Multiple-wavelength Variability and Quasi-periodic Oscillation of PMN J0948+0022

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Abstract

We present a comprehensive analysis of multiple-wavelength observational data of the first GeV-selected narrow-line Seyfert 1 galaxy PMN J0948+0022. We derive its light curves in the γ-ray and X-ray bands from the data observed with Fermi/LAT and Swift/XRT, and generate the optical and radio light curves by collecting the data from the literature. These light curves show significant flux variations. With the LAT data we show that this source is analogous to typical flat spectrum radio quasars in the L_{γ}−Γ_{γ} plane, where L_{γ} and Γ_{γ} are the luminosity and spectral index in the LAT energy band. The γ-ray flux is correlated with the V-band flux with a lag of ∼44 days, and a moderate quasi-periodic oscillation (QPO) with a periodicity of ∼490 days observed in the LAT light curve. A similar QPO signature is also found in the V-band light curve. The γ-ray flux is not correlated with the radio flux in 15 GHz, and no similar QPO signature is found at a confidence level of 95%. Possible mechanisms of the QPO are discussed. We propose that gravitational-wave observations in the future may clarify the current plausible models for the QPO.

Key words: galaxies: individual (PMN J0948+0022) – galaxies: jets – galaxies: Seyfert – gamma rays: galaxies

1. Introduction

PMN J0948+0022 (redshift z = 0.584; Zhou et al. 2003) is the first γ-ray source detected with Fermi/LAT (Large Area Telescope; Abdo et al. 2009a) among narrow-line Seyfert 1 galaxies (NLS1s). Seven NLS1s have been detected with Fermi/LAT so far (Abdo et al. 2009b; D’Ammando et al. 2012, 2015; Yao et al. 2015), and PMN J0948+0022 is still the brightest one in the GeV band among these GeV-selected NLS1s. Both the radio power and radio loudness of this source are analogous to the classical radio quasars, i.e., P_{rad} > 10^{25} W Hz^{-1} and R_{RL} > 1000 (Zhou et al. 2003). It displays blazar characteristics and may also host a relativistic jet (Zhou et al. 2003; Yuan et al. 2008). This was confirmed with the Fermi/LAT observations. Its broadband spectral energy distributions observed in different campaigns can be well explained by the one-zone leptonic models (Abdo et al. 2009a; Foschini et al. 2012; Zhang et al. 2013), and the derived jet properties are consistent with flat spectrum radio quasars (FSRQs, e.g., Sun et al. 2015).

Significant flux variations were observed with Fermi/LAT in PMN J0948+0022 (e.g., Foschini et al. 2012; Sun et al. 2014, 2015), and were similar to the characteristics observed in blazars. It is also interesting that the flux variations of some blazars also show the phenomenon of quasi-periodic oscillation (QPO), such as the 12 year QPO in OJ 287 (e.g., Sillanpaa et al. 1988, 1996), the 1884 ± 88 day QPO in PG 1302–102 (Graham et al. 2015), the 630 ∼ 640 day QPO in PKS 2155–304 (Sandrinelli et al. 2014; Zhang et al. 2017b), the 2.18 ± 0.08 year QPO in PG 1553+113 (Ackermann et al. 2015), etc. By studying the variability of six blazars in the optical–near-infrared and γ-ray bands, Sandrinelli et al. (2016) also suggested that a year-like QPO may be often observed in blazars.

This paper presents a comprehensive analysis of multiple-wavelength observational data of PMN J0948+0022. It is known that the flux variation of blazars is usually accompanied by variation of the spectral index (e.g., Cui 2004; Massaro et al. 2008; Tramacere et al. 2009; Nalewajko 2013). We focus on revealing its flux variations in multiple wavelengths and spectral variation features. We try to find out the possible QPO signature from the long-term observation data in the γ-ray, optical, and radio bands. As described in Section 2, we derive its light curves in the γ-ray and X-ray bands from the data observed with Fermi/LAT and Swift/XRT, and generate the optical and radio light curves by collecting the data from the literature. The cross-correlation analysis of variability among multiple-wavelength light curves is given in Section 3. With the well-sampled observation data of Fermi/LAT, we investigate the flux variation and spectral evolution in the GeV band in Section 4. The search for the possible QPO signature in multiple-wavelength light curves is presented in Section 5. A discussion is given in Section 6 and conclusions are reported in Section 7.

