Multiwavelength observations of the $\gamma$-ray emitting narrow-line Seyfert 1 PMN J0948+0022 in 2011

F. D'Ammando$^{1,2}$, J. Larsson$^3$, M. Orienti$^{1,4}$, C. M. Raiteri$^5$, E. Angelakis$^6$, A. Carramiñana$^7$, L. Carrasco$^7$, A. J. Drake$^8$, L. Fuhrmann$^6$, M. Giroletti$^1$, T. Hovatta$^9$, W. Max-Moerbeck$^9$, A. Porras$^7$, A. C. S. Readhead$^9$, J. L. Richards$^{10}$

$^1$INAF - Istituto di Radioastronomia, Via Gobetti 101, I-40129 Bologna, Italy
$^2$Dipartimento di Fisica, Università degli Studi di Perugia, Via A. Pascoli, I-06123 Perugia, Italy
$^3$KTH, Department of Physics, and the Oskar Klein Centre, AlbaNova, SE-106 91 Stockholm, Sweden
$^4$Dipartimento di Astronomia, Università di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
$^5$INAF - Osservatorio Astrofisico di Torino, Via Osservatorio 20, I-10025 Pino Torinese (TO), Italy
$^6$Max-Planck-Institute für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
$^7$Instituto de Astrofísica, Óptica, y Electrónica, Tonantzintla, 72840 Puebla, Mexico
$^8$California Institute of Technology, 1200 E. California Blvd, CA 91125, USA
$^9$Cahill Center for Astronomy and Astrophysics, California Institute of Technology 1200 E. California Blvd, Pasadena, CA 91125, USA
$^{10}$Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA

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ABSTRACT

We report on radio-to-$\gamma$-ray observations during 2011 May–September of PMN J0948+0022, the first narrow-line Seyfert 1 (NLSy1) galaxy detected in $\gamma$-rays by Fermi-LAT. Strong variability was observed in $\gamma$-rays, with two flaring periods peaking on 2011 June 20 and July 28. The variability observed in optical and near-infrared seems to have no counterpart in $\gamma$-rays. This different behaviour could be related to a bending and inhomogeneous jet or a turbulent extreme multi-cell scenario. The radio spectra showed a variability pattern typical of relativistic jets.

The XMM spectrum shows that the emission from the jet dominates above $\sim$2 keV, while a soft X-ray excess is evident in the low-energy part of the X-ray spectrum. Models where the soft emission is partly produced by blurred reflection or Comptonisation of the thermal disc emission provide good fits to the data. The X-ray spectral slope is similar to that found in radio-quiet NLSy1, suggesting that a standard accretion disc is present, as expected from the high accretion rate. Except for the soft X-ray excess, unusual in jet-dominated AGNs, PMN J0948+0022 shows all characteristics of the blazar class.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – galaxies: individual (PMN J0948+0022) – gamma-rays: general

1 INTRODUCTION

Narrow-line Seyfert 1 (NLSy1) galaxies, first suggested as a distinct class of active galactic nuclei (AGNs) by Osterbrock & Pogge (1985), are characterized in optical by their narrow permitted emission lines (full-width at half maximum FWHM $\leq$ 2000 km s$^{-1}$), weak [OIII]/H$\beta$ (< 3), and strong Fe$^{II}$ emission lines. They also exhibit strong X-ray variability, steep X-ray spectra, substantial soft X-ray excess and relatively high luminosity (Boller et al. 1996; Zhou et al. 2006). These characteristics suggest that NLSy1s have smaller masses of the central black hole (M$_{\text{BH}} = 10^6$–$10^8$ M$_{\odot}$) and higher $\dot{M}/\dot{M}_{\text{Edd}}$ values (up to the Eddington limit or above) than those observed in blazars and radio galaxies. Only a small percentage (<7%) of NLSy1 are radio-loud (Komossa et al. 2006) compared to $\sim$15% of the quasars. In the radio-loud NLSy1s, flat radio spectra and flux density variability suggest that several of them could host relativistic jets (Zhou et al. 2003; Doi et al. 2006; Yuan et al. 2008).

PMN J0948+0022 shows optical properties typical of a NLSy1 (i.e. FWHM(H$\beta$) = 1432±87 km s$^{-1}$).
After the discovery of γ-ray emission from PMN J0948+0022, this source has been the target of different multifrequency campaigns with the aim of understanding its nature. The first spectral energy distributions (SEDs) collected for this object, as well as for the other three γ-ray NLsY1s detected in the first year of Fermi operation, showed clear similarities with blazars: a double-humped shape with a first peak in the IR/optical band due to synchrotron emission, a second peak in the MeV/GeV band likely due to inverse Compton emission, and an accretion disk component in UV. The physical parameters of these NLsY1s are blazar-like, and jet powers are in the average range of blazars (Abdo et al. 2009b). In addition, the comparison of the SED of PMN J0948+0022 during the 2010 July flaring activity with that of 3C 273, a typical flat spectrum radio quasar (FSRQ), showed a more extreme Compton dominance in the NLsY1. The disagreement between the two SEDs can be due to the difference in black hole (BH) masses and Doppler factor of the two jets (Foschini et al. 2011). The radio-to-γ-ray light curves of the source collected over years showed correlated variability, with a delay of a few months of the radio emission with respect to the γ-ray, as usually observed in FSRQs (Abdo et al. 2009c; Foschini et al. 2012).

In this paper, we discuss the results of the analysis of the multiwavelength data of PMN J0948+0022 collected during 2011 May–September. Part of the data presented here has already been published in Foschini et al. (2012). XMM-Newton and Catalina Real-time Transient Survey data are presented here for the first time. Fermi-LAT, Swift, and MOJAVE data are re-analyzed. The paper is organized as follows. In Section 2, we report the LAT data analysis and results, while in Sections 3 and 4 we present the X-ray and optical/UV results of the Swift and XMM-Newton observations, respectively. Near-infrared (NIR) and optical data from ground-based observatories are presented and discussed in Section 5. Radio data collected by the Very Long Baseline Array (VLBA) interferometer, the 40 m Owens Valley Radio Observatory (OVRO), the 32 m Medicina, the 13.7 m Metsähovi, and 100 m Effelsberg single-dish telescopes are presented and discussed in Section 6. In Section 7, 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 parameterized as $dN/dE \propto E^{-\Gamma}$, where $\Gamma$ is the photon index. We adopt a $\Lambda$ cold dark matter ($\Lambda$-CDM) cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.73$, and $\Omega_\Lambda = 0.27$. The corresponding luminosity distance at $z = 0.5846$ is $d_L = 3413$ Mpc, and 1 arcsec corresponds to a projected size of 6.590 kpc.

2 FERMI-LAT DATA: ANALYSIS AND RESULTS

2.1 Observations and data reduction

The Fermi-LAT is a pair-conversion telescope operating from 20 MeV to > 300 GeV. It has a large peak effective area (~8000 cm$^2$ for 1 GeV photons), an energy resolution of typically ~10%, and a field of view of about 2.4 sr with an angular resolution (68% containment radius) better than 1° for energies above 1 GeV. Further details about the Fermi-LAT are given in Atwood et al. (2009).

