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Application of the MST clustering to the high energy γ -ray sky.

III - New detections of γ -ray emission from blazars

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Abstract We present the results of a photon cluster search in the γ -ray sky observed by the *Fermi* Large Area Telescope, using the new Pass 8 dataset, at energies higher than 10 GeV. By means of the Minimum Spanning Tree (MST) algorithm, we found 25 clusters associated with catalogued blazars not previously known as γ -ray emitters. The properties of these sources are discussed.

Keywords γ -rays: observations – γ -rays: source detection

1 Introduction

In two previous papers, Campana et al. (2015, hereafter Paper I) and Campana et al. (2016, hereafter Paper II), we successfully applied a cluster-finding method, the Minimum Spanning Tree (hereafter MST) algorithm, to the *Fermi*-LAT sky at energies higher than 10 GeV. The aim was to search new clusters in the arrival directions of γ -ray photons, which could be an indication for localized high energy sources. These papers illustrated the good performance of MST for finding clusters having a small number of photons, but likely related to pointlike sources.

In particular, in Paper I we applied the algorithm to the 6.3 years LAT Pass 7 dataset, searching for sources coincident with blazars not previously known as γ -ray emitters, because these objects are the majority of identified sources at these high energies (see the recent review paper by Massaro et al. 2016). The most recent and improved release of the LAT data (Pass 8, Atwood et al. 2013) was used in Paper II for an MST search of clusters likely associated with new High Synchrotron Peaked infrared-selected candidate blazar sources reported in the 1WHSP catalogue (Arsioli et al. 2015).

In this paper we report the results of a new MST analysis in the same Pass 8 sky (above 10 GeV for Galactic latitudes $b > |25^\circ|$) which gave a list of 25 clusters located very close to blazars reported in the 5th Edition of the Roma-BZCAT (Massaro et al. 2014, hereafter 5BZCAT) but not in Fermi Collaboration catalogues (2FGL, Nolan et al. 2012; 3FGL, Acero et al. 2015; 1FHL, Ackermann et al. 2013). Three of these clusters, however, correspond to sources in the 2FHL catalogue (The Fermi-LAT Collaboration 2015). As in Paper II we adopted more severe selection criteria with respect to those used in the Paper I to obtain a “safer” sample.

In Section 2 the MST algorithm is briefly summarized, while in Section 3 we discuss its application to the *Fermi*-LAT sky and the properties of the selected clusters. In Section 4 the standard maximum likelihood analysis is applied to the candidate sources, in Section 5 some of these sources are discussed in detail and in Section 6 we draw our conclusions.

2 Photon cluster detection by means of the MST algorithm

In this Section a short summary of the MST algorithm principal characteristics is given. A more detailed description of the method is presented in Papers I and II,

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and an extensive discussion of its statistical properties can be found in Campana et al. (2008, 2013).

The Minimum Spanning Tree algorithm is based on graph theory and searches for clusters in a field of N points (*nodes*). The MST is the (unique) graph without closed loops, i.e. a *tree*, that connects all the nodes with the minimum total weight. In our case, the node coordinates are the photon arrival directions on the celestial sphere, and the edge weights λ_i are the angular distances between the locations of photon pairs. The total weight is simply the sum of all the edges.

After the computation of the MST, a 2-step *primary selection* extracts a set of subtrees corresponding to photon clusters. The first step (*separation*) removes all the edges having a length $\lambda > \Lambda_{\text{cut}}$, the separation value, usually defined in units of the mean edge length $\Lambda_m = (\sum_i \lambda_i)/N$. The resulting set of disconnected subtrees is further filtered by the second step (*elimination*), that removes all the sub-trees having a number of nodes $n \leq N_{\text{cut}}$, leaving only the clusters having a size over a properly fixed threshold. A first list of clusters is therefore given by remaining set of sub-trees.

