Fermi-LAT Observations of Transient Gamma-Ray Sources in the Galactic Plane

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***Abstract*. The Large Area Telescope (LAT) on the *Fermi* Gamma-ray Space Telescope has been surveying the sky in gamma rays from 20 MeV to >300 GeV since August 2008. The observatory continuously scans the entire sky every three hours with unprecedented sensitivity and source localization in this energy range. This is well-suited to studying transient sources in the Galactic plane. Previous gamma-ray observations made by EGRET suggested a class of variable Galactic sources, but failed to associate most of these with counterparts at longer wavelengths, and the LAT is poised to address the nature of these events. The LAT has reported brightening of several sources in the Galactic plane since beginning survey operations. We report here on the detected gamma-ray transients and rapid multiwavelength follow-up.**

***Keywords*: gamma-ray observations, transient, Galactic, Fermi**

I. Introduction

The Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton Gamma-Ray Observatory firmly established two classes of variable sources in the high-energy gamma-ray sky, a population of variable gamma-ray blazars above 100 MeV [1] and gamma-ray bursts [2]. However, EGRET also left the legacy of a large fraction of unidentified sources in the 3EG catalog. Many of these were found at low Galactic latitudes, thus believed to be Galactic in nature. EGRET established gamma-ray pulsars as a Galactic population and these were thought to contribute to the unidentified sources. Several studies found indications of variability in some of the sources along the Galactic Plane ([3], [4]), a behavior not expected of the pulsars, which are steady on these time scales. Additionally, no blazar counterpart was identified in several cases. This suggested the possible existence of a new Galactic gamma-ray class.

Several sources showed both strong variability and a convincing lack of a blazar within the EGRET localization errors. One of these, 3EG J0241+6103 (2CG 135+01), has emerged as a new type of gamma-ray source with the firm identification of 0FGL J0240.3+6113 with the high mass X-ray binary (HMXB) system LS I +61° 303 [6]. The most dynamic example from EGRET is GRO J1838-04, which produced an intense outburst in 1995. The flux above 100 MeV in a 3.5 day period was found to be a factor of 7 brighter than in later observations of the region. Notably, no blazar counterpart is known within the 99% EGRET error contour. The absence of a flat spectrum radio source at the levels typical of the EGRET blazars made this a candidate for a different type of gamma-ray emitter. The proximity of such a unique outburst to the inner Galaxy led to speculation of a possible Galactic origin. The question of the progenitor of this activity remains as well as the broader question of the existence of similar sources of this type.

The *Fermi* Large Area Telescope (LAT) [7] is very well-suited for monitoring variability in the GeV sky. A notable departure from previous observations is that the energy range of the LAT (20 MeV to >300 GeV) extends above that covered by EGRET. The large effective area (>8000 cm^2 on axis above 1 GeV), wide field-of-view (~2.4 sr), and excellent angular resolution (better than 1 deg above 1 GeV) greatly enhance the sensitivity to transient activity in comparison to previous gamma-ray instruments in this energy range. The combination of the wide field-of-view with the sky scanning observational mode supplies coverage of the sky every ~3 hours (2 orbits). This enables the detection of fainter objects in shorter intervals than previously possible. The PSF is important in two ways. Source detectability improves because of the separation of a point source signal from other nearby sources and background gamma-rays. Also, the localizations for sources above threshold are much better than 1 deg. even on short time scales. These capabilities are critical for triggering rapid multiwavelength follow-up observations of LAT transients.

The LAT has detected two transient events near the Galactic Plane that have not been associated with blazars. In this paper, we report on the gamma-ray characteristics and the multiwavelength follow-up observations that were triggered shortly after the detections.

II. LAT Detection and Analysis

Both of the unidentified transients were first detected by the LAT automated science processing (ASP)[8]. The ASP flare search locates and analyzes detected point sources in the LAT photon data as these become available for processing on the ground. The search currently runs on 6-hour, 1-day, and 1-week intervals. The latency between the time the data are acquired and when they are available for ground processing is short enough to allow alerts to be communicated and follow-up observations triggered within a day. The LAT team continuously monitors the output of the automated searches for new source detections and flares from known LAT sources.

The automated processing reports candidate locations and flux estimates. Additionally, a 3D maximum likelihood analysis is conducted for each target using the *gtlike* tool in the *Fermi* Science Tools package [9]. "Diffuse" class events are selected and the corresponding P6_V1 IRFs are used to model the instrument performance[1]. Events with energies below 100 MeV are excluded to reduce systematic effects on the spectral fit. A maximum zenith angle of 105° is required to reduce albedo gamma-ray contamination from the Earth. Times when the region used for the source analysis exceeds the maximum zenith angle are excluded.

