THE VARIABLE OPTICAL POLARIZATION AND FERMI OBSERVATIONS OF PMN J0948+0022

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ABSTRACT

We report on observations of the γ-ray and optical photopolarimetric behavior of the radio-loud, narrow-line type-1 Seyfert galaxy PMN J0948+0022 over a 27 month period. As this object has recently been suggested to represent a prototype of an emerging class of blazar-like objects, the observed properties are compared to those of blazars. We extract doubling timescales of roughly 4 hr for the optical and γ-ray bands. The rapid microvariability in the optical/near-IR, significant and variable optical polarization, and strong yet rapidly variable γ-ray emission we observe for PMN J0948+0022 are all classical observational characteristics associated with blazars. However, since these observations do not show a clear correlation between the γ-ray and optical behavior, they do not offer conclusive proof that the emissive behavior of PMN J0948+0022 is due to a relativistic jet oriented close to our line of sight.

Key words: galaxies: active – galaxies: individual (PMN J0948+0022) – galaxies: photometry – galaxies: Seyfert – polarization

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Recently, several members of a sub-class of active galactic nuclei (AGNs) have been observed with properties that would have previously been divided among Seyfert galaxies, broad-line radio galaxies, and blazars. These objects, the radio-loud narrow-line type-1 Seyferts (RL NLS1), possess the standard identifying properties of narrow-line Seyfert-1 (NLS1; Osterbrock & Pogge 1985; Kellermann et al. 1989); strong optical emission of Fe II, weak emission from forbidden lines (i.e., [O iii]/Hβ < 3), and FWHM(Hβ) ≤ 2000 km s⁻¹ (Goodrich 1989). However, the property of radio loudness (R ≥ 10, where R = f5 0 GHz/f4400 λ) (Kellermann et al. 1989) is markedly rare in galaxies of this type, occurring in <7% of such systems (Komossa et al. 2006). High brightness temperature (≥10¹³ K), radio loudness (Zhou et al. 2003), and strong/rapid variability are, however, properties of blazars. It is the combination of these various observational properties that lead many to now believe that RL NLS1 and blazars may both play host to relativistic jets.

It is now widely accepted that all varieties of AGNs are manifestations of the same basic phenomenon—accretion of matter onto a supermassive black hole (SMBH) at the center of a galaxy. The different classes of AGNs that we then observe result, to a large degree, from these objects being oriented differently with respect to our line of sight. Blazars, a class of AGNs characterized by strong and variable emission across all wavelengths and strong and highly variable polarization in the radio and optical (Blandford & Rees 1978), are believed to result from the orientation of our line of sight near the axis of a relativistic jet of particles being emitted from the central engine of the source. Until recently, blazars were almost exclusively observed to be hosted in elliptical galaxies, with very few exceptions (McHardy et al 1994). Since the majority of NLS1 hosts are spiral galaxies, finding evidence of blazar-like behavior in such systems would help to fill in a curiously barren demographic of the blazar population.

PMN J0948+0022 is an object that displays the expected properties of an NLS1 galaxy as described above (Zhou et al. 2003), as well as those of blazars, such as strong and variable emission in the radio through γ-ray energies over long timescales (Abdo et al. 2009; Foschini et al. 2012), and microvariability in the optical (Maune et al. 2013). Ikejiri et al. (2011) also observed PMN J0948+0022 to exhibit a very high degree of linear polarization (18.8%) in the optical (V band), when the object was very bright (V = 17.028 ± 0.014).

To date, no comprehensive, long-term program investigating the optical polarimetric/photometric characteristics of RL NLS1 has been reported. This paper provides the results of such a study for the prototype for this class of objects, PMN J0948+0022.