2. Data Reduction

2.1. Fermi/LAT Data Analysis

The Pass 8 Fermi/LAT data of PMN J0948+0022 with a temporal coverage from 2008 August 5 (Modified Julian Day, MJD 54683) to 2016 December 31 (MJD 57753) were downloaded from the Fermi Science Support Center (http://fermi.gsfc.nasa.gov/ssc). The data analysis was performed using the standard ScienceTools v10r0p5 software package. Events from 100 MeV to 100 GeV within a circular region of interest of 10° radius centered on the location of PMN J0948+0022 (R.A. = 147.238837, dec. = 0.373767) were selected with P8R2_SOURCE_V6 instrument response functions. We used the standard unbinned maximum-likelihood fit technique.
and a power-law (PL) spectral model to analyze each time bin. The integrated flux and photon spectral index of the PL were taken as free parameters during the fitting. In order to eliminate the contamination from the $\gamma$-ray-bright Earth limb, the events with zenith angles $>100^\circ$ were excluded. The recently released files gll_iem_v06 and iso_P8R2_SOURCE_V6_v06 were used to model the Galactic and isotropic diffuse emission. The significance of the $\gamma$-ray signal from the source was evaluated with the maximum-likelihood test statistic (TS). The LAT light curve with TS $> 5$ in time bins of 10 days is shown in panel (a) of Figure 1.

### 2.2. Swift/XRT Data Analysis

PMN J0948+0022 was observed on 2008 December 5 with the X-Ray Telescope (XRT) on board the Swift satellite, soon after the detection of the $\gamma$-ray emission from this source (Abdo et al. 2009a). During the multi-wavelength monitoring campaigns in 2009, there were 11 observation snapshots (Abdo et al. 2009c). An exposure of 1615 s was carried on 2010 July 3 (Foschini et al. 2012). Ten more exposures were performed in 2011, as part of a monitoring program linked to the Effelsberg radio observations (Foschini et al. 2012). There were 15 observation snapshots in 2012, and 3 exposures were performed in 2013 and in 2016, respectively. In total, there are 44 observation snapshots of Swift/XRT, with each exposure time of 1–5 ks, from 2008 to 2016. We downloaded the XRT data from http://www.swift.ac.uk/archive/. We used the Swift software (HEASoft v.6.17 package and the CALDB version updated on 2016 June 9) to deduce the XRT data of PMN J0948+0022. The spectra in the XRT band (0.3–10 keV) are fitted with a single PL model and the Galactic absorption corresponding to a hydrogen column density is fixed at $N_H = 5.22 \times 10^{22} \text{ cm}^{-2}$ (Kalberla et al. 2005). The derived XRT light curve is shown in the panel (b) of Figure 1.

### 2.3. Radio and Optical Data

We collect the V-band and 15 GHz radio data from the literature and show them in panels (c) and (d) of Figure 1. The V-band data, which cover $\sim$3000 days (from 2005 April 4 to 2013 May 14; MJD 53464–56426), are taken from the Catalina Real-Time Transient Survey (CRTS; http://crts.caltech.edu/; Drake et al. 2009; Mahabal et al. 2011), which is an unfiltered optical survey for transients. The 15 GHz data are obtained from the continuum observations with the 40 m Owens Valley Radio Observatory (OVRO; http://wwwastro.caltech.edu/ovrobazars/data/data.php) radio telescope. OVRO instrumentation, data calibration, and reduction are described in Richards et al. (2011). The OVRO supports the ongoing blazar monitoring program of the Fermi satellite, hence the light curve in 15 GHz almost covers the same observation period of Fermi/LAT.

### 3. Cross-correlations among Multiple-wavelength Light Curves

As shown in Figure 1, PMN J0948+0022 shows significant flux variation at multiple wavelengths. It is very active without showing any quiescent stage during the data coverage from MJD 53500 to MJD 57500. We first analyze the cross-correlations of the $\gamma$-ray flux to optical and radio fluxes with the data observed in the same temporal coverage. Due to the poor sampling, we do not make correlation analysis for the X-ray data. Our analysis results with a discrete cross-correlation function (DCF, Edelson & Krolik 1988) are presented in Figure 2. One can observe that the $\gamma$-ray flux is correlated with the optical flux with a lag of $\sim$44 days, and the correlation coefficient is 0.78. The correlation of variability between the $\gamma$-ray and optical bands for blazars has been widely reported (e.g., Ghisellini & Tavecchio 2009; Arlen et al. 2013; Jorstad et al. 2013).

