A new flaring high-energy γ -ray source

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ABSTRACT

We report the detection of a new γ -ray source in the *Fermi*-LAT sky using a source detection tool based on the minimal spanning tree algorithm. The source, not reported in previous LAT catalogues but very recently observed in the X-rays and optical bands, is characterized by an increasing γ -ray activity in 2012 June–September that reached a weekly peak flux of $(3.3 \pm 0.6) \times 10^{-7}$ photons cm⁻² s⁻¹. A search for a possible counterpart provides indication that it can be associated with the radio source NVSS J141828+354250, whose optical SDSS colours are typical of a blazar.

Key words. gamma rays: general – gamma rays: galaxies – galaxies: active – methods: data analysis

1. Introduction

We report here the detection of a new high-energy γ -ray source (J1418+3542) performed in the analysis of archival *Fermi*-Large Area Telescope (LAT) sky images at energies higher than 3 GeV, using a source detection method based on the minimal spanning tree (MST) algorithm (Campana et al. 2008, and in prep.).

The LAT experiment (Atwood et al. 2009) is observing the entire sky in the 0.03 to >300 GeV band, about once every 3 h since 2008 August 04. With the increase of the sky exposure it is reasonable to expect that the number of detected stationary or moderately variable sources increases, thanks to the improved statistics. Moreover, it is also possible that a number of transient sources that exhibit a high variability (like many blazars) and provide a measurable signal only for a limited time interval can unexpectedly emerge in the γ -sky. Among these sources only γ -ray bursts (GRBs) and sources that exceed the threshold set by the LAT Collaboration of a daily average flux of 10^{-6} photons cm⁻² s⁻¹ are announced as a bright γ -ray source¹. Other transient sources can only be observed by performing a periodic and systematic data analysis over time intervals of weeks or months. The new source was detected for the first time during an MST analysis of some selected regions of the sky of low Galactic diffuse emission background, over suitable time intervals, typically 6–12 months. Subsequently, the analysis was performed in a particular region of interest surrounding the source, and extended to the entire LAT archival dataset. This source started its measurable activity in 2011 February and it was not detected in the first two years of *Fermi*-LAT observations (2008 August–2010 August). It exhibited a moderate activity in 2011 June and its flux highly increased from 2012 June

to September. The source was recently observed in flaring activity in November 2012 and its discovery was communicated by an Astronomer’s Telegram (ATel) on December 12 (Dutka et al. 2012; Mahabal et al. 2012). After the MST detection, we investigated the new source using the *Fermi* Science Tools² to obtain count maps, light curves, and test statistics (TS) values by applying the maximum likelihood (ML) method. We also searched for possible counterparts.

2. MST detection of the new γ -ray source

MST is a topometric cluster-finding algorithm that exploits the pattern of “connectedness” of the detected photons, which are treated as the *nodes* in a graph, where the *edges* are the angular distances that connect them. The advantage of MST, and of other cluster-finding algorithms such as DBSCAN (Tramacere & Vecchio 2013), is the capability to quickly find potential γ -ray sources by examining only the incoming directions of the photons, regardless of their energy distribution. For our MST method we defined and successfully tested on simulated and real fields various selection parameters that are useful to assess the significance of the detected clusters and therefore their possible nature as genuine astrophysical sources (Campana et al. 2008, and in prep.; Massaro et al. 2009). In particular, we found that the parameter M , the so-called *magnitude*, which is defined as the number of photons N of a cluster multiplied by its *clustering degree*, i.e. the ratio of the mean edge length in the cluster to the mean value in the field, is a very good indicator of the detection significance. As shown by Campana et al. (in prep.), M values higher than 20 correspond to significance values higher than 4 standard deviations. Detected clusters can

¹ <http://fermi.gsfc.nasa.gov/ssc/data/policy/summary.html>

² <http://fermi.gsfc.nasa.gov/ssc/data/analysis/software>

Table 1. Main MST parameters of the source J1418+3542 in the energy range 3–300 GeV and different time intervals.

Time interval	RA (J2000)	Dec (J2000)	l	b	N	M	Notes
2008 Aug. 04–2011 Jan. 31	–	–	–	–	–	–	undetected
2011 Feb. 01–2012 Dec. 14	214.63	35.71	63.17	69.59	113	457.4	active period
2011 Feb. 01–2012 May 31	214.59	35.63	63.00	69.66	46	167.4	pre-flare
2012 Jun. 01–2012 Sep. 30	214.67	35.73	63.20	69.56	53	403.2	flare
2008 Aug. 04–2012 Dec. 14	214.64	35.71	63.16	69.59	91	364.4	full time
2008 Aug. 04–2012 Dec. 14	214.64	35.75	63.28	69.58	–	–	ML position

Notes. The mean positional accuracy of the MST detections is 0".06. The maximum likelihood position was computed with the `gtfindsrc` tool with an error circle radius of 0".02 (68% c.l.).