The test statistic (TS) derived from the likelihood analysis determines the significance of the detection. Sources with TS>25 (corresponding to $\sim 5\sigma$) are considered for rapid follow-up. Near the Galactic Plane a higher TS requirement is necessary to ensure a reliable result due to the high backgrounds and potential source confusion. An additional criteria is the detection of a candidate in multiple time intervals. The two transients presented here are both high-confidence detections that appeared in multiple 6-hour and daily ASP searches.

In the case of a newly detected LAT source, the location is further refined using the *gtfindsrc* tool in the *Fermi* Science Tools software package. This is particularly important for objects near the Galactic Plane, where the gamma-ray background increases and nearby sources can degrade the position measurement. Important considerations for the follow-up analysis are the inclusion of additional data to maximize the statistical precision and the addition of known LAT sources within in the region of interest to the source model used in the likelihood assessment. For scanning mode observations on the order of a day, the errors in the localization are dominated by statistical effects [10]. Because of the energy dependence of the LAT PSF, higher energy photons play a more important role in the localization, and the size of the error circle for a given source will depend on the spectral shape in addition to the flux.

The spectral analysis of the source is also refined following the initial detection. This accounts for data that may not have completed processing at time of the ASP analysis. The follow-up analysis allows more accurate modeling of the region for known LAT sources in order to reduce errors in the spectral fit. It also benefits from use of the refined localization. It is particularly important to include nearby bright sources in the sky model used in the likelihood analysis of transients in the Galactic Plane. This reduces possible flux contamination that may lead to a spurious detection and limits bias in the spectral fit at low energy, where the angular resolution permits significantly more confusion with nearby sources.

A. *3EG J0903-3531*

LAT observations on 6 October 2008 revealed a newly detected LAT source [11] spatially associated with 3EG J0903-3531 in the 3EG catalog [1]. The preliminary localization (J2000.0: RA=136.25 deg, DEC=-35.45 deg, the 68% containment radius, *r68* = 0.12 deg)[2] was based on one day of observation. Additional analysis demonstrated the source was detected (TS >25) on 5, 6, and 7 October 2008 before falling below the daily sensitivity threshold for this region. The LAT flux (E>100 MeV) reported for the flare exceeded 10^{-6} ph cm^{-2} s^{-1}, which is about a factor of 5 greater than the EGRET peak flux.

Despite being bright over several days, this source did not exceed the 10σ criteria for the LAT bright source list [6], which includes data from 4 August 2008 through 30 October 2008.

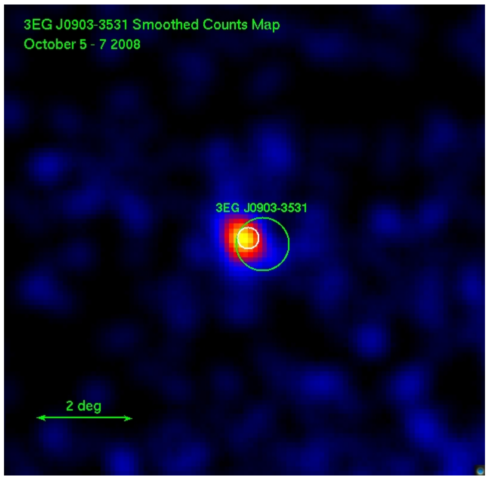

Fig. 1. LAT counts map (E>100 MeV) in celestial coordinates of 3EG J0903-3531 from 5 October through 7 October 2008. The image is smoothed with a Gaussian with kernel, r = 0.5°. The green circle shows the 3EG 95% error circle. The white circle represents the LAT 95% error circle based on the preliminary analysis of the flare period.

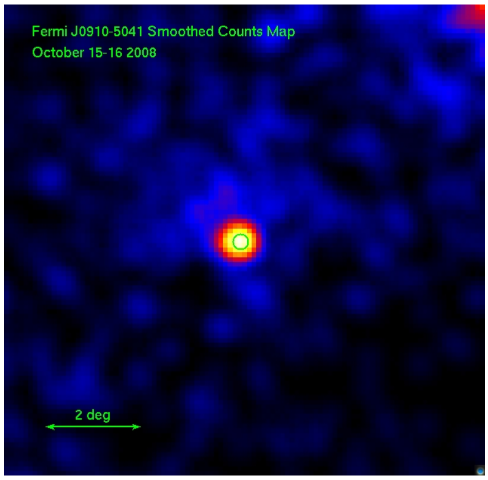

Fig. 2. LAT counts map (E>100 MeV) in celestial coordinates of J0910-5041 from 15 October through 16 October 2008. The image is smoothed using a Gaussian with kernel, r = 0.5°. The green circle represents the LAT 95% error circle based on the preliminary analysis of the flare period.