Throughout this manuscript, Julian Dates (JD) are expressed as Modified Julian Dates (MJD). The conversion to MJD is expressed as MJD = JD − 2.4566.
reduction tools.\textsuperscript{1} Bias frames were taken at the beginning of every night and combined into a master bias that was subtracted from each image. Flat frames were taken at least once per run, using a featureless screen inside the dome. Each position of the wave plate required its own set of flats, which would later be combined into one master flat per P.A. for application to the appropriate science image(s). Cosmic-ray cleaning was performed on all science images, with the threshold and flux-ratio parameters set to 35 and 5, respectively. Aperture cleaning was performed on all science images, with the threshold of every night and combined into a master flat that was subtracted from each image. 

For ease of comparison with $\gamma$-ray data, which are expressed as photon fluxes in this manuscript, optical data were converted from magnitudes to units of flux (mJy) using the following equation:

$$ F = 2941 \times 10^{-0.4 \times \text{Mag}}, $$

where $F$ is the flux in mJy and Mag is the $R$-band magnitude.

2.2. Optical and Infrared Photometry with SMARTS

Much of our optical and all of our near-IR (NIR) data were obtained by the 1.3 m telescope at the Cerro Tololo Inter-American Observatory under the Small and Moderate Aperture Research Telescope System (SMARTS) program. We obtained simultaneous data in the optical $R$ and infrared $J$ bands using ANDICAM, which is a dual-channel instrument that uses a dichroic to simultaneously feed optical and IR CCD imagers, allowing the acquisition of IR data from 0.4 to 2.2 $\mu$m. Our limited data set of $J$-band images consisted of four NIR images—one for each corresponding optical $R$-band image—which were flat-fielded, overscan-corrected, bias-subtracted, and co-added using standard PyRAF/IRAF packages and scripts. To be consistent with the background, optical data, a 7 arcsec aperture radius was used to perform differential photometry.

2.3. Fermi-LAT Data

Gamma-ray data were obtained through the Fermi-LAT public data server. The Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope, is a pair-conversion detector sensitive to $\gamma$-rays in the 20 MeV to several hundred GeV energy range (Atwood et al.\textsuperscript{2009}). The instrument has worked almost continuously in all-sky-survey mode since its launch in 2008 June, which allows coverage of the entire $\gamma$-ray sky approximately every 3 hr. The data were reduced and analyzed using ScienceTools v9r27p1 and instrument response functions P7SOURCE_V6. We utilized the likelihood analysis procedure as described at the FSSC Web site. Photon fluxes were calculated using data from MJD 5562 to 6045 (2011 January 1–2013 April 25).

Our data were downloaded from the Fermi Web site on 2013 April 29 and cover a region on the sky 15$^\circ$ in radius, centered on the location of PMN J0948+0022 (2FGL0948.8+0020 from the Fermi two-year Point Source Catalog), and in an energy range of 100 MeV–300 GeV. Our $\gamma$-ray light curve consists of 112 equally sized bins, each of which is 637,861 s in length, or one-quarter of the lunar synodic period, as our observing runs at Lowell Observatory were centered around the time of the New Moon. The first bin began on 2011 February 3, while the last bin ended on 2013 April 25. Only data corresponding to the source class (evclass = 2) were utilized, with a 52$^\circ$ cutoff rock-angle of the spacecraft, while an additional cut utilizing an angle of 100$^\circ$ from the zenith was imposed so as to minimize the contamination due to $\gamma$-rays coming from Earth’s upper atmosphere. Since PMN J0948+0022 is within 20$^\circ$ of the ecliptic, and the Sun is a source of $\gamma$-rays comparable to our target (Abdo et al.\textsuperscript{2011b}), a final cut was used to exclude exposures that occurred when the Sun was within the 10$^\circ$ Radius of Interest (RoI). Photon fluxes and spectral fits were derived using an unbinned maximum likelihood analysis which was accomplished using the ScienceTool GTLIKE.