A *secondary selection* is then applied to extract the most robust candidates for γ -ray sources. A suitable parameter for this selection was found to be the *magnitude* of the cluster, defined as $M_k = n_k g_k$, where n_k is the number of nodes in the cluster k and the *clustering parameter* g_k is the ratio between Λ_m and $\lambda_{m,k}$, the mean length of the k -th cluster edges. As shown in Campana et al. (2013), \sqrt{M} has a linear correlation with other statistical significance parameters and that it can be a good estimator of the significance of a MST cluster. Usually (Campana et al. 2013, Papers I, II) a lower threshold of $M \sim 20$ is used.

From a weighted mean of the cluster photon's coordinates the *cluster centroid* location can be computed (see Campana et al. 2013). Another quantity that can be evaluated in order to investigate the compatibility of the cluster with a γ -ray source is the radius of the circle centred at the centroid and containing the 50% of photons in the cluster, the *median radius* R_m . For a cluster likely associated with a genuine pointlike γ -ray source, R_m should be smaller than or comparable to the 68% containment radius of instrumental Point Spread Function (PSF). This radius varies from $0^\circ 25$ at 3 GeV to $0^\circ 12$ at 10 GeV in the case of front-converting events (Ackermann et al. 2013), using the latest instrumental response files¹. We also expect that the angular distance between the positions of the cluster centroid and the possible optical counterpart are lower than the latter value.

3 The MST cluster populations

As reported in Paper II, *Fermi*-LAT data (Pass 8) above 10 GeV, covering the whole sky in the 7 years time range from the start of mission (2008 August 04) up to 2015 August 04, were downloaded from the FSSC archive². Standard cuts on the zenith angle (100°) and data quality were applied.

The search for clusters of γ -ray photons by means of MST was performed after the exclusion of the Galactic belt up to a latitude $|b| \leq 25^\circ$ to reduce the possibility of finding clusters originated by local high background fluctuations. Each of these two spherical broad regions was then divided into ten smaller parts where MST was applied. The parameters of primary selection of clusters in the 10 GeV sky were $N_{\text{cut}} = 4$ and $\Lambda_{\text{cut}} = 0.7\Lambda_m$; then a secondary selection was applied with a rather robust threshold, $M > 20$. A sample of 921 clusters was obtained, of which 716 have a firm 2FGL or 3FGL counterpart and one is coincident with the well known GRB 130427A (Maselli et al. 2014; Ackermann et al. 2014). For 165 clusters 1FHL counterparts were found, five of which not included in the 3FGL catalogue. Therefore, the remaining sample contains 199 clusters, of which 189 are not related to previously known γ -ray sources and 10 are associated with the very recently published 2FHL catalogue (The Fermi-LAT Collaboration 2015) at energies higher than 50 GeV, also based on the Pass 8 sky.

The superposition of the positions of these 199 clusters with the 5BZCAT blazars with a positional matching within a maximum angular separation, computed using the cluster centroids' coordinates, of $6'$ ($0^\circ 1$, this value was found in Paper I to be optimal), provided 34 clusters: 9 of them were already found in Paper I using the Pass 7 sky³ and the remaining 25 new clusters are listed with their most important parameters in Table 1.

Three of these 25 clusters were found to match new sources in the 2FHL catalogue (The Fermi-LAT Collaboration 2015) at energies higher than 50 GeV. Their angular distance is lower than $2'$ and therefore these associations can be considered as safe. These 3 sources are reported in the lower section of Table 1, where their 2FHL counterpart is also shown. Therefore, a total of 22 clusters associated with blazars not previously known as γ -ray emitters is found. It should be pointed out that, as shown in Table 1, 4 of these clusters are in good positional coincidence (between $0^\circ 05$ and $0^\circ 24$)

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

³In that paper a more loose selection threshold was used, $M > 15$. See also Section 6 for a discussion.

