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Using variability to find counterparts for unidentified gamma-ray sources in the galactic plane

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Blazar counterparts have been proposed for two EGRET gamma-ray unidentified sources in the Cygnus region: 3EG J2016+3657 and 3EG J2027+3429. Here we present the analysis of the *Fermi*-LAT gamma-ray data accumulated during 27 months. We obtained gamma-ray light curves and radio light curves at 15 GHz taken with the 40-m telescope at the Owens Valley Radio Observatory (OVRO). Simultaneous variability is seen in both bands for the two blazar candidates. Additionally, we find a third gamma-ray source with similar variability and spectral characteristics to the known LAT pulsars.

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1. Introduction

Previous gamma-ray studies of the Cygnus region have proposed possible origin for two unidentified EGRET sources, 3EG J2016+3657 and 3EG J2027+3429. Mukherjee et al. [1, 2] proposed possible association of 3EG J2016+3657 with the blazar B2013+370 based on spatial coincidence with a compact ROSAT X-ray source. Similarly, the blazar QSO B2023+336 ($z = 0.219$) was proposed as counterpart for 3EG J2027+3429 [3, 4]. Other studies suggested the association of this unidentified gamma-ray source with an undiscovered pulsar [5, 6]. Due to the sensitivity limitations of EGRET, definite identifications could not be made.

Now a decade later, the next generation gamma-ray instrument, the *Fermi* Gamma-ray Space Telescope, provides better spatial, temporal and spectral resolution. In its first 11 months of observations, from August 2008 to July 2009, the Large Area Telescope (LAT) on board the *Fermi* Gamma-ray Space Telescope detected 1451 gamma-ray sources in the 100 MeV to 100 GeV energy range [7]. Of the 1451 *Fermi* 1FGL sources, 630 are unidentified. 1FGL J2015.7+3708 and 1FGL J2027.6+3335 are two such unidentified sources in the Cygnus region. Due to the high density of gamma-ray emitting candidates in this region, it is often difficult to make associations.

In the following we describe the analysis of 1FGL J2027.6+3335 and 1FGL J2015.7+3708 using 27 months of *Fermi* data and simultaneous radio observations at 15 GHz taken with the 40-m telescope at the Owens Valley Radio Observatory (OVRO). Section 2 describes the observations and data analysis. The results of the spatial, spectral and variability analysis are presented in Section 3, and discussed in Section 4, where the main conclusions of the study are given.

2. Observations and Data Analysis

The *Fermi* Large Area Telescope is the main instrument on-board the *Fermi* Gamma-ray Space Telescope. It is a multi-purpose observatory sensitive between 100 MeV and 300 GeV, including the largely unexplored energy window above 10 GeV. It is designed as a low aspect ratio, large area pair conversion telescope to maximize its field of view ($\sim$2.4 sr) and affective area ($\sim$8000 cm^2) [8]. The LAT angular, energy and timing resolution rely on solid state detectors and electronics: a multi-layer silicon-strip tracker, interleaved with tungsten converters; a CsI(TI) calorimeter; a segmented anticoincident plastic scintillator detector and a flexible, programmable trigger and filter logic for on-board event filtering.

This analysis was performed using the *Fermi*-LAT `ScienceTools` software package (version v9r18). We selected photons with $E > 300$ MeV from the first 27 months of the *Fermi* mission (Aug 2008 - Oct 2010). Diffuse class photons (Pass6 V3 IRF, [8]) were selected in the region 10° around 1FGL J2015.7+3708, a Region of Interest (ROI) which also contains 1FGLJ2027.6+3335.

We generated a source model of our ROI, which includes all the *Fermi* 1-year catalog sources, and Galactic and isotropic diffuse emission. All of the 1FGL sources are modeled by a simple power-law spectrum with free normalization and spectral index, with the exception of the known pulsars, which have been fit by a power-law with exponential cutoff. In this case, the cutoff energy was fixed during the likelihood fit. Table 1 lists the parameters of the known pulsars in the ROI [9]. Known gamma-ray sources outside the ROI but within 5° from the edges where also included in the model, but their normalization and spectral index were fixed to the 1FGL values. The isotropic

Name	Photon Flux 1-100 GeV [10^{-9} cm^{-2} s^{-1}]	$E_{\rm cutoff}$ (GeV)	Spectral Index Γ
1FGL J2021.0+3651	69.4 ± 1.9	2.6 ± 0.3	1.65 ± 0.07
1FGL J2021.5+4026	110.1 ± 2.5	3.0 ± 0.2	1.79 ± 0.04
1FGL J1952.9+3252	20.3 ± 1.0	4.5 ± 1.2	1.75 ± 0.12
1FGL J2032.2+4127	22.5 ± 1.4	2.1 ± 0.6	0.68 ± 0.46