In order to accurately measure the flux and spectral parameters of the source, one needs to account for $\gamma$-rays emitted from the background. To this end, two models were used: an isotropic background model accounting for extragalactic diffuse emission

\begin{table}[h]
\centering
\caption{Photopolarimetric Observations of J0948+0022 Obtained between 2011 February and 2012 May}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
MJD & $R$ Magnitude & $P$ & EVPA & MJD & $R$ Magnitude & $P$ & EVPA \\
& (err) & (err) & (err) & & (err) & (err) & (err) \\
\hline
5599.8 & 19.18 (0.02) & 0.86 (0.50) & –32.08 (11.3) & 6008.7 & 19.48 (0.02) & 1.92 (0.39) & –46.7 (0.3) \\
5602.8 & 19.18 (0.02) & 2.02 (0.30) & –36.9 (19.2) & 6039.8 & 19.07 (0.02) & 3.89 (0.61) & 28.9 (13.5) \\
5705.7 & 18.21 (0.02) & 1.35 (1.29) & 93.4 (8.6) & 6040.7 & 18.89 (0.03) & 3.13 (0.36) & 9.0 (1.7) \\
5706.7 & 17.88 (0.03) & 12.31 (1.21) & 22.6 (9.3) & 6059.7 & 19.19 (0.03) & 0.90 (0.28) & 6.2 (62.7) \\
5708.7 & 18.90 (0.02) & 4.00 (1.51) & 117.4 (42.0) & 6251.9 & 18.94 (0.02) & 2.29 (0.69) & –44.0 (0.1) \\
5951.8 & 19.05 (0.03) & 1.66 (0.26) & –50.74 (2.6) & 6253.0 & 18.68 (0.02) & 2.82 (0.58) & 15.2 (3.6) \\
5982.8 & 18.678 (0.03) & 1.70 (0.48) & 19.4 (13.6) & 6300.0 & 18.06 (0.03) & 1.89 (1.26) & 9.0 (6.5) \\
5983.8 & 18.82 (0.03) & 5.95 (0.50) & –59.3 (2.0) & 6301.0 & 18.86 (0.02) & 2.62 (0.65) & –64.0 (3.0) \\
5984.7 & 18.61 (0.03) & 2.45 (0.16) & 19.9 (5.3) & 6302.0 & 19.00 (0.04) & 1.17 (0.28) & 79.7 (27.2) \\
6007.8 & 18.71 (0.03) & 8.17 (0.74) & 58.4 (13.5) & 6393.8 & 18.78 (0.02) & 1.20 (0.11) & 66.14 (1.4) \\
\hline
\end{tabular}
\end{table}
and residual charged particle background, and a Galactic diffuse emission model to account for diffuse sources from within our own Galaxy. The isotropic model we used was the one contained in the file iso_p7v6source.txt, while the Galactic component was given by the file gal_2year7v6_v0.fits. The normalizations of both components were left to vary freely during likelihood analysis.

In order to determine the significance of the γ-ray signal from PMN J0948+0022, we used the test statistic (TS). The TS is defined as $TS = 2 \log(\text{likelihood})$, where likelihood refers to the likelihood ratio test as described in Mattox et al. (1996). Determining the likelihood of a given photon flux being produced by a source with a given spectral model was accomplished using the cgtlike Science Tool. Our source model consisted of all the known γ-ray point sources located within a 15° radius of 2FGLJ0948.8+0020. Initial values for all spectral parameters for these sources were taken from the LAT two-year Point Source Catalog. Along with PMN J0948+0022 and the aforementioned background models, several point sources were allowed to vary (i.e., photon indices, normalization factors, and spectral slope indices were left as free parameters) during the likelihood analysis, so as to account for the inherent variability of many γ-ray sources. The type of spectral model used for a given source was the same model used for that source in the LAT two-year catalog (Nolan et al. 2012).

For PMN J0948+0022 specifically, we used a LogParabola model to describe the γ-ray spectrum of the source in this study. This model takes the form

$$N(E) = N_0 \left( \frac{E}{E_b} \right)^{\alpha + \beta \ln(E/E_b)},$$

(2)

where $N_0$ is the normalization index, $\alpha$ is the photon index at the pivot energy $E_b$, and $\beta$ is the curvature index. These parameters were left unfixed with the exception of $E_b$: this was fixed at a value of 271.597 MeV, which is the value reported for this object in the LAT two-year catalog. All γ-ray fluxes presented in this paper are integrated over the entire energy range cited above (100 MeV to 300 GeV), with corresponding units of (photons cm$^{-2}$ s$^{-1}$).