Fig. 1. Photon count maps centred at the new γ -ray source J1418+3542 for the data from 2008 Aug. 04–2012 Dec. 14 in the energy band 0.1–300 GeV (left panel), for the data from 2012 June 01 to 2012 September 30 (flare) in the energy band 0.1–300 GeV (central panel) and 3–300 GeV (right panel). The new source is circled at the centre of the region. White crosses mark 2FGL sources.

be further analysed with other well-recognized statistical methods, such as ML (Mattox et al. 1996), to obtain an independent evaluation of their statistical significance and to study the time and energy properties of the source. Our MST method was already applied to obtain lists of seed clusters for the 1FGL and 2FGL *Fermi*-LAT catalogues (Abdo et al. 2010; Nolan et al. 2012).

We considered all data collected by *Fermi*-LAT from 2008 August 04 to 2012 December 14 in a region in the north Galactic hemisphere, defined by a Galactic latitude $b \geq 60^\circ$. Data were filtered using the standard LAT science tools routines `gtselect` and `gtmktime` with a cut on the zenith angle ($<100^\circ$) limb γ -rays and a cut on the rocking angle ($>52^\circ$) to limit contamination from the Earth limb.

The MST analysis was applied to events in the 3–300 GeV energy range to avoid the low-energy background. This resulted in many clusters that were further filtered by applying a suitable threshold on M . Most of them matched within a 0.25° radius 2FGL sources in the region, but we also found 16 new significant clusters without any obvious γ -ray counterpart in LAT catalogues; three of them have $M > 35$ and one was found to have a very significant $M = 286.8$. The coordinates of its centre were computed by a weighted mean of the event coordinates with the inverse of their connecting edges Campana et al. (in prep.). Table 1 reports the equatorial and Galactic coordinates of the cluster centre together with the number of events and the MST magnitude for several time intervals: active period (2011 Feb. 01–2012 Dec. 14), pre-flare (2011 Feb. 01–2012 May 31), flare (2012 Jun. 01–2012 Sep. 30), all time (2008 Aug. 04–2012 Dec. 14).

The source is quite evident in Fig. 1, left panel, which shows the event count map of a region of interest (ROI)

of 20° radius centred at the position of the cluster. This ROI contains 52 2FGL sources; the new source is one of the six brightest ones in the region. The two other panels in Fig. 1 show its brightening during the flare time window.

3. Time and spectral properties

To inspect rough features in the long-term light curve (LC) of the source we performed simple photometry following the standard *Fermi*-LAT aperture photometry procedure³. Figure 2 (top panel) shows the resulting monthly LC for the entire period (2008 Aug. 04–2012 Dec. 14) in the 0.1–100 GeV energy band, obtained by selecting events within a 1° aperture radius. No model source was assumed. The background level was evaluated from a close spatial region of equal size without detectable sources. Until about 2011 February (MJD $\sim 55\,600$) the source was undetectable and remained at a quite low level until 2012 May. After that epoch its brightness increased and reached its maximum in about five weeks, followed by a decay of comparable duration.

An ML analysis was performed on data collected from 2011 Feb. 01 to 2012 Dec. 14, using the science tools package. We used the `gtselect` tool to apply the cuts suggested by the *Fermi*-LAT collaboration for point-like sources⁴ to minimize the impact of the systematics and the contamination from non-photon events. We extracted photons with energies between 100 MeV and 100 GeV, and used the `P7SOURCE_V6` class

³ http://fermi.gsfc.gov/ssc/data/analysis/scitools/aperture_photometry.html

⁴ http://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

Fig. 2. *Top panel:* monthly aperture photometry light curve for the 0.1–100 GeV band from 2008 Aug. 04 to 2012 Dec. 14. The dashed line represents the background level. *Central panel:* weekly maximum likelihood light curve in the 0.1–100 GeV band, from 2011 Feb. 01 to 2012 Dec. 14. Downward triangles represent upper limits. *Bottom panel:* time evolution of the photon index; solid lines represent the mean value over the entire interval (black line) and during the flare (red line).

event selection and the corresponding instrument response functions (IRF).