The LAT data reported in this paper were collected from 2011 May 1 (MJD 55682) to September 30 (MJD 55835). During this time, the Fermi spacecraft operated almost entirely in survey mode. The analysis was performed with the ScienceTools software package version v9r27p1. The LAT data were extracted within a region of 20° radius centred at the location of PMN J0948+0022. 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 $\gamma$-rays, which are produced by cosmic rays interacting with the upper atmosphere. The spectral analysis was performed with the instrument response functions P7SOURCE_V6 using an unbinned maximum-likelihood method implemented in the Science tool gtlike. A Galactic diffuse emission model and isotropic component, which is the sum of an extragalactic and residual cosmic-ray background, were used to model the background. The normalizations of both components in the background model were allowed to vary freely during the spectral fitting.

We analysed a region of interest of $10^5$ radius centred at the location of PMN J0948+0022. We evaluated the significance of the $\gamma$-ray signal from the sources by means of a maximum-likelihood test statistic $TS = 2 \log(\frac{L_1}{\log L_0})$, 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 PMN J0948+0022 [Mattix et al. 1996]. Following the second Fermi LAT source catalogue (2FGL; Nolan et al. 2012), the spectral model used for PMN J0948+0022 is a log-parabola, $dN/dE \propto (E/E_0)^{-\alpha - \beta \log(E/E_0)}$ [Landau et al. 1982; Massaro et al. 2004], where the parameter $\alpha$ is the spectral slope at the energy $E_0$ and the parameter $\beta$ measures the curvature around the peak. We fixed the reference energy $E_0$ to 272 MeV as in the 2FGL catalogue. The source model used in gtlike includes all of the point sources from the 2FGL catalogue that fall within $15^\circ$ of PMN J0948+0022. The spectra of these sources were parametrized by power law functions, $dN/dE \propto (E/E_0)^{-\gamma}$, except for 2FGL J0090.1+0121, for which we used a log-parabola as in the 2FGL catalogue. A first maximum-likelihood analysis was performed to remove from the model the sources having $TS < 25$ and/or a predicted number of counts based on the fitted model $N_{\text{pred}} < 3$. A second maximum-likelihood analysis was performed on the updated source model. The fitting procedure has been performed with the sources within $10^5$ of PMN J0948+0022 included with the normalization factors and the photon indices left as free parameters. For the sources located between $10^5$ and $15^\circ$ from our target, we kept the normalizations and the photon indices fixed to the values of the 2FGL catalogue.

### 2.2 Results

Integrating over the period 2011 May 1–September 30 (MJD 55682–55835) the fit yielded a $TS = 674$ in the 0.1–100 GeV energy range, with an average integral flux of $(21.6 \pm 1.5) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$, a spectral slope $\alpha = 2.41 \pm 0.10$, and a curvature parameter around the peak $\beta = 0.20 \pm 0.06$. The corresponding apparent isotropic $\gamma$-ray luminosity is $\sim 1.8 \times 10^{47}$ erg s$^{-1}$. As a comparison during the first two years of Fermi operation (2008 August 4–2010 August 4) the average integral flux was $(9.2 \pm 0.5) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$, with a spectral slope $\alpha = 2.26 \pm 0.08$, and a curvature parameter around the peak $\beta = 0.26 \pm 0.06$ [Nolan et al. 2012]. Thus the average 0.1–100 GeV flux over 2011 May–September is about a factor of 2 higher than the 2FGL flux, but no significant spectral changes were observed.

Fig. 3 shows the $\gamma$-ray light curve for the period considered, using a log-parabola spectral model and 7-day time bins. For each time bin, the spectral parameters of PMN J0948+0022 and all sources within $10^5$ of it were frozen to have the parameter values resulting from the likelihood analysis over the entire period. For the highest significance periods, we also reported as open circles the fluxes in $1^\circ$-day time intervals. If $TS < 10$, $2\sigma$ upper limits were calculated. All uncertainties in measured $\gamma$-ray flux and index reported throughout the paper are statistical only. The systematic uncertainty in the effective area is energy dependent: it amounts to 10% at 100 MeV, decreasing to 5% at 560 MeV, and increasing to 10% above 10 GeV [Ackermann et al. 2012].

A daily peak flux of $(101 \pm 20) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ in the 0.1–100 GeV energy range was detected on 2011 June 20 (MJD 55732), representing an increase of a factor of 5 with respect to the 2011 May–September average flux and more than an order of magnitude above the average 2FGL flux of the source. The corresponding apparent isotropic $\gamma$-ray luminosity is $\sim 8.8 \times 10^{47}$ erg s$^{-1}$. Preliminary results about this $\gamma$-ray flaring activity were reported by D’Ammando & Ciprini (2011) and Lucarelli et al. (2011). A second $\gamma$-ray flaring activity was observed at the end of 2011 July, peaking on July 28 (MJD 55770) with a flux of $(87 \pm 25) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ in the 0.1–100 GeV energy range. By means of the gtsrcprob tool, we estimated that the highest energy photon emitted from PMN J0948+0022 (with probability $> 80\%$ of being associated with the source) was observed on 2011 September 13 (MJD 55807), at a distance of $0.09^\circ$ from the source and with an energy of 3.2 GeV. This suggests that this NLSy1 emits mainly at $E < 10$ GeV, even during flaring activity (see e.g. Foschini et al. 2011).

### 3 SWIFT DATA: ANALYSIS AND RESULTS

The Swift satellite [Gehrels et al. 2004] performed six observations of PMN J0948+0022 between 2011 April 29 and July 2. The observations were performed with all three on board instruments: the Burst Alert Telescope (BAT; Barthelmy et al. 2005, 15–150 keV), the X-ray Telescope (XRT; Burrows et al. 2003, 0.2–10.0 keV), and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2003, 170–600 nm). The hard X-ray flux of this source is below the sensitivity of the BAT instrument for the short exposures of these observations and therefore the data from this instrument were not used. Moreover, the source is not present in the Swift/BAT 7-month hard X-ray catalogue [Baumgartner et al. 2013].

#### 3.1 Swift-XRT

The XRT data were processed with standard procedures (xrtpipeline v0.12.6), filtering, and screening criteria by using the HEASoft package (v6.12). The data were collected in photon counting mode for all of the observations. The source count rate was low (< 0.5 counts s$^{-1}$); thus pile-up correction was not required. 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 away from the source

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1. [http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Background Models.html](http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Background Models.html)
region or other 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. When the number of photons collected was too low (< 200 counts), the spectra were rebinned with a minimum of 1 count per bin and the Cash statistic (Cash 1979) was used. Since the effective area of Swift-XRT is a factor of ∼10 lower than that of the XMM-Newton EPIC cameras, detailed spectral modeling was not performed with the XRT observations. The spectrum was fitted with an absorbed power law using the photoelectric absorption model TBABS (Wilms et al. 2000), with a neutral hydrogen column density fixed to its Galactic value (5.07×10²⁰ cm⁻²) (Kalberla et al. 2003). The fit results are reported in Table 1. The relatively harder X-ray spectrum observed for PMN J0948+0022 with respect to the other NLSy1s (e.g., Grupe et al. 2010; Zhou & Zhang 2010) could be due to the contribution of inverse Compton radiation from a relativistic jet, similarly to what is found in FSRQs. A photon index 1.4–1.5 was observed in X-rays also for another γ-ray NLSy1, SBS 0846+513 (D’Ammando et al. 2012a; 2013b).