Sources outside our 10° RoI but within 15° of the target were also included in the source model, as the point-spread functions of these objects could result in extra photons seeping into the RoI of our target. All parameters for these sources were fixed to their 2FGL catalog values during the analysis.

3. RESULTS

3.1. Polarimetry

Our polarimetric results are detailed in Table 1 and displayed for comparison in Figure 1. The top panel of Figure 1 also displays all of our optical data for comparison, binned in 24 hr increments as described in Section 3.2. Below. Note that all photometric data points in the aforementioned table and second panel of Figure 1 were derived from polarimetric measurements. PMN J0948+0022 displays a moderate but significant variability in both the percent polarization ($P$) and EVPA, with a maximum $P$ of 12.31% ± 1.21% and an EVPA which varied substantially. While there does seem to be evidence for a correlation between the optical state and the polarimetric quantities in the data—a high optical state coupled with a high value of $P$, for example—the data also contain notable exceptions to such a relationship (e.g., the lack of any increase in $P$ during an outburst in early 2013). No significant correlation was observed between the optical or polarimetric quantities and the γ-ray flux. It should also be noted that the 180° uncertainty inherent in the measurement of the P.A. may produce the appearance of trends where none exist.

A plot of each value of $P$ versus the concurrent $R$ magnitude is shown in Figure 2. A clear trend between these two values is not immediately obvious. However, closer inspection of the three brightest data points revealed notable characteristics. The brightest data point (corresponding to the data from MJD = 5706.7 in Table 1) also represents the largest value of $P$ and was taken when the object was observed to be in a persistent (42 minute duration) and stable (variation of 0.35 ± 0.05 mag) bright state. The second-highest point corresponds to the data at MJD = 6300.0 from Table 1 and occurred 4.44 hr after the object was observed to be 0.75 ± 0.2 mag fainter via differential photometry. The third-brightest point was obtained 24 hr before the brightest data point, and though they differ in time and brightness by relatively very little, they have quite different polarimetric values. Possible interpretations of these observations are discussed later in Section 4.

3.2. R-band Photometry

The optical photometric data utilized in the present study were obtained from the following sources: (1) polarimetry obtained by the group at Georgia State University (Table 1), (2) optical data presented in Maune et al. (2013), and (3) additional data collected since the publication of Maune et al. These data sets were merged to make a master optical light curve, which contained 1321 $R$-band observations obtained between 2011 February 7 and 2013 April 19. A program was written which binned the optical data with the same temporal bounds as the γ-ray data. An average value was then calculated for each bin to provide a single data point (42 optical photometric data points in total, displayed in Figure 3), allowing us to better match the optical photometric data to the cadence of the Fermi observations. We also binned the $R$-band data in 24 hr bins centered on 00:00 UT; as the latitudes at which our data were obtained resulted in acquisition times roughly centered on this time of day. The 24 hr binned data (114 data points) can be seen in the top panel of Figure 1 and are also accessible via the online version of this manuscript. A sample of these data is provided in Table 2. This technique also served to “smooth” some of the large changes in the optical flux over short time periods that are often manifest in PMN J0948+0022 (see below).