¹http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Table 1 Coordinates and main properties of MST clusters detected at energies higher than 10 GeV ($\Lambda_{\text{cut}} = 0.7 \Lambda_m$, $N_{\text{cut}} = 4$) associated with 5BZCAT sources. The second and third columns give the J2000 coordinates of MST clusters, angular distances $\Delta\theta$ are computed from these values and the catalogue positions of the 5BZCAT sources. In the last column, *c* indicates a candidate BL Lac in the 5BZCAT, *el* the presence of emission lines in the optical spectrum, *conf* a possible confusion, e.g. the presence of more than one possible counterpart. The lower section of the table reports the clusters associated with 2FHL sources.

MST cluster	RA J2000	DEC J2000	5BZCAT source	$\Delta\theta$ '	<i>n</i>	<i>g</i>	<i>M</i>	R_m °	Note
MST 0216+2314	34.050	23.185	5BZB J0216+2314	5.9	13	3.466	45.058	0.117	c
MST 0219−1725	34.767	−17.376	5BZB J0219−1725	1.7	9	3.162	28.460	0.113	
MST 0314+0619	48.576	6.341	5BZB J0314+0619	1.5	7	4.837	33.856	0.033	D3PO ¹
MST 0503−1115	75.889	−11.228	5BZB J0503−1115	1.5	6	5.024	30.146	0.043	D3PO ²
MST 0712+5719	108.171	57.337	5BZB J0712+5719	3.0	9	2.328	20.951	0.112	
MST 0723+5841	110.893	58.677	5BZB J0723+5841	2.7	8	3.736	29.890	0.058	c, 1FGL [†]
MST 0820+2353	125.237	23.889	5BZB J0820+2353	1.4	6	3.708	22.247	0.037	
MST 0828+2312	126.985	23.161	5BZB J0828+2312	2.9	8	2.854	22.836	0.081	
MST 0913+8133	138.496	81.552	5BZB J0913+8133	1.3	9	2.745	24.704	0.070	
MST 1055−0126	163.910	−1.439	5BZB J1055−0126	1.0	10	6.300	63.003	0.058	D3PO ³
MST 1105+3946	166.469	39.747	5BZG J1105+3946	2.1	6	8.265	49.588	0.024	
MST 1134−1729	173.667	−17.482	5BZB J1134−1729	1.1	9	2.522	22.700	0.094	
MST 1208+3015	182.000	30.296	5BZB J1208+3015	2.1	5	4.073	20.366	0.038	
MST 1215+0732	183.767	7.516	5BZG J1215+0732	2.0	5	5.547	27.735	0.018	
MST 1402+1559	210.658	15.989	5BZB J1402+1559	1.7	5	4.031	20.153	0.042	el
MST 1449+2746	222.389	27.780	5BZG J1449+2746	0.5	9	2.717	24.450	0.094	conf
MST 1506−0540	226.623	−5.677	5BZB J1506−0540	1.9	6	5.584	33.501	0.018	
MST 1515+2426	229.000	24.395	5BZG J1515+2426	2.8	7	3.488	24.416	0.062	
MST 1518+4045	229.637	40.737	5BZG J1518+4045	1.4	7	5.382	37.671	0.035	
MST 2148−0733	327.011	−7.556	5BZB J2148−0733	1.2	6	4.508	27.047	0.029	D3PO ⁴
MST 2156−0037	329.087	−0.625	5BZU J2156−0037	1.3	9	4.122	37.096	0.078	
MST 2254−2725	343.733	−27.415	5BZB J2254−2725	0.6	7	4.112	28.783	0.049	
MST 0022+0008	5.492	0.135	5BZG J0022+0006	1.3	10	2.629	26.291	0.136	2FHL ^a
MST 0115−3400	18.742	−34.004	5BZB J0115−3400	0.8	9	4.786	43.077	0.032	2FHL ^b
MST 0304−0055	46.160	−0.921	5BZB J0304−0054	1.6	8	3.515	28.122	0.094	2FHL ^c

[†]1FGL J0722.3+5837. See text for discussion.