### 3.2 Swift-UVOT

During the Swift pointings the UVOT instrument observed PMN J0948+0022 in its optical (v, b, and u) and UV (w1, m2, and w2) photometric bands. The data analysis was performed using the uvotsource task included in the HEASoft package (v6.12). 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 of 10 arcsec radius in the source neighbourhood. We calculated the effective wavelengths, count rate to flux conversion factors, and Galactic extinctions for the UVOT bands according to the procedure explained in Raiteri et al. (2010, 2011) and D’Ammando et al. (2012a). The observed magnitudes are reported in Table 2 and flux densities for the v, u, and w2 filters are shown in Fig. 2. The optical u-band magnitude ranged from 17.67 to 17.11, with the peak detected on 2011 June 4 (MJD 55716). No significant variability was observed in UV, but we noted that no UV observations were available during the optical peak in u-band.

### 4 XMM-NEWTON DATA: ANALYSIS AND RESULTS

#### 4.1 Observations and data reduction

XMM-Newton [Jansen et al. 2001] observed PMN J0948+0022 on 2011 May 28–29 (MJD 55709–55710) for a total duration of 93 ks (observation ID 067370101, PI: D’Ammando). A simultaneous observation was performed by Swift on 2011 May 28.

The EPIC pn was operated in the large window mode and the EPIC MOS cameras (MOS1 and MOS2) were operated in the prime partial mode. The data were reduced using the XMM-Newton Science Analysis System (SAS v11.0.0), applying standard event selection and filtering. Inspection of the background light curves showed that strong flaring was present during the whole observation. The flaring time intervals were removed for the spectral analysis, leaving good exposure times of 36, 58 and 60 ks for the pn, MOS1 and MOS2, respectively. For each of the detectors the source spectrum was extracted from a circular region of radius 34 arcsec centred on the source, and the background spectrum from a nearby region on the same chip. All the spectra were binned to contain at least 20 counts per bin to allow for χ² spectral fitting.

The Optical Monitor (OM) and Reflection Grating Spectrometers (RGS1 and RGS2) were also operating during the observation. No spectral lines were detected in the RGS spectra. This could be because the signal was rather low. The RGS data are not discussed further in this work. The data from the OM are discussed in Sect. 4.4.

#### 4.2 X-ray spectral analysis

All spectral fits were performed over the 0.3-10 keV energy range using XSPEC v.12.7.1. The energies of spectral features are quoted for the rest frame of the source while plots are in the observed frame, unless otherwise stated. All errors are quoted for 90% confidence for one interesting parameter (Δχ² = 2.7). The data from the three EPIC cameras were initially fitted separately, but since good agreement was found (< 5%) we proceeded to fit them together. As for the Swift spectra, Galactic absorption was included in all fits using the TBABS model. The results of all the fits are presented in Table 3. It is clear that a simple power law model was insufficient to describe the data, while a broken power law yielded an acceptable fit (the improvement between the models is Δχ² = 969 for two additional
Table 2. Results of the Swift-UVOT observations of PMN J0948+0022.

| Date (UT)   | Date (MJD) | v    | b    | u    | w1   | m2   | w2   |
|-------------|------------|------|------|------|------|------|------|
| 2011-Apr-29 | 55689      | –    | –    | 17.27±0.03 | –    | –    |
| 2011-May-15 | 55996      | 18.20±0.13 | 18.43±0.08 | 17.67±0.07 | 17.46±0.05 | 17.44±0.06 | 17.46±0.04 |
| 2011-May-28 | 55709      | 18.05±0.15 | 18.31±0.09 | 17.48±0.07 | 17.31±0.05 | 17.35±0.06 | 17.33±0.04 |
| 2011-June-04| 55716      | –    | –    | 17.11±0.03 | –    | –    | –    |
| 2011-June-14| 55726      | 17.86±0.11 | 18.31±0.08 | 17.34±0.06 | 17.34±0.05 | 17.35±0.05 | 17.29±0.04 |
| 2011-July-02| 55744      | –    | –    | 17.64±0.30 | –    | –    | –    |

However, it is well known that such a high temperature is inconsistent with standard accretion disc theory, which predicts that the thermal emission from the disc around a super-massive BH should peak in the ultraviolet band. Indeed, from the SED of the source (see e.g., [Foschini et al. 2011, 2012]) the observed emission from the accretion disc seems to peak at 20 eV, corresponding to a disc temperature of 11 eV in the rest frame of the source.

The soft X-ray emission may instead be due to Comptonisation of the disc emission by a population of electrons with low temperature and large optical depth, which may exist in a transition region between the disc and the corona (Done et al. 2012). To investigate this model we proceeded to fit the spectrum with a power law and a Comptonised blackbody, using the COMPTT model [Titarchuk 1994] and fixing the seed temperature at 11 eV. As seen in Table 3 and the left panel of Fig. 3, this model provides a good fit to the spectrum, with best-fit electron temperature $kT_e = 0.50^{+0.16}_{-0.09}$ keV and optical depth $\tau = 10.2^{+0.3}_{-0.1}$.

We note that allowing a higher seed temperature of 20 eV changes only the normalisation of the Comptonised component, without significantly affecting any of the other best fit values presented in Table 3. The photon index of the power law in this model is $\Gamma = 1.44±0.03$. In principle the model should also contain a second power law to account for any emission from the corona, but such a component was not required in the fits.

An alternative explanation for the soft excess is that it is due to relativistically blurred reflection from the accretion disc. Such a model can explain the fact that the energy of the soft excess is observed to be fairly constant for black holes spanning several orders of magnitude in mass (Gierlinski & Done 2004; Bianchi et al. 2006), and has been successfully applied for a large number of sources (Crummy et al. 2006). In this picture the X-ray spectrum of PMN J0948+0022 would be composed of a steep power law associated with the corona, a reflection component resulting from irradiation of the disc by this power law, as well as a hard power law associated with the jet, dominating at high energies.

The large number of parameters in such a model are impossible to constrain with the available data, especially given that there is no Fe line or Compton hump for the reflection model to anchor to. To set some constraints on such a scenario we constructed a model made of two power laws (with the photon indices constrained to be steeper and flatter than 2, for the corona and jet, respectively) together with a relativistically blurred reflection component with parameters fixed at ‘standard’ values. The reflection was modelled with KDBLUR acting on the RE-
FLIONX model by Ross & Fabian (2005), with the photon index of the illuminating power law tied to the steep power law. The inner and outer radii of the disc were fixed at 6 gravitational radii ($r_g$) and 400 $r_g$, respectively. Solar abundances were assumed and the emissivity index was fixed at $q = 3$ (i.e. assuming a standard emissivity profile of $r^{-3}$ from a central point source). The inclination was fixed at $i = 3^\circ$, which is the angle of the jet inferred by Foschini et al. (2011). The disc may not be exactly perpendicular to the jet, but we note that allowing a larger value, i.e. up to around $i = 15^\circ$, did not change the results. After optimisation the ionisation state of the disc was fixed at $\xi = 3000$ erg cm s$^{-1}$. As seen in Table 3 this model results in a fit of quality comparable to the Comptonised blackbody. However, it should be noted that it is the steep power law and not the reflection component that provides most of the flux at low energies, as seen in Fig. 3 which shows the model components. In fact, a fit with two power laws but no reflection is only marginally worse ($\Delta \chi^2 = 6$ for one more degree of freedom, see Table 4). Allowing each of the parameters of the reflection model to vary did not significantly change these results.