[1]These results are based on data reconstruction and event analysis using "P6" as described in [7].

[2]The error radius in [11] is the projected 1σ Gaussian error. The localization error given here is the corresponding *r68*.

B. Fermi J0910-5041

This source was first detected on 15 October 2008 [12]. It appears in the LAT bright source list as 0FGL J0910.2-5044 [6] and is flagged as variable. The preliminary localization, (J2000.0: RA, Dec = 137.69 deg, -50.74 deg, *r68* = 0.07 deg), is based on one day of data and only accounts for statistical errors. The reported flux above 100 MeV exceeded 10^{-6} photons cm^{-2} s^{-1}.

The bright source list analysis includes three months of observations and uses a more detailed prescription for calculating the 95% error circle that also includes systematic effects (see [6]). The preliminary coordinates are consistent with the bright source list position, providing an additional confirmation of the LAT capability for consistent localization on relatively short time scales.

In general, the analysis of transients must account for effects of strong, nearby sources. The extremely bright Vela pulsar is 11 deg away from 3EG J0903-3531 and 8 deg away from J0910-5041. These angular separations are well outside the PSF at 1 GeV. This, in combination with the high significance of the detections ($>10\sigma$), ensures that they are not spurious fluctuations. The emission from the Vela pulsar only becomes noticeable at the edges of the count maps shown in Figures 1 and 2. However, the PSF is broad at low energy and the overlap should be considered in the flux estimate. Follow-up analysis of the transients includes an updated model of the sky with nearby LAT sources represented.

III. Multiwavelength Observations

Following each LAT transient detection, we triggered target of opportunity Swift [13] observations designed to search for plausible counterparts. A pair of snapshot (4-7 ksec) exposures were obtained approximately two and three days after the onset of gamma-ray activity for both targets, with a third observation obtained 2 weeks (3EG J0903−3531) and 1 month later (J0910−5041) in order to search for variability on longer timescales.

Within the LAT *r68* of 3EG J0903-3531, there are four 2.4-4.0 σ X-ray sources in the summed XRT exposure (Figure 3). The observed (unabsorbed) 0.3-10 keV fluxes are in the range 2.7 (5.3) - 6.3 (12.5) $\times 10^{-14}$ ergs s^{-1} cm^{-2}, assuming Γ=2 and Galactic absorption = 2.6 $\times$ 10^{21} cm^{-2}. There are no radio counterparts to the X-ray sources at the depth of the 1.4 GHz NVSS [14] image, although two faint (2.5-3.9 mJy at 1.4 GHz) radio sources are found within *r68* (NVSS J090428.87-353007.5, NVSS J090458.76-353145.4).

In the case of J0910−5041, a single X-ray source (Swift J091057.47−504808.5) was detected within the LAT *r68* (Figure 4) . The observed (unabsorbed) 0.3-10 keV flux of 3.2 (13.3) $\times$ 10^{-13} ergs s^{-1} cm^{-2}, assuming Γ=2 and Galactic absorption = 1.3 $\times$ 10^{22} cm^{-2}. There is weak evidence for X-ray variability in this source. The X-ray source has a radio counterpart detected in the SUMMS image [15] with a flat-spectrum [16]. An additional radio source is found within the LAT *r68* (SUMMS J091042-504103).

IV. Discussion

The localization achieved for the LAT transients greatly exceeds the resolution possible in previous observations in this waveband. The reduction in the search area is significant and comparable to the field of view available for X-ray and radio follow-up observations. This is crucial for enabling rapid multiwavelength observations. While reducing possible counterparts in the X-ray and radio observations is desirable, locating a counterpart with a correlated activity is necessary to support a firm identification.

Although gamma-ray sources near the Galactic Plane are more likely to be Galactic objects, there is likely contamination from background blazars. Indeed, blazar associations have been made with LAT detections at low Galactic latitudes [6], [17]. The LAT bright AGN sample (LBAS) predicts 20–25 blazars at $|b|<10$ deg in the three-month observation used to generate the LAT bright source list, but this should be considered an upper limit. The simple extrapolation overestimates the number of detectable blazars and should be modified to include the degradation of sensitivity near the Galactic plane, where the diffuse gamma-ray emission becomes brighter and source confusion increases. Additional study will improve predictions for the blazar contribution to activity at low Galactic latitudes.

Gamma-ray blazars are commonly characterized by bright, flat-spectrum radio sources [18]. In this context, the association of Fermi J0910-5041 with the flat spectrum radio source coincident with Swift J091057.47-504808.5 (section II) would imply a blazar nature for this transient. Like in the case of GRO J1838-04, no similarly bright radio source is found within the LAT localization circle for 3EG J0903-3531, thus they are unlikely blazars (at least of the kind found associated with LBAS blazars).