¹1DF163831; ²1DF145964; ³1DF022985; ⁴1DF164164

^a2FHL J0022.0+0006; ^b2FHL J0114.9-3359; ^c2FHL J0304.5-0054;

Table 2 Standard unbinned likelihood analysis of the *Fermi*-LAT data, see Sect. 4 for details. The third and fourth columns report photon fluxes in units of 10^{-11} ph cm $^{-2}$ s $^{-1}$. For sources below the usual significance threshold ($\sqrt{TS} = 5$) only upper limits are given. Radio, optical data and redshift from 5BZCAT are also given.

MST cluster	\sqrt{TS}	Flux 3–300 GeV	Flux 10–300 GeV	Photon index	$F_{1.4}$ mJy	R	z
MST 0216+2314	6.4	10.0 ± 2.8	3.3 ± 1.1	1.9 ± 0.3	36	18.4	0.288
MST 0219–1725	8.3	10.0 ± 2.4	2.9 ± 1.0	2.0 ± 0.3	62	17.1	0.128
MST 0314+0619	9.2	13.0 ± 2.9	3.7 ± 1.2	2.0 ± 0.3	29	17.5	—
MST 0503–1115	8.0	10.0 ± 2.5	3.3 ± 1.1	1.9 ± 0.3	10	19.9	—
MST 0712+5719	4.3	< 4.9	< 1.0	—	8	20.1	0.095
MST 0723+5841	4.6	< 4.7	< 1.0	—	16	18.2	—
MST 0820+2353	6.3	5.0 ± 1.7	2.0 ± 0.8	1.7 ± 0.3	49	18.0	0.402
MST 0828+2312	4.2	< 4.3	< 1.4	—	36	19.9	—
MST 0913+8133	4.8	< 5.2	< 1.1	—	5	20.4	0.639
MST 1055–0126	8.5	9.0 ± 2.5	4.2 ± 1.3	1.6 ± 0.2	12	18.5	—
MST 1105+3946	6.1	5.8 ± 1.9	1.7 ± 0.8	2.0 ± 0.4	43	15.1	0.099
MST 1134–1729	4.8	< 5.5	< 1.7	—	5	19.2	0.571
MST 1208+3015	6.1	6.1 ± 1.8	2.2 ± 0.8	1.8 ± 0.1	36	22.1	—
MST 1215+0732	6.7	6.8 ± 2.1	2.3 ± 0.9	1.9 ± 0.3	137	16.4	0.136
MST 1402+1559	4.5	< 3.1	< 0.9	—	849	17.7	0.244
MST 1449+2746	6.3	4.1 ± 1.5	2.1 ± 0.9	1.5 ± 0.4	91	18.2	0.227
MST 1506–0540	6.1	6.7 ± 2.3	1.8 ± 0.8	2.1 ± 0.4	15	19.1	0.518
MST 1515+2426	5.1	3.8 ± 1.5	1.7 ± 0.8	1.6 ± 0.4	34	17.9	0.228
MST 1518+4045	7.7	8.8 ± 2.2	2.0 ± 0.8	2.2 ± 0.3	44	15.1	0.065
MST 2148–0733	7.6	8.9 ± 2.4	2.6 ± 1.0	2.0 ± 0.3	8	18.4	—
MST 2156–0037	9.3	17.0 ± 3.3	3.4 ± 1.1	2.3 ± 0.3	233	20.9	0.495?
MST 2254–2725	9.6	14.0 ± 3.0	3.3 ± 1.1	2.0 ± 0.3	53	17.8	0.333
MST 0022+0008	6.9	6.0 ± 3.1	3.2 ± 1.5	1.4 ± 0.7	2	18.6	0.306
MST 0115–3400	8.4	5.8 ± 1.7	3.2 ± 1.1	1.4 ± 0.1	6	19.1	0.482
MST 0304–0055	6.3	6.7 ± 2.2	2.5 ± 1.0	1.8 ± 0.3	28	18.6	0.511

with sources included in the D3PO⁴ catalogue (Selig et al. 2014).

In the 5BZCAT the large majority (18) of these associated blazars are classified as BL Lac objects (BZB), six are classified as galaxy-dominated blazars (BZG) while one is a blazar of uncertain classification (BZU).