4.3 X-ray variability

The EPIC pn light curve is shown in Fig. 4 with the time intervals with low background that were used for the spectral analysis marked in red. The source was only mildly variable during the XMM observation, as suggested by the count rate light curve. The observed fluxes corrected for Galactic absorption are $F_{2-10\ keV} = (2.56 \pm 0.05) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and $F_{0.3-10\ keV} = 4.59^{+0.03}_{-0.05} \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, in agreement with the Swift-XRT results (see Table 1).

The root-mean-square (RMS) variability spectrum of the observation is shown in Fig. 5 and it is calculated following Vaughan et al. (2003) using light curves with 0.5 ks bins. The RMS spectrum shows the variability amplitude of the source as a function of energy, corrected for the variance due to measurement errors and normalised by the mean count rate in each energy band. The error bars represent the uncertainty expected from the Poisson noise (Vaughan et al. 2003). Since the flaring background becomes increasingly dominant with energy we plot the RMS spectrum only up to 5 keV (at which energy the ratio of signal to background is about 4). The variability clearly decreases with energy up
to around 1.7 keV, but then starts to increase again. It is interesting to note that this break coincides with the break energy of the broken power law model (see Table 3), since it is consistent with our interpretation that the Seyfert and jet components dominate at low and high energies, respectively (see further Section 7.3). The RMS spectrum presented in Bhattacharyya et al. (2013) has a different energy binning, but exhibits an overall shape that is consistent with our results. While we find that the increase in RMS variability above ~ 2 keV is not affected by our choice of energy binning, it will be important to confirm these results with an observation where the variability analysis can be extended to higher energies.

We further investigated the spectral variability by fitting the broken power law model to spectra extracted in 15 ks intervals (corresponding to 3–7.5 ks of good exposure time per spectrum). Fig. 6 shows the evolution of the best-fit parameters and the flux as a function of time. There are no systematic trends with time and only the flux is found to vary significantly above the 3σ level. However, the photon index and $E_{\text{break}}$ are found to be marginally variable (> 90% CL).

### Table 3. Summary of fits to the 0.3–10 keV XMM-Newton spectra. All fits also included absorption fixed at the Galactic value. Superscript $f$ indicates that a parameter was kept fixed. See text for a description of the models.

| Model                  | Parameter | Value          |
|------------------------|-----------|----------------|
| power law              | $\Gamma$  | $1.88 \pm 0.01$ | $\chi^2$/d.o.f. | 2342/1254 |
|                        | Norm      | $6.53 \pm 0.05 \times 10^{-4}$ |                   |
| Broken power law       | $\Gamma_1$ | $2.14^{+0.03}_{-0.02}$ | $\chi^2$/d.o.f. | 1379/1252 |
|                        | $E_{\text{break}}$ (keV) | $1.73^{+0.09}_{-0.11}$ |                   |
|                        | $\Gamma_2$ | $1.45^{+0.04}_{-0.03}$ |                   |
|                        | Norm      | $6.28 \pm 0.06 \times 10^{-4}$ |                   |
| power law +            | $\Gamma$  | $1.44 \pm 0.03$ | $\chi^2$/d.o.f. | 1329/1251 |
| compTT                 | PL Norm   | $4.13 \pm 0.17 \times 10^{-4}$ |                   |
|                        | $T_0$ (keV) | $1.10 \times 10^{-2}$ |                   |
|                        | $kT_0$ (keV) | $0.50^{+0.10}_{-0.09}$ |                   |
|                        | $\tau$    | $10.2^{+1.3}_{-0.7}$ |                   |
|                        | Comp Norm | $0.38^{+0.07}_{-0.06}$ |                   |
|                       | $\chi^2$/d.o.f. | 1329/1251 |                   |
| power law (jet) +      | $\Gamma_j$ | $2.12^{+0.07}_{-0.04}$ |                   |
|                        | PL Norm$_j$ | $2.4 \pm 0.2 \times 10^{-4}$ |                   |
| power law (corona) +   | $\Gamma_c$ | $2.53^{+0.14}_{-0.09}$ |                   |
|                        | PL Norm$_c$ | $2.7 \pm 0.1 \times 10^{-4}$ |                   |
| Blurred reflection      | $q$       | $3$ |                   |
|                        | $R_{\text{in}}$ ($r_g$) | $6$ |                   |
|                        | $R_{\text{out}}$ ($r_g$) | $400$ |                   |
|                        | incl (deg) | $3$ |                   |
|                        | $F_{\text{Fe}}$/solar | $1$ |                   |
|                        | $\xi$ (erg cm s$^{-1}$) | $3000$ |                   |
|                        | Ref Norm  | $2.3^{+1.2}_{-0.9} \times 10^{-9}$ |                   |
|                       | $\chi^2$/d.o.f. | 1333/1251 |                   |
| power law (jet) +      | $\Gamma_j$ | $1.20^{+0.08}_{-0.09}$ |                   |
|                        | PL Norm$_j$ | $2.4 \pm 0.4 \times 10^{-4}$ |                   |
| power law (corona) +   | $\Gamma_c$ | $2.65^{+0.11}_{-0.10}$ |                   |
|                        | PL Norm$_c$ | $3.7 \pm 0.05 \times 10^{-4}$ |                   |
|                       | $\chi^2$/d.o.f. | 1339/1252 |                   |

Figure 6. Results of fits to time-resolved spectra of the XMM-Newton observation using a broken power law model. The top panel shows the temporal evolution of the photon indices (the indices below and above the break energy are shown as filled circles and filled triangles, respectively), the middle panel shows the break energy, and the bottom panel shows the 0.3–10 keV unabsorbed flux derived from the fits.

### 4.4 Optical Monitor data

The Optical Monitor (OM; Mason et al. 2011) on board XMM-Newton is a 30 cm telescope carrying six optical/UV filters, and two grisms. Observations of PMN J0948+0022 in 2011 May 28–29 consisted of seven subsequent exposures in $v$-band, followed by ten in $b$-band, nine in $u$-band, ten in $u1$-band and $m2$-band, then five in $w2$-band. All optical exposures were 800 s long, while UV exposures were 1600 s and 2700 s long. We used the SAS task omichain to reduce the data and the tasks omsource and omphotom to derive the source magnitude. Average observed magnitudes are: $v = 18.28 \pm 0.06$, $b = 18.63 \pm 0.02$, $u = 17.64 \pm 0.02$, $w1 = 17.27 \pm 0.02$, $m2 = 17.24 \pm 0.03$, and $w2 = 17.33 \pm 0.11$. The difference of 0.2–0.3 mag in the optical filters with respect to the Swift-UVOT observations performed on 2011 May 28 at least partially could be due to the source variability.
5 GROUND-BASED OPTICAL AND INFRARED OBSERVATIONS

5.1 CRTS

The source has been monitored by the Catalina Real-time Transient Survey (CRTS)\(^3\) (Drake et al. 2009; Djorgovski et al. 2011), using the 0.68 m Schmidt telescope at Catalina Station, AZ, 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 observation, 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 by \(V = V_{\text{CSS}} + 0.31(B - V)^2 + 0.04\) with a scatter of 0.056 mag.\(^2\) The flux densities collected by CRTS in V band are reported in Fig. 7.