By making use of high-cadence data presented in our previous work, as well as new data obtained in January of 2013, we were able to make very precise measurements of the doubling/halving timescale ($\tau$) for this object in the $R$ band. The formula for calculating the observed timescale $\tau$ is given by the equation (Foschini et al. 2011)

$$F(t) = F(t_0) * 2^{-\frac{(t-t_0)}{\tau}},$$

(3)

where $F(t)$ and $F(t_0)$ are flux values at the times $t$ and $t_0$, respectively. Throughout the remainder of this manuscript, we will use $\tau_P$ and $\tau_R$ to refer to the doubling timescales measured for the optical $R$ and γ-ray bands, respectively. This quantity was calculated for PMN J0948+0022 in several wavebands by Foschini et al. (2012), although they did not have access to significant microvariability data (especially in

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2 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Background/Models.html
Figure 1. Comparison of all $R$-band optical data binned at 24 hr intervals (top panel), only optical data obtained with polarimetry (second panel), the percent polarization (third panel), position of the electric vector in degrees (fourth panel), and the integrated $\gamma$-ray flux (bottom panel) of PMN J0948+0022. Upper limits have been removed for clarity. Details on the photopolarimetric data can be found in Table 1. The same horizontal axis is common to all five plots.

the optical bands) in their study. Microvariability data collected by the present authors on two nights were used to calculate $\tau_R$, and are shown in Figures 4 and 5. Figure 4 (first presented in Maune et al. 2013) reveals the target to be highly variable on very short (a few minutes) timescales, with the object going from a minimum brightness of $R = 18.69 \pm 0.02$ to a maximum of $R = 17.92 \pm 0.02$ in 4.45 hr. This resulted in a doubling timescale of $\tau_R = 4.39 \pm 0.19$ hr. Conversely, Figure 5 (original to this work) illustrates a rapid decrease in the brightness of PMN J0948+0022, though over a similar magnitude range and duration as the doubling event. Here we see the object fall from $R = 18.13 \pm 0.04$ to $R = 18.96 \pm 0.02$ in 3.97 hr, for a halving timescale of $\tau_R = 3.60 \pm 0.23$ hr. Together, these light curves yield an average value of $\tau_R = 3.99 \pm 0.15$ hr.

Concerning the aforementioned figures, there are two items of note. The first is that the above value for $\tau_R$ should be taken as an upper limit. The gaps in the light curves presented in Figures 4 and 5 may contain higher or lower flux states which would drastically reduce the doubling timescale. The second item is that both light curves show discrete brightening events (flares—three in total) that are not only well sampled, but also roughly symmetric in their brightening and dimming profiles and are on the order of an hour in duration.

In 2013 March, PMN J0948+0022 underwent a dramatic brightening in the $R$ band (Figure 6), achieving a maximum brightness of $R = 17.140 \pm 0.021$, which was unprecedented for the object in this band. We were fortunate to have obtained simultaneous $J$-band data during this flaring episode, although we currently lack calibrated values for field stars in the $J$ band. However, as can be seen in Table 3, the degree of the fractional change of the optical flux was closely mirrored by that in the NIR flux. Interestingly, there was no indication of correlated activity in the $\gamma$-ray regime, on any timescale, which could be linked to the optical/NIR activity. While correlation of activity across multiple wavebands is a common characteristic of blazars (see, for example, Rani et al. 2013; Abdo et al. 2010), it is also not unusual to find examples of high activity in one band without the presence of similar activity in other bands (Krawczynski et al. 2004).

3.3. $\gamma$-Ray Observations

The long-term behavior of PMN J0948+0022 in $\gamma$-rays is shown in Figure 3. Our long-term $\gamma$-ray data set consists of 112 data points in total, including 31 upper limit values. The TS value may be used as a proxy for the confidence in the measurement, with $TS \geq 9$ (corresponding roughly to $\sigma \geq 3$; Mattox et al.
Figure 2. Plot of concurrent R-band magnitudes and \( P \), based on the data in Table 1 so that each data point represents a measurement of the value of \( P \) and the R magnitude that coincide in time.