Remarkably, no Flat Spectrum Radio Quasar (BZQ), the most numerous class of blazars in the 5BZCAT with 1909 objects over a total of 3561 sources ($\sim 54\%$), was found. If the MST-5BZCAT associations were due to chance, it could be expected that more than 50% of blazars should be BZQ. A simple calculation of the binomial probability to have zero positive cases over 25 with a probability of $1909/3561 = 0.536$ gives the very low value of $\approx 5 \times 10^{-9}$.

An estimation of the expected number of correspondences N_{ex} assuming a random matching between MST cluster centroids and catalogued sources can be derived (see also Paper II) from the ratio between the sum of solid angles of clusters ω_i to the total solid angle of the explored sky region Ω , multiplied by the number of blazars N_b :

$$N_{\text{ex}} = N_b \frac{\sum_i \omega_i}{\Omega} = N_c N_b \frac{\omega}{\Omega} \quad (1)$$

where N_c is the number of clusters, assumed all having the same solid angle ω corresponding to a circular region of radius equal to 0.1. From $\Omega = 7.256$ sr and $\omega = 9.57 \times 10^{-6}$ sr, with $N_c = 199$ and $N_b = 1652$, that is the number of objects in the 5BZCAT excluding FSRQs (BZQ), we obtain $N_{\text{ex}} = 0.43$, a value much smaller than our result.

⁴The Denoised, Deconvolved, and Decomposed Fermi γ -ray Sky, <http://www.mpa-garching.mpg.de/ift/fermi/>. Note that this catalogue uses data starting from 600 MeV, where the PSF and the source localisation is worse.

4 Maximum likelihood analysis

Similarly to the analysis performed in Papers I and II, a standard unbinned likelihood analysis was done for each MST cluster. The Region of Interest (ROI), with a radius of 10° , is centered at the MST cluster centroid coordinates, and standard screening criteria were applied to the *Fermi*-LAT data above 3 GeV. This lower energy threshold was chosen in order to confirm the detection of sources also at lower energies, where MST is less efficient for selecting clusters because of the much higher photon density and the presence of a rich population of bright sources. The likelihood analysis was performed considering all the 3FGL sources within 20° from the cluster centroid, as well as the Galactic and extragalactic diffuse emission. A further source with a power-law spectral distribution was assumed at the MST coordinates. The normalization and spectral index of all the 3FGL sources within the ROI was allowed to vary in the fitting, while the parameters of the sources between 10° and 20° from the center of the field of view were fixed to their catalogue values. The likelihood Test Statistics (TS) was derived from this analysis, together with the fluxes in the two 3–300 and 10–300 GeV bands for the sources with $\sqrt{TS} > 5$. The results are reported in Table 2.

ML analysis thus confirmed all these findings and only six objects have $4 < \sqrt{TS} < 5$: two of them have a high clustering with $g > 3$, whereas for the other four clusters it is lower. In the following subsections we discuss about the actual significance of these detections.

Finally, the aperture photometry lightcurve was computed for each cluster. No significant variability was detected for any source.

4.1 High g clusters with low TS

The two panels in Figure 1 show the $6^\circ \times 6^\circ$ regions containing the two low-significance clusters that have high g values (MST 0723+5841 and MST 1402+1559): in both panels all the known BL Lac objects correspond to photon clusters detected at energies above 10 GeV and also above 7 GeV.

In the left panel three blazars corresponding to clusters are visible: 5BZB J0723+5841 is located close to the most significant cluster (marked with “A” in the figure); it was already reported in the 1FGL catalogue with a statistical significance of 4.56σ and a photon flux of $(6.26 \pm 2.66) \cdot 10^{-10}$ ph cm $^{-2}$ s $^{-1}$ but not confirmed in the 2FGL and 3FGL catalogues. The other two blazars were previously undetected in the γ -ray band: 5BZB J0712+5719 is very close to the low g cluster MST 0712+5719 (marked with “B”, see next Section) and

5BZG J0737+5941 is near a cluster detected above 7 GeV but below our M threshold at higher energy. The latter object is a flat spectrum radio galaxy (UGC 3927, S4 0733+59) at the redshift $z = 0.0405$ already considered as a possible GeV-TeV source (Abdo et al. 2009).