5.2 INAOE

NIR observations of PMN J0948+0022 were performed during 2011 April–May, at the 2.1 m telescope “Guillermo Haro”, with the NIR camera “CANICA” equipped with a Rockwell 1024 × 1024 pixel Hawaii infrared array, working at 75.4 K, with standard \(J(1.164-1.328 \mu m), H(1.485-1.781 \mu m),\) and \(Ks\) (1.944-2.294 \(\mu m\)) filters. The plate scale is 0.32 arcsec pixel\(^{-1}\.\) Observations were carried out in series of 10 dithered frames in each filter. Data sets were co-added after correcting for bias and flat fielding. Flats were obtained from sky frames derived from the dithered ones. Magnitudes in \(J, H, \) and \(Ks\) filters are reported in Table 4. The flux densities collected in \(J\) and \(H\) band are reported also in Fig. 7.

6 RADIO OBSERVATIONS

6.1 Effelsberg 100 m

The radio spectrum of PMN J0948+0022 was observed with the Effelsberg 100 m telescope between 2011 May 24 and October 1 within the framework of a \textit{Fermi}-related monitoring programme of \(\gamma\)-ray blazars (F-GAMMA programme: Fuhrmann et al. 2008). The measurements were conducted with the secondary focus heterodyne receivers at 2.64, 4.85, 8.35, 10.45, 14.60, 23.05, and 32.00 GHz. The observations were performed quasi-simultaneously with cross-scans, that is, slewing over the source position, in azimuth and elevation directions, with adaptive numbers of sub-scans for reaching the desired sensitivity (for details, see Fuhrmann et al. 2008; Angelakis et al. 2008). Corrections for pointing offset, gain, atmospheric opacity, and sensitivity have been applied to the data. The different spectra collected by Effelsberg are represented in Fig. 8.

Radio spectra and fluxes indicate that the source was highly active already in 2011 May 24 (MJD 55705), before the first peak of the \(\gamma\)-ray activity, followed by a flux decrease and a flattening of the spectrum in 2011 August–October. The spectral index calculated between 8.4 and 32 GHz changes between \(-0.4\pm0.1\) and \(0.2\pm0.1\) from 2011 May to October. No significant flux changes were observed at frequencies below 8.4 GHz. This is likely due to opacity effects at the low frequencies. Flux densities at 32 GHz and 14.6 GHz are also shown in Fig. 7.

6.2 Metsähovi

Observations at 37 GHz were made with the 13.7 m Metsähovi radio telescope, which is a radome enclosed paraboloid antenna situated in Finland. The measurements were made with a 1 GHz-band dual beam receiver centred at 36.8 GHz. The observations are ON-ON measurements, alternating between the source and the sky in each feed horn. A typical integration time to obtain one flux density data point is between 1200 and 1400 s. The detection limit at 37 GHz is on the order of 0.2 Jy under optimal conditions. Data points with a signal-to-noise ratio < 4 are handled as non-detections. The flux density scale is set by observations of DR 21. Sources NGC 7027, 3C 274 and 3C 84 are used as secondary calibrators. A detailed description of the data reduction and analysis is given in Teräsranta et al. (1998). The error on the flux density includes the contribution from the measurement RMS and the uncertainty of the absolute calibration. Flux densities at 37 GHz are shown in Fig. 7.

6.3 OVRO 40 m

As part of an ongoing blazar monitoring program, the OVRO 40 m radio telescope has observed PMN J0948+0022 at 15 GHz regularly since the end of 2007 (Richards et al. 2011). This monitoring program includes about 1700 known and likely \(\gamma\)-ray loud blazars above declination \(-20^\circ\). The sources in this programme are observed in total intensity twice per week with a 4 mJy (minimum) and 3% (typical) uncertainty on the flux densities. Observations were performed with a dual-beam (each 2.5 arcmin FWHM) Dicke-switched system using cold sky in the off-source beam as the reference. Additionally, the source is switched between beams to reduce atmospheric variations. The absolute flux density scale is calibrated using observations of 3C 286, adopting the flux density (3.44 Jy) from Baars et al. (1977). This result in about a 5% absolute scale uncertainty, which is not reflected in the plotted errors. During the OVRO monitoring, the flux density varied from 671 mJy (on MJD 55725; 2011 June 13) to 335 mJy (on MJD 55836; 2011 October 2), as shown in Fig. 7.
Figure 7. Multifrequency light curve of PMN J0948+0022 for the period 2011 May 1–September 30 (MJD 55682–55834) collected (from top to bottom) in: γ rays by Fermi-LAT (0.1–100 GeV; in units of $10^{-8}$ ph cm$^{-2}$ s$^{-1}$); X-rays by Swift-XRT (filled circles) and XMM-Newton (open square) (0.3–10 keV; in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$); $w_2$ band by Swift-UVOT (filled circles) and XMM-OM (open square); $u$ band by Swift-UVOT (filled circles) and XMM-OM (open square); $V$ band by Swift-UVOT (filled circles), XMM-OM (open square) and CRTS (open pentagons), and $R$ band taken from [Eagen et al. 2013] (filled triangles); $J$ (open squares) and $H$ (filled circles) bands by INAOE; 37 GHz by Metsähovi (filled circles) and 32 GHz by Effelsberg (open squares); 15 GHz by OVRO (filled circles) and Effelsberg (open squares). The flux densities collected from $w_2$ to 15 GHz are reported in units of mJy. In the top panel daily integrated γ-ray fluxes are reported as open circles.

6.4 Medicina

PMN J0948+0022 was observed with the 32 m Medicina radio telescope eight times between 2011 May and October. The new enhanced single-dish control acquisition system, which provides enhanced sensitivity and supports observations with the cross scan technique, was used. Observations were performed at both 5 and 8.4 GHz; the typical on-source time was 1.5 minutes and the flux density was calibrated with respect to 3C 286. Since the signal-to-noise ratio in each scan across the source was low (typically~3), we performed a stacking analysis of the scans, which allowed us to significantly improve the signal-to-noise ratio and the precision of the measurement. The flux densities at 5 and 8.4 GHz are reported in Table 5. The peak of the flux density was observed by Medicina first at 8.4 GHz on 2011 August 1 (MJD 55774), and then at 5 GHz on August 10 (MJD 55783), about 7-8 weeks after the peak observed at 15 GHz by OVRO. Using the Medicina data at 5 GHz and 8.4 GHz together with the nearest OVRO observation spectral indices of $-0.54\pm0.04$, $-0.36\pm0.03$, and $-0.04\pm0.06$ were measured for 2011 June 12, August 1, and August 10, respectively, suggesting a radio spectral evolution in agreement with the behaviour observed by Effelsberg.
Figure 8. Radio spectra of PMN J0948+0022 collected from 2.64 and 32 GHz by Effelsberg in 5 epochs: 2011 May 24 (MJD 55705; empty circles), 2011 June 5 (MJD 55717; empty triangles), 2011 August 6 (MJD 55779; empty squares), 2011 September 17 (MJD 55821; filled circles), and 2011 October 1 (MJD 55835; filled stars).