Table 2
A Sample of Our Optical Data, Binned at One-day Intervals as Described in the Text

| JD          | R Magnitude | R (err) | No. of Images |
|-------------|-------------|---------|---------------|
| 2,455,599.79411 | 19.180      | 0.020   | 1             |
| 2,455,602.79159 | 19.179      | 0.024   | 1             |
| 2,455,624.71679 | 19.382      | 0.003   | 7             |
| 2,455,625.62464 | 19.129      | 0.003   | 16            |
| 2,455,626.34594 | 19.198      | 0.005   | 16            |
| 2,455,627.31249 | 19.004      | 0.003   | 28            |
| 2,455,627.80059 | 18.812      | 0.001   | 11            |
| 2,455,647.70671 | 18.761      | 0.002   | 18            |
| 2,455,648.34777 | 18.798      | 0.001   | 68            |
| 2,455,649.27107 | 18.798      | 0.001   | 84            |

Notes. Columns: (1) time of the observations in JD, (2) optical R-band magnitude, (3) uncertainty in the magnitude, and (4) the number of observations used to create the binned data point.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 3
Data Corresponding to the Strong Optical Flaring We Observed in 2013 March

| MJD  | R Magnitude (err) | \( \Delta R \) (err) | \( \Delta J \) (err) |
|------|-------------------|----------------------|----------------------|
| 6360.5 | 17.271 (0.016)   | −1.373 (0.026)       | −1.375 (0.028)       |
| 6363.5 | 18.644 (0.021)   | 1.504 (0.030)        | 1.334 (0.028)        |
| 6364.5 | 17.140 (0.021)   | −0.880 (0.028)       | −0.793 (0.028)       |
| 6368.5 | 18.020 (0.018)   | N/A                  | N/A                  |

Notes. Columns: (1) time of the observations in MJD, (2) optical R-band magnitude, (3) difference in magnitude between the measurement of the current row and next row, and (4) same as (3), but for the J-band data.

1996) being the threshold above which we considered a positive detection. We applied the method for extracting upper limits, as described on the Fermi Web site, to bins with TS < 9. As PMN J0948+0022 is a well-established \( \gamma \)-ray source (Abdo et al. 2009), and less than 1/3 of our data points are below this threshold, we feel it is reasonable to treat all of our remaining gamma-ray data points as direct detections.

PMN J0948+0022 was observed to undergo a significant increase in \( \gamma \)-ray brightness in the spring of 2011, which was mirrored by a steady increase of the average R-band luminosity over the next few months, as can be seen in the top two panels of Figure 3. Unfortunately, the \( \gamma \)-ray brightening which was observed in the spring of 2001 continued into the summer when PMN J0948+0022 could not be viewed in the optical due to the close proximity of the Sun. Nevertheless, when optical monitoring resumed in 2011 November, the object was observed to be back at a low state in both the optical and \( \gamma \)-rays and would remain in that state until the end of optical monitoring in the spring of 2012. The resumption of optical monitoring in the fall of 2012 was accompanied by an increase in \( \gamma \)-ray activity which was dominated by two especially active periods centered roughly on MJD 6225 and 6290. Perhaps
most interestingly, the optical activity remained generally much higher than average after MJD 6300, even though γ-ray activity dropped to a relatively inactive state.

On 2012 December 18, PMN J0948+0022 was observed to undergo a flare in the NIR (Carrasco et al. 2012), followed by a strong γ-ray peak as observed by Fermi-LAT (D’Ammando & Orienti 2013). The measured flux for the bin in which the peak of this event fell (MJD = 6294) was \(9.22 \times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\), with a TS = 194.27. Due to the strength of this event, we were able to bin the data to much higher cadence (6 hr) around the peak of the flare. Figure 6 illustrates the rapidly evolving nature of the flare with 24 hr (top panel) and 6 hr (bottom panel) bins. One quickly notes that the flux appears to double twice (within a 2σ uncertainty) in the 6 hr light curve.

Applying Equation (3) to the relevant bins yields a measurement of the doubling timescale in the γ-ray regime of \(\tau_\gamma = 3.55 \pm 4.29\) hr—see Table 4 for the values used to calculate this result. A doubling timescale of approximately 4 hr not only roughly agrees with our measurement of \(\tau_R\), but is also comparable to the γ-ray variability timescales found for 3C 454.3 during that object’s recent outbursts in 2009 (Ackermann et al. 2010) and 2010 (Abdo et al. 2011a), who found doubling timescales of 3 hr and 6 hr, respectively.