The region on the right panel contains three known BL Lacs of which only one was already reported as a 3FGL source. One of the other two corresponds to the cluster found in this work, while no apparent concentration of high energy photons is close to the other 5BZ-CAT object.

It is interesting to note that, in addition to two low significance clusters, there is another one with 7 photons (>10 GeV) but a very high $g = 5.259$ and $M = 36.811$ (marked as “B” in the map) without an obvious counterpart. The centroid of this cluster is at only $\sim 20''$ from the flat spectrum radio source TXS 1408+148, with the optical counterpart SDSS J141028.05+143840.1 a galaxy at $z = 0.144$ and proposed as a γ -ray candidate by D’Abrusco et al. (2014) on the basis of its WISE colours. We found several other clusters with similar characteristics and not associated to known blazars or candidate, and this topic will be discussed in a forthcoming paper.

It appears, therefore, that the associations of these three low- TS , high- g clusters with BL Lac objects could be considered safe. In particular, the early 1FGL γ -ray detection of 5BZB J0723+5841 is now confirmed by the well apparent photon cluster above 10 GeV in Figure 1.

4.2 Low g clusters with low TS

Clusters with g values lower than 3 can reach a significance above the TS threshold, as in the cases of MST 1449+2746 (associated with 5BZG J1449+2746) and MST 0022+0008 (5BZG J0022+0006 and 2FHL J0022.0+0006), but more frequently they are also found with $\sqrt{TS} < 5$. This fact can be interpreted in different ways, considering that their photon number must generally be higher than 8 to reach the M threshold for the secondary selection. The low clustering can be thus due either to a small dense core in a low density halo or to a rather sparse cluster structure. In any case, these clusters do not have a good *stability*, in the sense that a small change of the selection parameters, as the size of the search region (affecting the value of Λ_m) or the adopted Λ_{cut} , can produce a variation of M across the threshold. These clusters might be related to weak sources but the possibility of a local background fluctuation cannot be excluded. In any case, an inspection with a finer study of their environment could help to understand their nature.

The cluster MST 0712+5719 corresponding to the BL Lac object 5BZB J0712+5719, that has the lowest