Table 5. Results of the Medicina radio observations at 5 GHz and 8.4 GHz of PMN J0948+0022.

| Date (UT) | Date (MJD) | $S_{5\text{GHz}}$ (mJy) | $S_{8.4\text{GHz}}$ (mJy) |
|-----------|------------|--------------------------|---------------------------|
| 2011-June-12 | 55724     | 0.37 ± 0.02              | 0.38 ± 0.02               |
| 2011-July-29  | 55771     | 0.35 ± 0.02              | 0.36 ± 0.02               |
| 2011-Aug-01   | 55774     | 0.35 ± 0.02              | 0.45 ± 0.02               |
| 2011-Aug-10   | 55783     | 0.45 ± 0.05              | 0.39 ± 0.05               |
| 2011-Sep-08   | 55812     | 0.35 ± 0.02              | –                         |
| 2011-Sep-22   | 55826     | 0.34 ± 0.02              | –                         |
| 2011-Oct-13   | 55847     | 0.33 ± 0.05              | –                         |
| 2011-Nov-16   | 55881     | 0.25 ± 0.05              | –                         |

6.5 MOJAVE: data analysis and results

We investigated the parsec-scale morphology and flux density variability at 15 GHz by means of 5-epoch VLBA data from the MOJAVE programme (Lister et al. 2009). The data sets span the time interval between 2011 February and December, in order to overlap with the Fermi-LAT data. We imported the calibrated uvs data into the National Radio Astronomy Observatory AIPS package. In addition to the total intensity images, we produced the Stokes Q and U images, to derive information on the polarized emission. The flux density was derived by means of the AIPS task JMFIT which performs a Gaussian fit on the image plane. Total intensity flux density and polarisation information are reported in Table 6. During some observing epochs we detected a hint of the jet emerging from the core component with a position angle of $\sim 30^\circ$ (see Fig. 9 and 10), in agreement with previous works (e.g., Doi et al. 2006; Giroletti et al. 2011). In accordance with the flux density observed by OVRO at 15 GHz, a clear decrease of the flux density was observed by MOJAVE from 657 mJy on 2011 May 26 (MJD 55707) to 378 mJy on 2011 December 12 (MJD 55907). In addition, a higher polarized emission ($S_{\text{pol}}$) and polarisation percentage was observed on May 26 with respect to December 12 (Table 6). On the other hand, the electric vector position angle (EVPA) of the core does not change significantly, ranging between 25$^\circ$ and 67$^\circ$.

Table 6. Flux density and polarisation of PMN J0948+0022 from 15 GHz MOJAVE data.

| Date (UT) | Date (MJD) | $S_{\text{Core}}$ (mJy) | $S_{\text{Jet}}$ (mJy) | $S_{\text{pol}}$ (mJy) | EVPA (deg) |
|-----------|------------|--------------------------|------------------------|-----------------------|------------|
| 2011-02-20| 55612      | 622                      | 3                      | 5 (0.8%)              | 25         |
| 2011-05-26| 55707      | 659                      | 6                      | 13 (2.0%)             | 51         |
| 2011-06-24| 55736      | 665                      | 6                      | 14 (2.1%)             | 49         |
| 2011-09-12| 55816      | 458                      | –                      | 6 (1.3%)              | 44         |
| 2011-12-12| 55907      | 380                      | –                      | 2 (0.5%)              | 67         |

Figure 9. VLBA image at 15.3 GHz of PMN J0948+0022 collected on 2011 May 26. On the image we provide the restoring beam, plotted in the bottom-left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is three times the off-source noise level. Contour levels increase by a factor of 2. The vectors superimposed on the total intensity contours show the percentage polarization and the position angle of the electric vector.
7 DISCUSSION AND CONCLUSIONS

PMN J0948+0022 is the best studied γ-ray NLSy1 (see e.g., Abdo et al. 2009b, Foschini et al. 2012). Simultaneous multiwavelength observations presented here allow a broad-band characterization of this source, including the first XMM-Newton observation of this NLSy1.

7.1 Behaviour of the light curves

In Fig. 10 we compare the γ-ray light curve collected by Fermi-LAT in the 0.1–100 GeV energy range to the X-ray (0.3–10 keV), UV (u′/u filter), optical (V, R, and u filters), NIR (J and H filters), and radio (37 GHz and 15 GHz) light curves collected by Swift, XMM, CRTS, INAOE, Mesehovi, Effelsberg, and OVRO. Strong variability was observed in γ rays, with two flaring periods peaked on 2011 June 20 and July 28 and a variability amplitude (calculated as the ratio of maximum to minimum flux) of ∼10.

Such a variability amplitude as well as the rapid flaring episodes and high apparent isotropic γ-ray luminosity (∼10^{46} erg s^{-1} at the peak) observed in 2011 are typical of FSRQs. During the Swift observations, PMN J0948+0022 was observed in an intermediate X-ray state (0.3–10 keV flux of 3.5–5.9×10^{-12} erg cm^{-2} s^{-1}) between the highest flux observed from this source on 2012 December 30 during a γ-ray flaring activity (12.6×10^{-12} erg cm^{-2} s^{-1}; see D’Ammando & Orienti 2013) and the low flux observed on 2008 December 8 (2.2×10^{-12} erg cm^{-2} s^{-1}; Abdo et al. 2009a). A clear increase of the flux was observed between 2011 June 14 (MJD 55726) and July 2 (MJD 55744), after the γ-ray flare observed by LAT. The flux increase was accompanied by a hardening of the X-ray spectrum. However, the lack of X-ray data during the peaks of the γ-ray activity does not allow us to draw conclusions regarding a contemporaneous increase of the activity in X-ray and γ rays.

The source increased its V-band flux by a factor of ∼3 from 2011 May 15 (MJD 55696) to May 26 (MJD 55707). An increase of flux density between 2011 May 24 and 25 of about 50% in R-band was reported by Eggen et al. (2013), with a significant decrease of a factor of ∼3.5 in two days. These rapid changes are in agreement with the optical intraday variability observed in 2011 March 27–31, with a total amplitude of ∼0.9 mag during ∼4 hours on April 1 (Maune et al. 2013). Similar intraday variability has been reported for this source by Liu et al. (2010); Maune et al. (2011); Paliya et al. (2013) and Itoh et al. (2013), indicating a relativistic jet as the most likely origin for the optical emission in PMN J0948+0022. If this variability is due to the accretion disc, the amplitude variability should be higher during faint states, when the jet activity is lower, and minimised during bright states, as already discussed in Maune et al. (2011). At the time of the optical peak on 2011 May 25 a high optical polarisation percentage (P=12.31%) was observed, with a significant increase with respect to the observation performed in May 24 (P=1.35%) (Eggen et al. 2013). An increase of polarisation percentage from 0.8% on 2011 February 20 to 2.0% on May 26 was also observed in the MOJAVE data (see Section 5.5).

The sparse sampling of the optical and NIR light curves does not allow us to make a detailed comparison with the γ-ray and radio light curves. However, it is worth noting that an increase of flux density was also observed in NIR in 2011 mid-May (about MJD 55700), with no counterpart in γ rays. In fact, PMN J0948+0022 was quite active in H-band on 2011 April 26 (MJD 55677), and after a decrease in the following 3 weeks, we observed on 2011 May 22 (MJD 55703) a significant increase by a factor of ∼4.5 in 24 hours. A similar behaviour seems to be observed in J-band, with an increase by a factor of ∼2.5 on May 22 (MJD 55703). On the other hand, no significant variability was observed in UV during the Swift-UVOT observations, probably due to the accretion disc emission that dilutes the variability in that part of the spectrum.

During the OVRO monitoring the flux density at 15 GHz changed more smoothly than at higher energies, with an amplitude variability of ∼2 between 670 mJy (2011 June 13; MJD 55725) and 335 mJy (2011 October 2; MJD 55836) and a gradual decrease. A flaring activity seems to start before the first γ-ray flare, with a peak at about MJD 55700, close to the optical and NIR flare, and a monotonic decreasing trend in the following months at 15 and 37 GHz. In the same way the radio spectra collected by Effelsberg, Medicina, and OVRO showed a significant spectral evolution with a high frequency component dominating the emission in 2011 May. A similar spectral evolution was already reported in Angelakis et al. (2013) for PMN J0948+0022 and
other $\gamma$-ray emitting NLSy1s with variability patterns typical of relativistic jets and thus similar to blazars.