4. DISCUSSION AND CONCLUSIONS

Multi-epoch Very Long Baseline Array observations of a number of γ-ray detected quasars and blazars (Jorstad et al.
Figure 4. Microvariability data presented in Maune et al. (2013), showing the doubling of the flux in $4.39 \pm 0.19$ hr. Arrows indicate the data points separated by the necessary flux difference and used to make the timescale calculation. Two discrete, roughly symmetric flares can also be seen in this figure.

Figure 5. Similar to Figure 4, but original to this work and showing a halving of the total optical flux in $3.60 \pm 0.23$ hr. Note the discrete flare near the end of the light curve.

2001) suggest that the γ-ray emission observed for these objects originates near the radio core, perhaps corresponding to a standing shock in the jet itself, and not specifically originating from a location near the central SMBH. It is thought that the oft-observed flares are produced as a result of turbulence/instabilities, which are present in the relativistic jet and arise as shocks in this outflow. With the passage of a shock down the jet, the magnetic field will be compressed within the
shock region, causing the field to become more highly ordered. Observationally, one would then expect that the fractional linear polarization would increase and the direction of the EVPA would change rapidly.

Figure 6. Top: γ-ray light curve centered on the high flux measurement which occurred on MJD = 6294 in Figure 3 with 24 hr time bins. Bottom: the data circumscribed by the blue dashed lines in the top panel, but analyzed with 6 hr time bins. (A color version of this figure is available in the online journal.)

The present observations allow us to evaluate if this is the case for the γ-ray/optical flux variations observed for PMN J0948+0022. In Figure 5, we have plotted the γ-ray and optical light curves for 2011–2013. A possible correlation between the optical and γ-ray regimes is suggested in parts of the dual light curve. To further evaluate this, in Figure 7 we have plotted the optical flux versus the γ-ray flux. While we do not see any evidence of a strong correlation, we do note that above a certain threshold in the γ-ray brightness (approximately $2 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$), we consistently see the object in an elevated optical state (approximately $9.5 \times 10^{-5}$ mJy or $R \leq 18.7$). However, the converse is not true: we do not always see PMN J0948+0022 in an elevated γ-ray state when it is optically bright—even during periods of extended and dramatic brightening, such as that of the period in 2013 March as detailed in Figure 8. The absence of a strong correlation suggests that there is substantial turbulence present in the jet and the magnetic field is not highly ordered, in turn suggesting that no strong shock is present during the time of these observations.

The picture becomes more complicated if we look at the photopolarimetry data as displayed in Figure 2. This plot appears to show a potential bimodal distribution in the $P$ versus $R$-magnitude plane. A positive correlation between these

### Table 4

Data Used to Calculate Doubling/Halving Timescales for Optical and γ-Ray Data

| R-band Data   | 6 hr γ-Ray Bins |
|---------------|-----------------|
| MJD $M_R$ (err) | $\tau_R$ | MJD Flux (err) | TS | $\tau_\gamma$ |
| 5652.61 18.69 (0.02) 4.39 (0.19) | 6292.15 2.78 (1.67) 14.05 2.81 (4.23) |
| 5652.79 17.92 (0.02) | 6292.40 12.21 (5.61) 15.66 |
| 6298.88 18.13 (0.04) 3.60 (0.23) | 6292.65 8.26 (7.49) 12.03 4.28 (7.47) |
| 6299.04 18.96 (0.02) | 6292.90 21.81 (8.723) 14.91 |
| Average $\tau_R$ 3.99 (0.15) | Average $\tau_\gamma$ 3.55 (4.29) |