The DCFs for the $\gamma$-ray and radio data show many peaks, but no statistical correlation can be claimed for the $\gamma$-ray and radio data. It is possible that the radio emission is radiated by an electron population different from that for the $\gamma$-ray and optical emission, since the radio emission at 15 GHz of the $\gamma$-ray-emitting region would not be detected, due to the synchrotron-self-absorption effect.

### 4. Flux and Spectral Variations in the GeV Energy Band

The flux variation is generally accompanied by the spectral index variation for blazars. In this section we analyze the correlation between the $\gamma$-ray luminosity ($L_\gamma$) and the photon spectral index ($\Gamma_\gamma$) using the observation data of Fermi/LAT for PMN J0948+0022, where $L_\gamma$ and $\Gamma_\gamma$ are derived with time bins of 10 days. Figure 3 illustrates the variation of PMN J0948+0022 in the $L_\gamma$–$\Gamma_\gamma$ plane. In order to compare PMN J0948+0022 with blazars, we also show the Fermi blazars in the $L_\gamma$–$\Gamma_\gamma$ plane. The blazar data, which are the average values of the first four years of science data from the Fermi/LAT, are taken from Ackermann et al. (2015); see also their Figure 14). These blazars belong to the clean sample with confirmed redshift, including 414 FSRQs, 162 high-frequency-peaked BL Lacs, 69 intermediate-frequency-peaked BL Lacs, and 68 low-frequency-peaked BL Lacs. The $\gamma$-ray luminosity of PMN J0948+0022 varies from $2.5 \times 10^{46} \text{ erg s}^{-1}$ to $4.2 \times 10^{47} \text{ erg s}^{-1}$, and $\Gamma_\gamma$ varies from $-4.26 \pm 1.03$ to $-1.85 \pm 0.54$ with a mean of $-2.65$ (see also Paliya et al. 2015). Our results
We analyze the correlation between $L_\gamma$ and $\Gamma_\gamma$, but do not find any statistical correlation for the global LAT data with the Pearson correlation analysis method. By dividing the global LAT light curve into seven episodes, we show the temporal evolution of $\Gamma_\gamma$ and $\Gamma_\gamma$, as a function of $L_\gamma$ in Figure 4. Except forepisode (4), we do not find a statistical correlation between $L_\gamma$ and $\Gamma_\gamma$, with a correlation coefficient of $r > 0.5$ in a chance probability of $p < 10^{-4}$ for other episodes. For episode (4), the Pearson correlation analysis yields $r = 0.534$ and $p = 3.27 \times 10^{-4}$, indicating a tentative correlation between $L_\gamma$ and $\Gamma_\gamma$. Note that the above analysis is based on the data in time bins of 10 days. The source experienced some extreme outbursts with timescales smaller than 10 days. Therefore, we also re-analyze the outbursts that have a peak luminosity $L_\gamma > 2.6 \times 10^{42}$ erg s$^{-1}$ in Figure 1(a) using a time bin of 1 day. Three outbursts (MJD [55381, 55402], MJD [56083, 56089], and MJD [56283, 56297]) are included in our analysis, and their 1-day binned light curves and evolution of $\Gamma_\gamma$ and $\Gamma_\gamma$ as a function of $L_\gamma$ are presented in Figure 5. A tentative correlation between $L_\gamma$ and $\Gamma_\gamma$ is found in flare (a) with $r = 0.79$ and $p \sim 0.001$, and a trend of anticorrelation is presented in flare (b) with $r = -0.92$ and $p \sim 0.01$, but no dependence of $\Gamma_\gamma$ on $L_\gamma$ is observed in flare (c). Our above results suggest that the spectral variation is not correlated with the $\gamma$-ray flux in the GeV band, similar to some flaring blazars (Nalewajko 2013).

5. Searching for Possible QPO Signatures

To reveal the flux variation feature we analyze the power density spectrum (PDS) of the $\gamma$-ray, V-band, and radio light curves with the Lomb–Scargle Periodogram (LSP) algorithm (Lomb 1976; Scargle 1982). The LSP code is taken from Press et al. (1986). As suggested in Sandrinelli et al. (2017), we also use a PL and an auto-regression function of the first-order (AR1) to fit the noise, respectively. The two models have been widely considered in the literature (e.g., Konig & Timmer 1997; Kelly et al. 2009; Edelson et al. 2013). The procedure of searching for possible periodic signals using Bayesian statistics that is described in Vaughan (2005, 2010) and Sandrinelli et al. (2017) is used to fit the PDS. Considering the large fluctuations in PDS, the PDS is re-binned in log scale, as presented in Figure 6. The re-binned PDS is used to search for possible periodic signals. We only consider the 50–1000 day interval during model-fitting in order to avoid the very noisy high-frequency part of the PDS and the limit of the light curve length. Our analysis results are shown in Figure 6. The following discussion is on the basis of the PL model-fitting.