The different behaviour observed in the radio-to-optical and the $\gamma$-ray energy bands could be related to a bending and inhomogeneous jet, as proposed for some blazars (e.g., [Raiteri et al. 2010, 2011]), with a variable misalignment between the zone responsible for the radio-to-optical emission and the zone responsible for $\gamma$ rays. The change of the viewing angle of the different emitting regions may produce a change of the Doppler factor, with the Doppler boosting of the radio-to-optical emission increasing first, followed by an increase of the Doppler boosting of the $\gamma$-ray emission. This complex behaviour also could be in agreement with the turbulent extreme multi-cells scenario proposed by Marscher (2012). Alternatively, the radio activity could be related to the $\gamma$-ray flaring activity observed in 2010 July–August, but the large delay of about 1 year makes this hypothesis unlikely. The sparse and irregular sampling, especially from NIR to X-rays, does not allow us to test the different scenarios.

7.2 Energetics

The high apparent isotropic $\gamma$-ray luminosity observed for PMN J0948+0022 in 2011 May–September ($\sim 1.8 \times 10^{47}$ erg s$^{-1}$) should reflect a small viewing angle with respect to the jet axis and thus high beaming factors, similarly to what is observed for the FSRQs and also for the NLSy1 SBS 0846+0513 (D’Ammando et al. 2012a, 2013b). This is consistent with the viewing angle of 3° used for modeling the SEDs of this source in Roschini et al. (2011, 2012). On the contrary, most of the radio galaxies detected by the LAT have an apparent isotropic $\gamma$-ray luminosity lower than $10^{46}$ erg s$^{-1}$, suggesting a smaller beaming factor and possibly a different structure of the jet (Abdo et al. 2010). Assuming a BH mass of $10^8 M_\odot$ (but see Section 7.3) we obtain an Eddington luminosity of $1.3 \times 10^{46}$ erg s$^{-1}$. During the 2011 June flare PMN J0948+0022 reached an apparent isotropic $\gamma$-ray luminosity of $L_\gamma = 8.8 \times 10^{47}$ erg s$^{-1}$, making the radiative power $L_{\text{rad}} = L_\gamma / \Gamma^2 = 3.5 \times 10^{45}$ erg s$^{-1}$, assuming a quite typical value for this source of $\Gamma = 16$ (Roschini et al. 2011, 2012). This is about 25% of the Eddington luminosity, comparable to the values observed for bright FSRQs detected by LAT (see e.g., Nemmen et al. 2012).

7.3 X-ray spectrum

Thanks to the first high quality XMM-Newton observation of PMN J0948+0022, we are able to study in detail its X-ray spectrum (see Section 1.2). The spectral modelling of the XMM data of PMN J0948+0022 showed that emission from the jet most likely dominates the spectrum above $\sim 2$ keV, while the emission from the underlying Seyfert galaxy can be seen at lower energies. Interestingly, the observation of such a component, typical in the X-ray spectra of radio-quiet NLSy1s, is quite unusual in jet-dominated AGNs, even if not unique (e.g., the FSRQ PKS 1510–089; Kataoka et al. 2008). Contrary to what is observed in some blazars (e.g., BL Lacertae; Raiteri et al. 2010), no excess absorption above the Galactic column density was necessary by the fit for modelling the low-energy part of the spectrum (Grupe et al. 2014). As well as for PKS 1510–089, we hypothesize that the emission below 2 keV was mainly due to the soft X-ray excess. However, we cannot distinguish between different models for the soft X-ray emission on a statistical basis. Models where the soft emission is partly produced by blurred reflection, or Comptonisation of the thermal disc emission, or simply a steep power law, all provide good fits to the data. Our reflection model differs substantially from that presented by Bhattacharyya et al. (2013). While we confirm that their model is a good fit to the spectrum, we note that it relies on a high inclination angle of $i = 74^\circ$, which is inconsistent with the blazar-like properties of the source, as well as the inclusion of a warm absorber, which is not required in any of the other models. Furthermore, their model does not allow the power law, which illuminates the disc, to also contribute directly to the spectrum.

A blackbody model also gives a comparable fit, but a temperature of $kT = 0.18$ keV is necessary. Such a high temperature is inconsistent with the standard accretion disc theory (see e.g., Shakura & Sunyaev 1973). Further long-duration X-ray observations with XMM-Newton, Suzaku and NuSTAR, preferably when the source is in a low $\gamma$-ray state, will be needed to place stronger constraints on these models.

Our interpretation that the X-ray emission above $2$ keV is produced by the jet is also supported by the RMS spectrum (Fig. 5), which shows a break at 1.7 keV, above which the variability increases with energy. While Seyfert galaxies typically exhibit RMS spectra decreasing with energy above $\sim 1 - 2$ keV (Markowitz et al. 2004; Ponti et al. 2007; Chitnis et al. 2001), the opposite behaviour is often observed in blazars (e.g., Ravasio et al. 2004; Gliozzi et al. 2006). It should be noted, however, that there is no one-to-one correlation between the RMS spectrum and AGN type and that RMS spectra often change substantially with time (as seen in e.g., Gliozzi et al. 2006; Larsson et al. 2008).

The spectrum of PMN J0948+0022 changed from a steep slope of $\Gamma \sim 2.1$ to a much harder one of $\Gamma \sim 1.5$ above 1.7 keV. A similar spectrum has also been observed in the XMM observation of the $\gamma$-ray NLSy1 PKS 2004–447 (Gallo et al. 2006). An X-ray spectrum unusually hard for a NLSy1 was observed by Swift-XRT in SBS 0846+513 (D’Ammando et al. 2012a, 2013b) and PKS 1502+036 (D’Ammando et al. 2013c), two other NLSy1s detected by LAT. Models more complex than the simple power law were not applicable in these cases due to insufficient statistics, in particular below 1–2 keV. Thus the 0.3–10 keV spectra collected by Swift-XRT seem to be dominated by the jet emission.

The small variability amplitude ($\sim 2$) observed in X-rays with respect to the $\gamma$ rays ($\sim 10$) could be an indication that the X-ray emission is produced by the low-energy tail of the same electron distribution. On the other hand, the peak flux in X-rays was observed on 2011 July 2 during a period of low $\gamma$-ray activity, suggesting that different mechanisms could be at work in the X-ray and $\gamma$-ray bands (e.g., synchrotron self-Compton and external Compton, respectively). The presence of the soft X-ray excess below 2 keV could dilute the X-ray variability over the 0.3–10 keV energy range, but an amplitude variability of a factor of $\sim 2$ (with fluxes between $2.1 - 4.1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) was also observed considering only the 2–10 keV energy range. In this context no obvious relation exists between the soft X-ray
excess and the $\gamma$-ray emission. An intriguing possibility is
that the excess observed below 2 keV is a signature of the
bulk Comptonisation process by a cold relativistic plasma
accelerating along the jet and scattering on disc photons
reprocessed by the broad-line region (BLR) (Celotti et al.
2007). A dedicated modeling of the source’s SED including
XM-M-Newton and Fermi-LAT data will be presented in a
forthcoming paper.