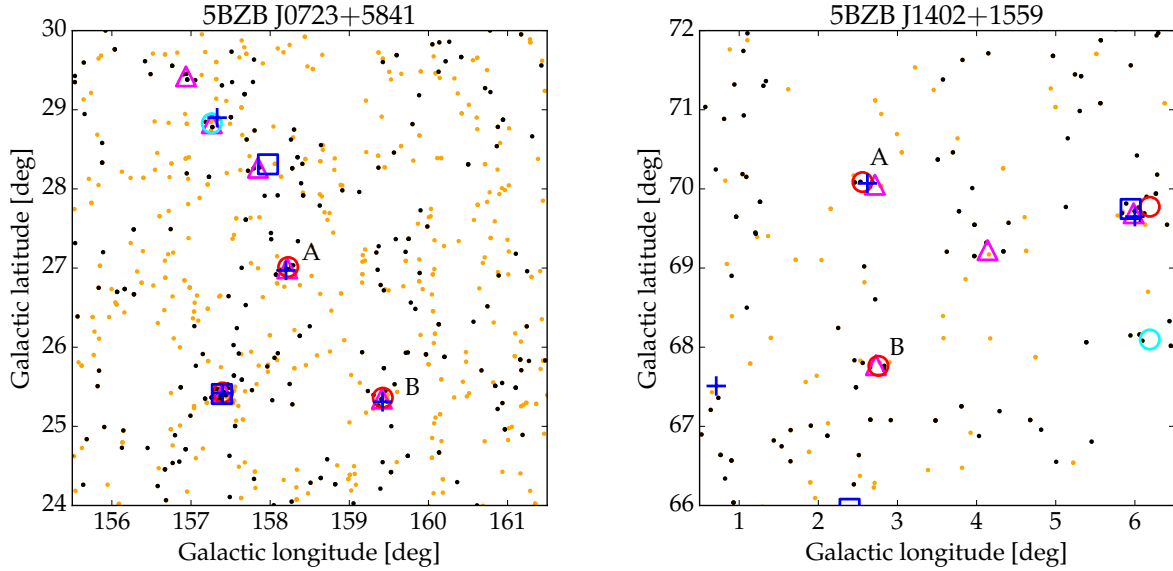


Fig. 1 Photon sky maps in Galactic coordinates of regions containing the BL Lac objects 5BZB J0723+5841 (left panel), and 5BZB J1402+1559 (right panel). Black filled circles mark the photon coordinates at energies higher than 10 GeV, **orange** points are photons with energies in the range [7, 10] keV; large black crosses correspond to the optical coordinates of BL Lac objects in the 5BZCAT blue open squares are the 3FGL sources, open red circles are the MST (>10 GeV, $M > 20$) cluster positions, **cyan** open circles are lower-significance clusters with $12 < M < 20$ and triangles are clusters detected at energies higher than 7 GeV ($M > 15$). In each panel the letter A marks the 5BZCAT source. The letter B in the left panel indicates the cluster corresponding to 5BZB J0712+5719 and in the right panel another interesting cluster discussed in the text and up to now not associated with a known blazar or γ -ray source.

g , is indicated by the letter “B” in the photon map in the left panel of Figure 1. As noticed above all the clusters at energies higher than 10 GeV present in this region were found very close to blazars and thus it appears very unlikely that random background fluctuations have such a good positional matching. In these $6^\circ \times 6^\circ$ fields the only clusters present are all coincident with BL Lac objects.

In the field of MST 0828+2312, whose g is close to 3, there are only three clusters above the M threshold (one corresponding to a 3FGL source and the other to 5BZB J0820+2353) and all are matching BL Lac positions. There is only one cluster (MST 0913+8133, $M > 20$) in a $6^\circ \times 6^\circ$ field around 5BZB J0913+8133 with a very good positional correspondence. Again, three clusters ($M > 20$) are in the last $6^\circ \times 6^\circ$ field: one is MST 1134–1729 associated with 5BZB J1134–1729, another matches a 3FGL source and the other corresponds to 5BZB J1137–1710. All these clusters in a very good positional agreement with BL Lac objects.

In conclusion, the analysis in small sky regions around all these objects demonstrated that all the selected clusters are related to astrophysical objects candidate to be γ -ray sources and the possibility that they are due to background density fluctuations at a so high energy could be considered negligible for all practical purposes.

5 Properties of the newly detected blazars

In Table 2 we reported in addition to γ -ray significance and spectral data some other interesting parameters: the radio flux density at 1.4 GHz from NVSS or FIRST, optical magnitude in the R or r (SDSS) bands and the redshift z , useful for the understanding of the main properties of these blazars.

Two of the BL Lac objects found in this search are classified as candidate in the 5BZCAT, while the other 16 are confirmed. Optical spectra of the latter type are therefore available in the literature or in the web, while those of the former ones are unpublished. Spectra are generally dominated by a continuum with a blue excess typical of HBL objects. 14 of the 18 BL Lacs are also in the 1WHSP catalogue (Arsioli et al. 2015) supporting this classification.

Note that there are six BL Lac objects at $z > 0.4$, two of which are also in the 2FHL catalogue. In the 5BZCAT redshifts are reported for 437 BL Lac objects and 208 have a value higher than 0.4. Figure 2 shows the plot of the radio flux density at 1.4 GHz as a function of z for the subsample of the latter sources. At radio flux densities higher than 100 mJy a large fraction of BL Lac objects was already detected in the γ -rays (magenta circles) whereas below this value the number

of detections decreases rapidly and none is present below 10 mJy. Three of our six sources are at flux levels under this limit. This result indicates that our findings increased the number of low luminosity sources detected at these energies.