We performed the spectral analysis using an unbinned ML estimator provided by the standard tool *gtlike*, and modelled each source by means of a power law (PL). Photons were extracted from a ROI centred at the MST coordinates, within a radius of 10° . The *gtlike* region model includes all point sources from the 2FGL catalogue (Nolan et al. 2012) that fall within 15° from the source and a background component of the isotropic and Galactic diffuse emissions (standard models are available from the *Fermi* Science Support Center⁵ (FSSC)). The ML analysis produced a weekly binned LC and a full-time spectral analysis. Since the 2FGL catalogue provides a list of sources detected in a time window that does not overlap with our full-time interval, and to take into account the possible changes in the activity of the 2FGL sources in each weekly bin, we adopted an iterative ML procedure to obtain an optimal subtraction of the contribution of these sources. We selected a sub-region of the ROI with a 7° radius: all sources of the region model within this radius have both the flux and the index parameter left free to vary. The remaining sources of the region model have the flux parameter left free and the index parameter frozen at the 2FGL value. A first likelihood run was performed to remove all sources with a detection significance below 3σ and number of photons <3 from the initial region model. A second likelihood run was performed on the updated source list. Upper limits (UL)

were evaluated for all sources within the 7° radius region that were removed from the initial list. The full-time spectral analysis was performed by testing a simple power law and a log-parabola (LP), $dN/dE \propto (E/E_0)^{-\Gamma-\beta \log(E/E_0)}$ (Massaro et al. 2004; Tramacere et al. 2011). In the case of LP spectral law, the parameter β measures the curvature around the peak. The LP distribution has only three free parameters, and the choice of the reference energy E_0 does not affect the spectral shape; we fixed its value to 300 MeV. We used a TS based on the likelihood ratio test⁶ (Mattox et al. 1996) to quantify the detection significance, and to check the PL model (null hypothesis) against the LP model (alternative hypothesis). In the former case, the TS is provided directly by *gtlike*, and the corresponding detection significance given by the $\sqrt{TS}$ is a $\approx 42\sigma$ confidence level (c.l.), a very robust detection. The TS for the comparison between the PL and the LP models returns a value of about 6, corresponding to about a 2.5σ c.l., meaning that we have no statistical evidence of a curved spectral shape. The same result is obtained using a broken power law spectral model instead of an LP. The resulting weekly LC is plotted in the central panel of Fig. 2 and the corresponding photon index evolution is given in the bottom panel. For the cases where the analysis returned flux upper limits, we did not plot any photon index value. The fluctuations were around the mean value of ~ 2 , with the only possible exception of the flaring period (from MJD 56080 to MJD 56150) when it was slightly harder, around ~ 1.8 . In any case, the photon index returned by the likelihood analysis can be biased when the statistics is low, hence we cannot draw any firm conclusion about a spectral change. The full-time spectral energy distribution (SED) is reported in Fig. 3: there is a mild indication of a steepening at high energies, although it is not statistically significant considering the rather large uncertainties. The best-fit parameters for the LP model are $\Gamma = 1.82 \pm 0.06$ at $E_0 = 300$ MeV, $\beta = 0.07 \pm 0.02$, while for the PL model they are $\Gamma = 2.03 \pm 0.03$. The 0.1–100 GeV integral flux during the activity period is $(1.14 \pm 0.06) \times 10^{-7}$ ph cm $^{-2}$ s $^{-1}$. The source has a marginally significant detection in the pre-active period 2008 Aug.–2011 Jan. with a $TS = 19^7$ and a 0.1–100 GeV flux of $(1.1 \pm 0.4) \times 10^{-8}$ ph cm $^{-2}$ s $^{-1}$.

4. Search for a possible counterpart

Considering that the accuracy for the coordinates of γ -ray sources detected above a few GeV is of a few arcminutes, we searched for possible counterparts within a cone of radius of $10'$ centred at the source's position using the ASDC sky explorer tool⁸. There are only a few interesting objects: the radio-quiet QSO SDSS J14186+3542 ($z = 1.58$) at $2:07$, the X-ray source 1WGAJ1418.1+3543 at $4:63$, which are not associated with a radio and optical source, and the radio source GB6 J1418+3542 at the angular distance of $1:23$ and with a radio flux density at 4.85 GHz of about 40 mJy. The last object appears as the most promising one. It is detected also at 1.4 GHz in the FIRST and NVSS catalogues which report flux densities of 52 and 61 mJy, respectively, and therefore its spectrum is rather flat. Well coincident with the FIRST position is the source SDSS J141828.58+354249.4 (RA = $214^\circ 62'$, Dec = $35^\circ 71'$)

⁶ The TS statistics is defined as $-2 \log(L_0/L_1)$, where L_0 and L_1 are the maximum likelihood estimated for the null and alternative hypothesis, respectively.