Interestingly, the LSPs of the $\gamma$-ray light curves show a peak at $493^{+71}_{-26}$ days at a 99% confidence level and $499^{+10}_{-32}$ days at a
95% confidence level for time bins of 10 days and 5 days, respectively, where the errors are derived with the confidence level lines. A similar QPO signature is also observed in the LSP of the V-band light curve, i.e., $443^{+12}_{-13}$ days at a 99% confidence level. As illustrated in Figure 6, the AR1 model-fitting yields similar results to the PL model. In the radio 15 GHz, no similar QPO signature to those of the $\gamma$-ray and optical bands is observed at a 95% confidence level with both models.

We also evaluate the global significance of any peak in the PDS (see Vaughan 2010 and Sandrinelli et al. 2017 for a deeper discussion), and the global 95% false-alarm levels are also presented in Figure 6. In this case, the QPO signature at $\sim$490 days in the $\gamma$-ray band and $\sim$440 days in the V-band would not be singled out at a 95% confidence level. However, as suggested in Sandrinelli et al. (2017), the modest significance peak at approximately the same frequency in different energy bands was still the most interesting feature of the sources. And the analysis results of the DCF between the $\gamma$-ray flux with the optical and radio fluxes described in Section 3 also strengthen the possible QPO signatures in the $\gamma$-ray and optical bands.

Figure 4. Temporal variations of luminosity ($L_\gamma$, black squares) and photon spectral index ($\Gamma_\gamma$, red circles) with time bins of 10 days, as well as $L_\gamma$ vs. $\Gamma_\gamma$ for the seven episodes.
6. Discussion

The QPO signature is physically interesting. As mentioned in Section 1, similar QPO signals are found in some blazars, and their physical mechanisms are under debate. A supermassive black hole binary (SMBHB) system may lead to a QPO signal since its Keplerian binary orbital motion would induce periodic accretion perturbations (e.g., Sillanpaa et al. 1988; Lehto & Valtonen 1996; Graham et al. 2015). The periodic accretion perturbations of a disk should also result in periodic oscillations of jet radiation. In this scenario, the periodicity of the system can be estimated with Kepler’s law, \( P = 4\pi^2 a^3/G(m + M) \), where \( a \) is the separation of the two black holes, \( M \) and \( m \) are the masses of the two black holes, and \( G \) is the Gravitational constant. The intrinsic orbital period of PMN J0948+0022 is given by \( 490/(1 + z) = 309 \) days. The SMBH total mass in PMN J0948+0022, estimated with the Mg \( \mu\lambda2798 \) and monochrome luminosity at 3000 Å (Zhou et al. 2003), is \( \sim 8.1 \times 10^8 M_\odot \). Assuming \( (m + M) \sim 8.1 \times 10^8 M_\odot \), we have \( a = 1.24 \times 10^{10} \) cm (\( \sim 0.004 \) pc), which is similar to the derived distance in PKS 1510–089 (Xie et al. 2002) and PG 1553+113 (\( \sim 0.005 \) pc, Ackermann et al. 2015). Such a system would be sufficiently bound and its orbit would be shrunk by gravitational radiation. The merger timescale can be estimated with \( t_m \sim 3 \times 10^4 (m/M) M_\odot^{-3} a_\odot^{-1} \) yr, where notation \( Q_a = Q/10^6 \) is used in cgs units (Begelman et al. 1980). Thus, the merger timescale of the system would be \( \sim 1.33 \times 10^3 (m/M)^{-1} \) yr. These kinds of systems should be potential objects for future gravitational-wave detectors.

In an SMBHB system with closer distances, the profile of the single-peaked spectral lines should be asymmetric, since the tightly bound black holes dynamically affect the broad-line region clouds as a single complex entity (Graham et al. 2015). We check whether the broad lines of PMN J0948+0022 show a similar feature. PMN J0948+0022 was spectroscopically observed in the Sloan Digital Sky Survey (SDSS). After correcting for the Galactic extinction and transforming into the source rest-frame, we re-analyze its SDSS spectrum following the same approach adopted in Yao et al. (2015). As shown in Figure 7, the asymmetric profiles of emission lines are not seen in PMN J0948+0022. This may give rise to an issue that explains the QPO as a signature of an SMBHB system.