Table 1: Pulsars in the Region of Interest

Name	Spectral Fit	Spectral Index Γ	Flux 1-100 GeV [10^{-9} cm^{-2} s^{-1}]
J2020.0+4158	Power-law	2.81 ± 0.09	4.12 ± 0.41
J2022.2+3840	Power-law	3.07 ± 0.12	2.49 ± 0.38
J2017.4+3628	Power-law	2.60 ± 0.59	7.35 ± 0.54
J2025.1+3342	Power-law	2.95 ± 0.09	3.34 ± 0.36
J2028.3+3333	PL ExpCutoff	$(3.09 \pm 0.39) \times 10^{-8}{\rm cm}^{-2}\,{\rm s}^{-1}{\rm GeV}^{-1} \cdot (E/1{\rm GeV})^{-1.01\pm0.20} e^{-\frac{E}{(1.40\pm0.21){\rm GeV}}}$	

Table 2: Extra Sources Included in Source Model

diffuse gamma-ray background was modeled as a simple power law with free normalization and spectral index, while the Galactic diffuse emission is modeled by a template released from the *Fermi* Collaboration (gll_iem_v02.fit). Because the sources of interest lie close to the Galactic plane and the background is therefore quite heterogeneous, we left the Galactic diffuse spectral parameters free, yielding a variation within 1% of the normalization and 2% of the spectral index. These additional degrees of freedom significantly improved the likelihood of the fit.

A likelihood analysis is performed using the `gtlike` tool, which computes spectral parameters for each source that best fit the data and calculates the test statistic (TS) value associated with each source. Additional sources that were not in the 1-year catalog were added to the model, when their TS>25. These additional sources are included in Table 2.

To compute the gamma-ray light curve, we use the time-averaged source model, and divide the data into time bins of 1 or 2 week duration, depending on the source average flux. The likelihood analysis is then performed for every time bin. To avoid having too many free parameters the spectral index for each source is fixed. The sources with negative TS after a first likelihood fit are removed from the model and the fit is repeated. Flux points are derived if TS>1. Otherwise a 90% confidence level upper limit is calculated.

To compute the spectrum, we again use the time-averaged source model, but this time divide the data into energy bins. The likelihood analysis is performed for every energy bin, and a spectrum is generated using the user-contributed LikeSED Python module available at the *Fermi* Science Support Center[1]. The spectral index for each source was fixed, along with the normalization and spectral index for the Galactic and isotropic diffuse emission models. The number of bins is chosen depending on the brightness of the source. A spectral point is calculated if the TS>9, otherwise a 95% confidence level upper limit is derived.

Contemporaneous 15 GHz radio light curves were obtained at the radio positions of the blazars

[1] http://fermi.gsfc.nasa.gov/ssc/

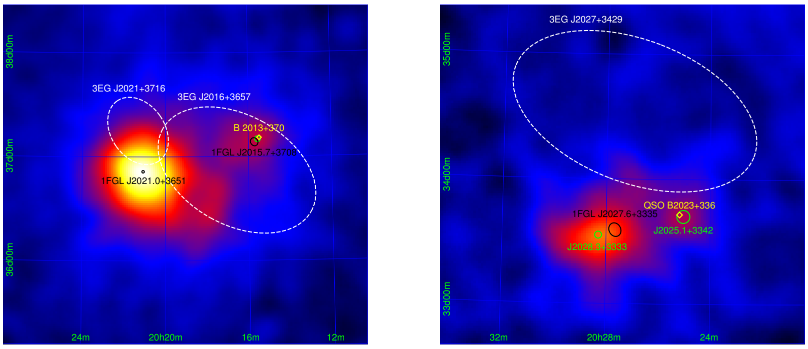

Figure 1: *Fermi* raw counts maps above 300 MeV. The white dotted contours are the EGRET 95% c.l. error ellipses. The black contours are the *Fermi* 1-year catalog 95% error contours. The green contours are our 95% error circles using 27 months of *Fermi* data. The yellow diamond marks the positions of the radio sources. *Left:* A close-up around 1FGL J2015.7+3708. The bright source corresponds to the pulsar PSR J2021+3651. *Right:* The region around 1FGL J2027.6+3335. In our analysis, we decomposed the one 1FGL source into two separate gamma-ray emitters. In both cases, the yellow error circles from our analysis with 27 months of data are spatially coincident with the radio sources.