⁷ The 2FGL catalogue (Nolan et al. 2012) used a threshold of $TS = 25$ and an integration time $\sim 20\%$ shorter.

⁸ <http://www.asdc.asi.it/>

⁵ <http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

Fig. 3. Spectral energy distribution of the new source J1418+3542. Solid blue lines are the PL best fit uncertainty range, while red dashed lines correspond to the LP fit.

having $r = 19.74$ mag and a colour index $u - r = 0.30 \pm 0.05$, corrected for the local interstellar reddening, which is quite low at this high Galactic latitude. This blue colour index is remarkably close to that of BL Lac objects of N type (Massaro et al. 2012a) and of many flat spectrum radio quasars (FSRQs) associated with γ -ray sources, providing a high confidence in the association with the new flaring γ -ray source. This source is positionally consistent ($0''.41$ offset) with the IR counterpart listed in the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) WISE J141828.61+354249.3, which according to the WISE All-sky catalogue⁹ is detected in the first three energy bands with the following magnitudes: $3.4 \mu\text{m} = 14.983 \pm 0.034$, $4.6 \mu\text{m} = 14.215 \pm 0.042$, $12 \mu\text{m} = 11.958 \pm 0.185$. The three-dimensional association procedure outlined in Massaro et al. (2012c,b) cannot be entirely applied to verify if WISE J141828.61+354249.3 has IR colours consistent with those of a blazar because it is not detected at $22 \mu\text{m}$. However, in the $[3.4] - [4.6] - [12] \mu\text{m}$ colour-colour diagram, it is consistent with typical IR colours of a high-synchrotron-peaked BL Lac (HBL) as described in Massaro et al. (2011) for the TeV BL lac objects. Finally, we note that the radio source FIRST J141828.5+354249 is positionally consistent both with SDSS ($0''.53$ offset) and with WISE ($0''.49$ offset) sources. Optical spectroscopic data of this source are not available and we cannot safely establish whether it is a BL Lac object or a FSRQ. Nevertheless its blazar nature appears to be well established and therefore it must be considered as the most interesting candidate for the counterpart of our new source. The same source was also indicated by the follow-up *Swift*-UVOT observations of Dutka et al. (2012) as the most likely counterpart.

5. Discussion

The high-energy γ -ray sky, according to the new scenario derived from *Fermi*-LAT observations, appears to be dominated by thousands of sources, many of which are observed to be variable over different time scales. Searching for transient sources is useful to investigate their behaviour and, particularly, to evaluate the typical duration of their activity periods and the possible

relations with their luminosity and spectral properties, which in turn useful for estimating their contribution to the diffuse background in different energy bands. The new γ -ray source, found by us by means of the MST algorithm at energies higher than 3 GeV with $M = 286.6$, is clearly bright enough to be detected by any method. Its discovery was reported to the astronomical community after a new flare occurred on November 20 (Dutka et al. 2012; Mahabal et al. 2012) when our analysis was already complete. Selecting shorter time windows during the flaring period would produce a large increase of M even though the event number in the cluster is reduced, which confirms that M is a good indicator of the signal-to-noise ratio. Table 1 shows that the positional accuracy of our MST implementation is very good, which confirms that this clustering method is very promising for the detection and location of transient sources.

The time and spectral behaviour of J1418+3542 in the γ -ray band appear to be those of a blazar. Therefore we are confident about the proposed counterpart; we cannot safely establish, however, whether it is a BL Lac object or a FSRQ because its properties appears to be borderline between these two types. Radio and γ -ray spectra are suggestive of a quasar, while the IR WISE colours are those of a HBL source. Spectral measurements in the optical band would be very useful to establish its nature.

Finally, we underline that the brighter flare has a typical FWHM duration (5 months) of about 10% of the entire observation period, suggesting that an elusive population of extragalactic sources characterized by even shorter activity time intervals can actually exist and contribute to the isotropic background. Efficient tools for detecting these sources are therefore very useful for a complete description of the high-energy cosmic landscape.

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⁹ <http://wise2.ipac.caltech.edu/docs/release/allsky/>