Alternative models were also proposed to interpret the QPO signal in blazars, such as the precession of jets (e.g., Stirling et al. 2003; Caproni et al. 2013) and the helical structure of jets (e.g., Conway & Murphy 1993; Villata & Raiteri 1999; Nakamura & Meier 2004; Mohan & Mangalam 2015). In an SMBHB system, misalignment between the accretion disk and the orbital plane of the secondary black hole could produce the torques that induce the precession of its jets. This mechanism is also used to explain the parsec-scale jet precession observed with the very-long-baseline interferometry technique (e.g., Caproni et al. 2013). In a single-BH system, jet precession could also be produced by misalignment of the rotation axes between accretion disks and a Kerr black hole (Caproni et al. 2004). Similarly, helical jets or helical structures in jets can also be ascribed to an SMBHB system (e.g., Villata & Raiteri 1999), or the hydrodynamical instabilities in magnetized jets (Hardee & Rosen 1999). Due to the variation of the viewing angle to the jet axis, a QPO signature could be found for radiation from precessing jets or helical jets. We should point out that if the viewing angle effect, i.e., the change in the Doppler-boosting factor, is responsible for the QPO signature, the observed spectrum would be harder to detect when the source is brighter (Liu et al. 2010). However, we do not find such a feature in the GeV band.

So far, there are several blazars that have been suggested to have a year-like QPO (e.g., Sandrinelli et al. 2014, 2016; Ackermann et al. 2015; Zhang et al. 2017a, 2017b), however, the relative abundance of detected QPOs in quasars is lower.

Figure 5. Temporal variations of luminosity (\( L_\gamma \), black squares) and photon spectral index (\( \Gamma_\gamma \), red circles) with time bins of 1 day, as well as \( L_\gamma \) vs. \( \Gamma_\gamma \) for the three flares (MJD [55381, 55402], MJD [56083, 56089], and MJD [56283, 56297]).
The solid and dashed lines indicate the PL and AR1 models, respectively. Single-frequency 95% and 99% confidence level lines are reported by blue and magenta lines, and the global 95% false-alarm levels of the PL model are shown as orange lines. The green dashed line and black solid line represent the best-fit Gaussian profile for their narrow components (blue lines), respectively. The green dashed line and black solid line are fitted with a single Lorentzian profile for their broad components (red lines) and a single Gaussian profile for their narrow components (blue lines), respectively. The solid and dashed lines indicate the PL and AR1 models, respectively.

As discussed above, the mechanism that causes the QPO in PMN J0948+0022 is uncertain with the current observational data. Hence, long-term monitoring observations, especially at multiple wavelengths, that prove or disprove the periodicity (see also Sandrinelli et al. 2017), or that prove or disprove the detection of gravitational waves, would be a robust probe for clarifying these models.

7. Conclusions

We dealt with and analyzed the eight-year observation data of Fermi/LAT and all the observation data of Swift/XRT for the first confirmed GeV-NLS1, PMN J0948+0022, and also collected its long-term observation data in the optical V-band and radio 15 GHz from the literature. It was found that this source shows significant flux variations at multiple wavelengths. This demonstrates similar characteristics to typical FSRQs, but does not show a dependence of the spectral index variation on the flux variation in the GeV band. A QPO of $\sim$490 days at a 99% confidence level in the $\gamma$-ray light curve is found for PMN J0948+0022. A similar QPO signature is also observed in the optical V-band, i.e., $\sim$440 days at a 99% confidence level. The observed correlation between $\gamma$-ray and optical fluxes further strengthens the QPO behavior in PMN J0948+0022. No similar QPO signature is observed in the 15 GHz light curve, and no statistical correlation of variability between $\gamma$-rays and 15 GHz is found. We discussed the possible mechanisms that may produce the QPO. A tightly bound SMBMB system could lead to the QPO, but we did not find any asymmetric profile feature of emission lines in PMN J0948+0022, which would be expected from such a system. The observations of a year-like QPO in jet-dominant sources may more potentially be due to jet instabilities or jet structures. Future long-term monitoring observations at multiple wavelengths, or gravitational-wave observations, may clarify these plausible models.

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