Name	l [deg]	b [deg]	$\sqrt{\mathrm{TS}}$	**Flux 1-100 GeV** $[10^{-9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	**Spectral Index** Γ	**Counterpart**
1FGL J2015.7+3708	74.86	1.20	28.3	9.80 ± 0.52	2.56 ± 0.05	B2013+370
J2025.1+3342	73.10	-2.35	16.7	3.34 ± 0.36	2.95 ± 0.09	QSO B2023+336
J2028.3+3333	73.37	-2.99	32.9	$(3.09 \pm 0.39) \times 10^{-8} \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \mathrm{GeV}^{-1} \cdot (E/1\mathrm{GeV})^{-1.01 \pm 0.20} e^{-\frac{E}{(1.40 \pm 0.21)\mathrm{GeV}}}$		

Table 3: Studied Gamma-Ray Sources

B2013+370 and QSO B2023+336 with the 40-m telescope at the Owens Valley Radio Observatory (OVRO). Since late 2007, about a year before the launch of *Fermi*, a large-scale, fast-cadence 15 GHz radio monitoring program has been ongoing using the 40-m telescope [10]. The survey encompasses over 1500 northern ($\delta > -20^\circ$) blazars, including the 1158 northern sources from the Candidate Gamma-ray Blazar Survey [11, 12] and blazars associated with *Fermi*-LAT γ-ray detections, including the two sources in this analysis. Sources in this program are observed twice per week in total power with about 4 mJy (minimum) and 3% (typical) uncertainty. The absolute flux density scale is based on the Baars et al. (1977) value for 3C 286, 3.44 Jy at 15 GHz, with about 5% scale uncertainty which is not reflected in the error bars presented here [13] .

3. Results

We present the results for our two sources of interest: 1FGL J2015.7+3708 and 1FGL J2027.6+3335. We resolve and characterize three gamma-ray sources, summarized in Table 3.

1FGL J2015.7+3708

In the analysis of 27 months of *Fermi* data 1FGL J2015.7+3708 is detected with a significance of 28σ. The time-averaged spectrum is well described with a power-law with spectral index of 2.56 ± 0.05, and the measured integral flux above 1 GeV is $(9.80 \pm 0.52) \times 10^{-9}$ cm^{-2}s^{-1}. The

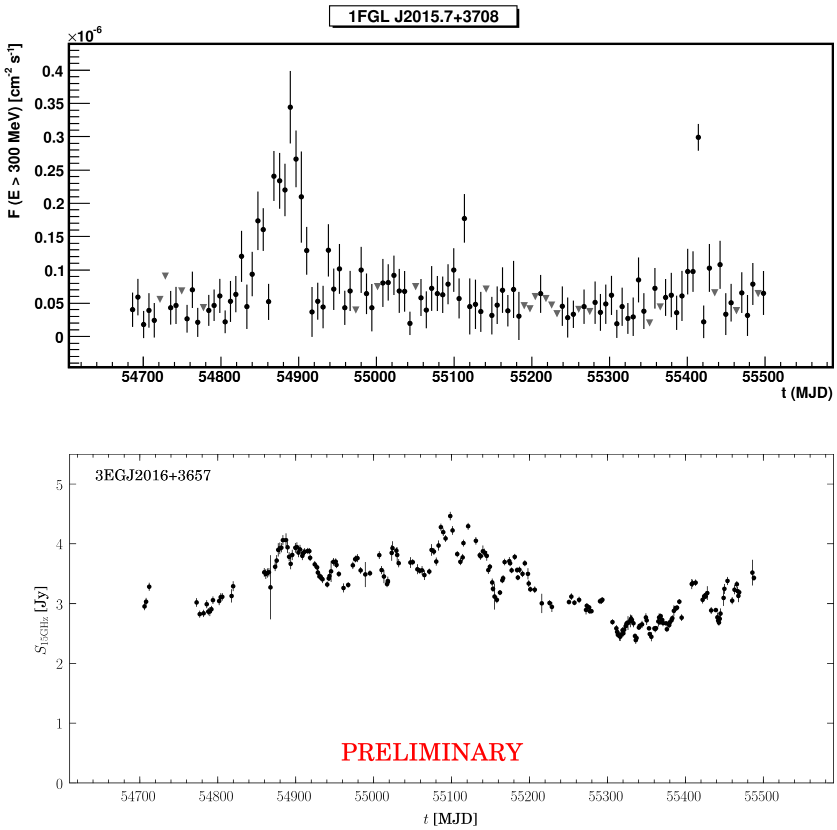

Figure 2: Top: *Fermi* likelihood lightcurve in 7-day bins from August 2008 - October 2010. The grey triangles represent to 90% c.l. upper limits. Bottom: OVRO radio light curve at 15 Gz for same 27 month period. Flares appear to be correlated in gamma-rays and radio. Further cross-correlation tests are to be completed for confirmation.