The task of identifying counterparts for unidentified transients remains challenging. Although greatly reduced from EGRET, the LAT error circles remain large compared to the resolution of telescopes in other wavebands. Additional arguments based on temporal and spectral characteristics are required to support firm associations. Ultimately, identifications of the Galactic transients require observations of related variability between the gamma-ray source and a candidate counterpart at lower frequency. In the absence of a detection of significant activity of the potential radio and X-ray counterparts for the LAT transients, they remain unidentified. These sources continue to be monitored regularly for gamma-ray activity as a part of the *Fermi* sky survey observations.

V. Acknowledgments

The *Fermi*-LAT Collaboration acknowledges support from a number of agencies and institutes for both the

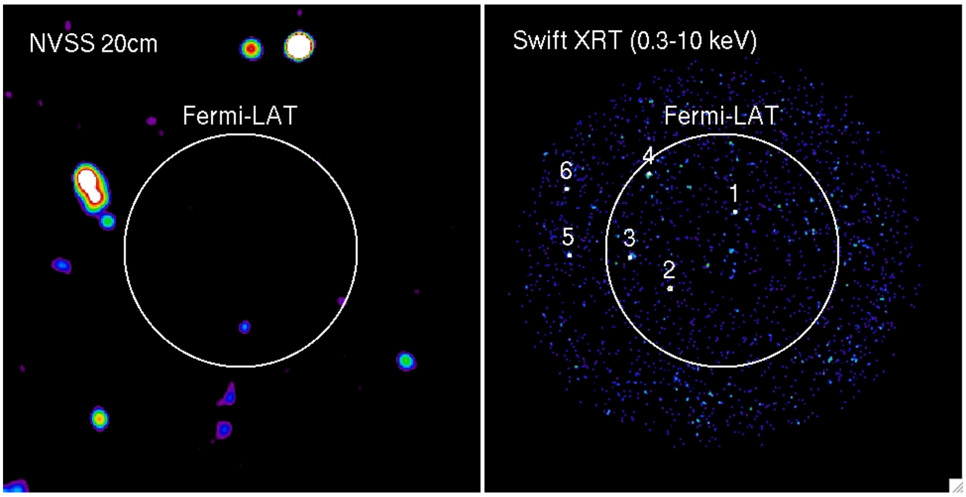

Fig. 3. Archival radio and Swift XRT images of the field containing 3EG J0903-3531. The white circle marks the 68% error circle for the LAT detection.

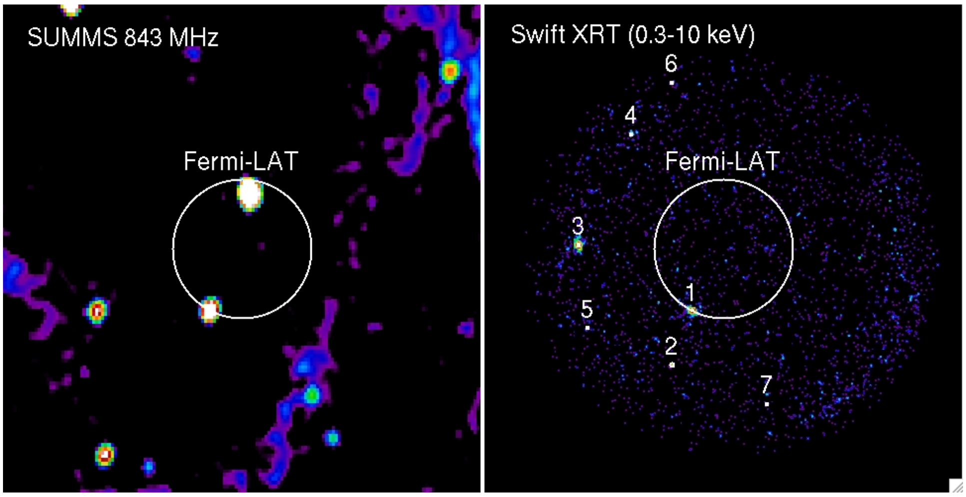

Fig. 4. Archival radio and Swift XRT images of the field containing Fermi J0910-5041. The white circle marks the 68% error circle for the LAT detection.

development and operation of the LAT as well as the scientific data analysis. These include NASA and the DOE in the United States, the CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy for science analysis during the operations phase is also gratefully acknowledged. We also thank the *Fermi*-LAT flare advocates for diligence in monitoring the gamma-ray sky.

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