Notes. Columns: (1) time (MJD) of the optical observation, (2) magnitude (error) in the $R$ band, (3) timescale $\tau_R$ (in hr) calculated from the two adjacent data points in Column 2, (4) midpoint in time of the 6 hr bin from which (5) the photon flux (error) in photons cm$^{-2}$ s$^{-1}$ was derived, (6) the TS value of the aforementioned γ-ray data, and (7) the timescale $\tau_\gamma$ calculated from the adjacent γ-ray data. The bottom row gives the average values (and uncertainties) for $\tau$ in each waveband.
values could be seen as supporting the so-called shock-in-jet interpretation (Marscher et al. 2008), though several data points, especially in the high-magnitude, low-polarization part of the figure, strongly disagree with this interpretation. However, as was noted in Section 3.1, the two brightest, low-polarization points occurred during times of rapid flux variation in the object, which may indicate that these “errant” data were the result of turbulence in part of the jet, rather than a standing shock affecting the entire optical emitting region.

Our measurements for the doubling timescales in the $R$ band and $\gamma$-rays—$\tau_R$ and $\tau_\gamma$, respectively—provide additional insight into the variability nature of PMN J0948+0022. As stated...
in Sections 3.2 and 3.3, the doubling timescale in the optical ($\tau_{R}$) was $3.99 \pm 0.15$ hr while the corresponding quantity in the $\gamma$-ray regime ($\tau_{\gamma}$) was $3.55 \pm 4.29$ hr. These values represent a significantly faster doubling timescale for this object as compared to those presented by Foschini et al. (2012), who found the values of $\tau$ in optical or $\gamma$-ray bands to be on the order of 2–4 days. The close agreement of the values presented in this work for $\tau_{R}$ and $\tau_{\gamma}$ could be used to argue in favor of comparable sizes for the emitting regions of both the optical and high-energy radiation, implying that these regions are located close to each other along the jet, though not necessarily cospatial. Localized turbulence in part of the jet, rather than (or in addition to) some sort of standing shock, may better explain the observed behavior.

It is, perhaps, not surprising that the short variability timescales of this object have gone undetected in previous studies, as it required several dedicated optical observing runs and constant monitoring at high energies to obtain data of sufficient quality to deduce such values for this work. Over two dozen nights of high-cadence, focused observations in the optical were required to obtain the two nights of data that allowed us to calculate $\tau_{R}$, while an exceptional episode of $\gamma$-ray emission in terms of both flux and confidence in the measurement was required to determine $\tau_{\gamma}$. Clearly, the observed behavior of PMN J0948+0022 is very complex and may require the application of models that take into account turbulence as well as shocks in the jet to explain this behavior adequately. All of this underscores the important role that dedicated, long-term monitoring programs can play in studying objects of this type.

5. SUMMARY

In this work, we have identified many common properties of blazars which seem to be present in PMN J0948+0022. These include a strong linear polarization which is highly variable in both the percentage of polarization ($P$) and orientation of the electric vector (EVPA), an optical flux which varied by more than 2.88 magnitudes over the 27 month observation period, infrared/optical flaring which was observed to have no $\gamma$-ray counterpart, and upper limits for the doubling timescales in both the optical and $\gamma$-ray regimes which were both measured to be very fast (around 4 hr).

We have also observed what may be evidence for localized turbulence in the jet, in the form of strong brightening events with no corresponding increase in the value of $P$, extremely rapid doubling timescales in the optical and $\gamma$-ray regimes, and strong/rapid flares in the optical and infrared which have no $\gamma$-ray counterpart.

While the present observations do not allow one to definitively confront the model, suggesting that the $\gamma$-ray emission is produced at a shock, downstream in the jet, some distance from the SMBH, it does suggest what is required. It will require quasi-simultaneous $\gamma$-ray and optical/photopolarimetric observations during a major $\gamma$-ray/optical flare consisting of a change in flux significantly greater than a factor of three, such as was observed in the present campaign. Under these conditions, one should be able to determine if there is a significant increase in the polarization ($P$) and the expected rapid change in the EVPA accompanying such an outburst. Therefore, we encourage continued photopolarimetric monitoring of this object in order to investigate the behavior of the polarization during the next major outburst of PMN J0948+0022.

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