### 7.4 Host galaxy

The discovery of a relativistic jet in a class of AGN thought
to be hosted in spiral galaxies such as the NLSy1s, as op-
posed to blazars and radio galaxies hosted in elliptical galax-
ies (Blandford & Rees 1978), was a great surprise challeng-
ing the current knowledge on how the jet structures are gen-
erated and developed (see e.g., Böttcher & Dermer 2002;
Marscher 2010). Unfortunately only very sparse observa-
tions of the host galaxies of radio-loud NLSy1s are available
and the sample of objects studied by Deo et al. (2006) and
Zhou et al. (2006) have redshifts $z < 0.03$ and $z < 0.1$, re-
spectively, while four out five of the NLSy1s detected in $\gamma$
rays have $z > 0.2$. Among the radio-loud NLSy1s detected
up to now by LAT only for the closest one, 1H 0323+342,
was the host galaxy clearly detected. Observations with the
Hubble Space Telescope and Nordic Optical Telescope re-
vealed a one-armed galaxy morphology or a circumnuclear
ring, respectively, suggesting two possibilities: the spiral arm
of the host galaxy (Zhou et al. 2007) or the residual of a
galaxy merger (Anton et al. 2008). These observations, to-
gether with the lack of information about the host galaxy of
the other $\gamma$-ray emitting NLSy1s, leaves room for the hy-
pothesis that the NLSy1s detected in $\gamma$ rays by LAT could
have peculiar host galaxies with respect to the other NLSy1s.
Therefore the possibility that the development of relativis-
tic jets in these objects occurs in hosts undergoing strong
merger activity, or with non-spiral morphology, cannot be
ruled out. Further high-resolution observations of the host
galaxies of PMN J0948+0022 and the other $\gamma$-ray NLSy1s
will be fundamental to obtain insights into the onset of pro-
duction of relativistic jets in these sources.

### 7.5 BH mass and jet formation

The mechanism for producing a relativistic jet is still un-
clear. In particular the physical parameters that drive the jet
formation are still under debate. One of the key parameters
should be the BH mass, with only large masses allowing an
efficient jet formation (see e.g., Sikora et al. 2007). Therefore
one of the most surprising facts related to the discovery of
PMN J0948+0022 was the development of a relativistic jet
in an object with a relatively small BH mass, $3.2 \times 10^6 \, M_\odot$
(Yuan et al. 2008). Recently, Chiaberge & Marconi (2011)
suggested that a BH mass higher than $10^8 \, M_\odot$ is necessary
for producing a radio-loud AGN and that the merger his-
tory together with the subsequent galaxy morphology plays
a fundamental role. In any case, the estimated mass of this
source, as well as for the other NLSy1s, has large uncertain-
ties. By means of the broad band SED modeling a BH mass
of $1.5 \times 10^8 \, M_\odot$ was estimated for PMN J0948+0022 in
Foschini et al. (2011). Marconi et al. (2008) suggested that
BH clouds are subjected to radiation pressure from the ab-
sorption of ionizing photons, and by applying a correction
to the virial relation we have higher masses for the NLSy1s.
Recently, also Calderone et al. (2013) pointed out that the
BH masses of the NLSy1s estimated by the modelling of
optical/UV data with a Shakura & Sunyaev disc spectrum
could be significantly higher than those derived on the ba-
sis of single epoch virial methods. In particular, for PMN
J0948+0022 they found a value of $10^9 \, M_\odot$ in agreement with
the typical BH mass of blazars. This may solve the problem
of the minimum BH mass predicted in different scenarios of
relativistic jet formation and development, but introduces
a possible new one. For spiral galaxies, the BH mass typi-
cally ranges between $10^6$ and $10^8 \, M_\odot$ (see e.g., Woo & Urry
2002). If the BH mass is on the larger side of the estimated
values, how is it possible to reconcile such a large BH mass
with a spiral galaxy?

A second fundamental parameter for the efficiency of
relativistic jet production should be the BH spin, with
super-massive black holes (SMBH) in elliptical galaxies hav-
ing on average much larger spins than SMBHs in disc-
spiral galaxies, as proposed in the “modified spin paradigm”
(Sikora et al. 2007). This is because the spin evolution of
BHs in spiral galaxies seems to be limited by multiple ac-
cretion events with random orientation of the angular mo-
mentum vectors and small increments of mass, while ellipti-
gical galaxies underwent at least one major merger with
large matter accretion triggering an efficient spin-up of the
SMBHs. Thus, the mass and the spin of the BH seem to
be related to the host galaxies, leading to the hypothesis
that relativistic jets can efficiently develop only in elliptical
galaxy (e.g. Böttcher & Dermer 2002; Marscher 2010). How-
ever, the presence of a rapidly spinning BH was inferred by
means of X-ray reflection spectroscopy in a few radio-quiet
AGNs hosted by spiral/disc galaxies, suggesting that the
BH spin is not the only parameter that drives the radio-
quiet/radio-loud dichotomy (see e.g., Reynolds 2013).

We noted that BH masses of radio-loud NLSy1s re-
ported in Komossa et al. (2006) and Yuan et al. (2008) are
generally larger than those in the entire sample of NLSy1s
($M_{BH} \approx (2-10) \times 10^7 \, M_\odot$), even if still smaller than those
in radio-loud quasars. The larger BH masses of radio-loud
NLSy1s could be related to higher mass accretion events that
can spin up the BHs. In the same way the smaller fraction
of radio-loud NLSy1s with respect to the radio-loud quasars
could be because the high accretion rate regime does not
last sufficiently long in all NLSy1s to substantially spin up
the central BH (Sikora 2009).

Another consideration which is likely to be important
for jet formation is the nature of the accretion flow. In
particular, a geometrically thick accretion flow is needed
in order to create large-scale poloidal magnetic fields,
which may play a dominant role in the launching of jets
(Reynolds et al. 2006; Sikora et al. 2013). In cases where
standard thin discs are present, the jet activity may be due
to the dissipation of coronal magnetic fields (Sikora et al.
2013). For PMN J0948+0022 it is clear that emission from
the jet dominates the X-ray spectrum above 2 keV,
while we are likely seeing the accretion disc plus corona
of the AGN at lower X-ray energies. Although we cannot
constrain detailed models for the soft X-ray emission with
the current observations, we note that the spectral slope
is similar to that found in radio-quiet NLSy1, indicating that a standard disc is present as also expected from the high accretion rate. Future deep X-ray observations with the jet in different states are needed to explore in detail the connection between the disc and jet in this source.

The presence of a relativistic jet in some radio-loud NLSy1 galaxies, first suggested by their variable radio emission and flat spectra, is now confirmed by the Fermi-LAT detection of five NLSy1s in γ rays. PMN J0948+0022 showed all characteristics of the blazar phenomenon with a BH mass of $10^8$–$10^9 M_\odot$, not much less than those of blazars. The impact on the γ-ray emission mechanisms of the properties of the central engine in radio-loud NLSy1s, derived from their peculiar optical characteristics, is still under debate. In addition, the detection of relativistic jets in a class of AGN thought to be hosted in spiral galaxies is very intriguing, challenging the theoretical scenario of relativistic jet formation proposed so far. Further multifrequency observations of this object and other γ-ray emitting NLSy1s will be fundamental for investigating in detail their characteristics over the entire electromagnetic spectrum.

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