarev et al. 2009).

From the observations of three sources, over 10 nights, using *C*-statistics we find a DC of variability of 57 per cent. However, this increased to 85 per cent when the *F*-statistics discussed in de Diego (2010) was used. Also, the amplitudes of variability (ψ) are found to be greater than 3 per cent for most of the time. Such high-amplitude ($\psi >$ 3 per cent), high DC (∼70 per cent) INOV are characteristics of the BL Lac class of AGN (Stalin et al. 2004) and thus we conclude that the INOV characteristics of γ-NLSy1 galaxies are similar to blazars. The present study therefore provides yet another independent argument for the presence of relativistic jets in these γ-NLSy1 galaxies closely aligned to the observer similar to the blazar class of AGN.

Our present observations also indicate that γ-NLSy1 galaxies do show LTOV on day to month-like time-scales, similar to that shown by other classes of AGN (Webb & Malkan 2000; Stalin et al. 2004). However, due to the limited nature of our observations, with each source observed over different time baselines, definitive estimates of the LTOV of these sample of sources could not be made. Though there are ample evidences for the presence of jets in these sources, both from the INOV observations reported here and other multiwavelength and multimode observations available in the literature, the optical spectra of them do not show any resemblance to that of blazar class of AGN with relativistic jets. Seyferts in general have spiral host galaxies. Optical imaging observations of 1H 0323+342 shows a ring-like structure, which hints of a possible collision with another galaxy (Antón, Browne & Marchã 2008). Such interaction with another galaxy could trigger an AGN activity (Alonso et al. 2007). Also, the images obtained from *HST* Wide Field Planetary Camera using the *F*702*W* filter corresponding to $\lambda_{\mathrm{eff}} = 6919$ Å is well represented when decomposed with a central point source plus a Sérsic component (Zhou et al. 2007). If the other two sources are also conclusively found to be hosted in spiral galaxies, then it points to a rethink of the well-known paradigm of jets being associated with elliptical galaxies. Further dedicated flux and optical polarization monitoring observations coupled with high-resolution optical imaging studies will give clues to the nature of this new class of γ-NLSy1 galaxies.

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