Fermi 1-year catalog reports 1FGL J2015.7+3708 as a variable unidentified source associated with 3EG J2016+3657 (Figure 1). The blazar B2013+370 does not lie within the *Fermi* catalog 95% error circle for 1FGL J2015.7+3708. However, upon making a better estimation of the source location with 27 months of data, we find that the blazar is spatially coincident with our new 95% error circle. 1FGL J2015.7+3708 lies next to a bright pulsar, 1FGL J2021.0+3651, and so it is possible that contamination from this bright nearby pulsar caused the position of the error circle to shift away from the actual location of the gamma-rays.

Figure 2 shows the gamma-ray light curve for 1FGL J2015.7+3708 in 7-day time bins. The source shows clear variability in gamma-rays with distinct flares occurring in May and October 2009 and August 2010. A comparison with the 15 GHz radio light curve shows simultaneous variability in both bands. This raises the possibility that a correlation can be measured which, if shown to be significant, would confirm the identification.

1FGL J2027.6+3335

The *Fermi* 11-month catalog reports one unidentified source outside of the original EGRET error ellipse for 3EG J2027+3429 (Figure 1). Our analysis using 27 months of data suggests the

PoS(Texas 2010)127

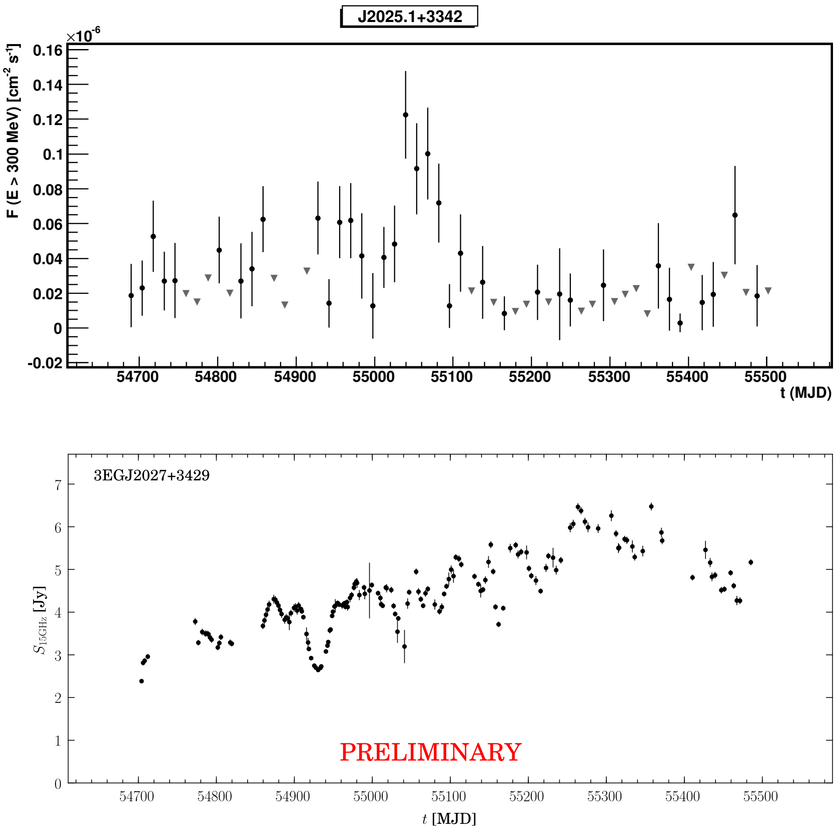

Figure 3: Top: *Fermi* likelihood lightcurve in 14-day bins from August 2008 - October 2010. The grey triangles represent to 90% c.l. upper limits. Bottom: OVRO radio light curve at 15 Gz for same 27-month period. Both gamma-ray and radio light curves exhibit significant variability. Cross-correlation tests are to be completed for confirmation of correlated variabililty.

presence of two independent gamma-ray sources. A source spatially coincident with the blazar QSOB2023+336 is detected at a significance of 17σ. This new source, J2025.1+3342, shows a power-law spectrum with index of 2.95 ± 0.09 and integral flux above 1 GeV of $(3.34 \pm 0.36) \times 10^{-9}$ cm^{-2}s^{-1}. A second, brighter source (J2028.2+3333) is detected with a significance of 33σ.

A likelihood ratio test (LRT) was completed to confirm that the data favors the 2-source hypothesis. We compared a model with only the *Fermi* 1-year catalog source, 1FGL J2027.6+3335, with a model with the two sources, J2025.1+3342 and J2028.3+3333. The LRT favors the 2-source hypothesis with $\chi^2/\text{dof} = 116/6$, which corresponds to a significance greater that 8σ.

We generated a gamma-ray light curve for J2025.1+3342 in 14-day bins (Figure 3). A χ^2 test to a constant flux is performed, producing a probability of 3.5×10^{-5}, indicating variability with a significance of 4.1σ. This variability in both the gamma-ray and radio bands supports the identification of this source as a blazar, though correlated variability does not appear to be present.

A further study of J2028.3+3333 reveals a steady gamma-ray source. The 7-day binned light curve is compatible with a constant flux with $P = 0.97$. The energy spectrum is best described by a power-law with exponential cutoff (Figure 4), which is typical for LAT pulsars [9]. A likelihood ratio test favors a power law with exponential cutoff to a power law with a $\chi^2/\text{dof}= 262/1$.

PoS(Texas 2010)127

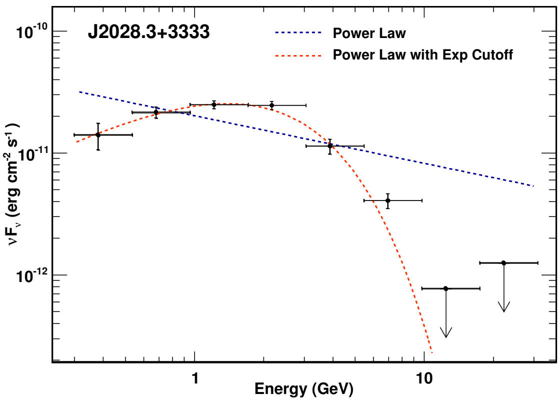

Figure 4: J2028.3+3333 spectral energy distribution in eight bins from 300 MeV-100 GeV. The blue line is the power-law fit, and the red line is the exponentially cut-off powerlaw. The spectrum is significantly better described with an exponentially cut off power-law, a model commonly used to describe LAT pulsars.

4. Discussion and Conclusions

The *Fermi* Large Area Telescope is an excellent tool to perform variability studies of gamma-ray sources given its unprecedented sensitivity and all-sky coverage. Variability studies are a very useful tool to identify gamma-ray sources with counterparts at other wavelengths. In the study presented above, we analyze two gamma-ray unidentified sources, 1FGL J2015.7+3708 and 1FGL J2027.6+3335, using 27 months of *Fermi* data and derive gamma-ray light curves that are compared to radio light curves at 15 GHz obtained with the OVRO telescope. The main results are:

- 1FGL J2015.7+3708 is spatially coincident with the blazar B2013+370. Its gamma-ray spectrum is well described by a power-law, which is consistent with LAT blazars. A study of the gamma-ray and radio light curves shows simultaneous variability in both bands. Further cross-correlation studies are to be done, which could confirm the identification of 1FGL J2015.7+3708 with the blazar B2013+370.

- The region of 1FGL J2027.6+3335 is resolved into two new gamma-ray sources.

- J2025.1+3342 is spatially coincident with the blazar QSO B2023+336. It shows a power law spectrum, and the gamma-ray light curve shows a hint of variability, which is also seen in the radio band. Cross-correlation studies will test for the presence of correlation.

- J2028.3+3333 is a steady gamma-ray source with a spectrum well described by a power-law with exponential cut-off. Given the similar properties to the known LAT pulsars, the new gamma-ray source is a good pulsar candidate.

The presented study gives strong arguments to support the blazar origin of the EGRET unidentified source 3EG J2016+3657. We also suggest that 3EG J2027+3429 could be a composite of two gamma-ray sources, one showing blazar-like properties and a second one that could be a pulsar. Future correlation studies of the gamma-ray and radio light curves are to be published, which could give stronger statistical basis to the simultaneous gamma-ray and radio variability observed for the two blazar candidates.

PoS(Texas 2010)127

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PoS(Texas 2010)127