In the following subsections the properties of some individual sources, in particular those classified as BZG and BZU, are discussed.

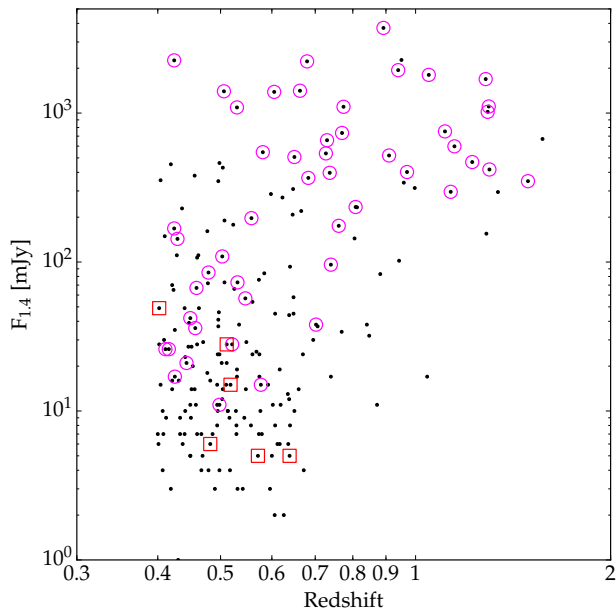


Fig. 2 Radio flux density at 1.4 GHz vs redshift for the BZB sources with $z > 0.4$ in the 5BZCAT (black points); large magenta circles mark sources previously detected at γ -ray energies while red squares mark the seven sources found in the present work.

5.1 5BZB J1402+1559

This source has the highest flux density in our sample and its optical spectrum presents either emission lines with a borderline equivalent width $EW \approx 6 \text{ \AA}$ between the typical values for BL Lacs and quasars or a featureless power law continuum (Falomo et al. 1994). In the 5BZCAT it is listed among BZB sources but a note claims for a possible BZU classification. A VLA image at 20 cm (Antonucci and Ulvestad 1985) reveals an extended complex structure with a dominant compact core and the radio spectrum can result steep according to the used resolution. In D’Abrusco et al. (2014) it was proposed as a candidate γ -ray source because its WISE mid-infrared colours are similar to those of confirmed γ -ray blazars. The present detection confirms these expectations for the occurrence of a blazar core.

5.2 5BZU J2156–0037

This optically faint source was classified of *uncertain* type in the 5BZCAT because the available spectra (Hook et al. 2003, SDSS) are noisy and the occurrence of weak emission lines could not be excluded. The redshift $z = 0.495$ given by Jackson et al. (2002) is therefore unsafe. It is possible that this source is a far BL Lac object similar to the other ones found in this search, and new spectroscopic analysis will be useful to establish its nature. In any case the detection in the high energy γ -ray band is strongly supported by the very significant $\sqrt{TS} = 9.3$.

5.3 The 5BZG sources

The 5BZCAT reports 274 BZG sources and only 27 of them ($\sim 10\%$) are associated with γ -ray sources. In Table 1 there are 6 objects of this type with redshifts in the range from 0.065 to 0.306; all were confirmed with $\sqrt{TS} > 5.0$ by the maximum likelihood analysis. Some of them exhibit characteristics closer to radio galaxies than BL Lacs and therefore are presented in some detail in the following.

5.3.1 5BZG J0022+0006

In the present sample this object is the faintest radio source. It was first indicated as a possible BL Lac counterpart to a ROSAT source by Brinkmann et al. (2000) and later by Collinge et al. (2005) using SDSS spectra. The WISE colours ($W1 - W2 = 0.34$, $W2 - W3 = 1.97$) are compatible with the blazar region defined by D’Abrusco et al. (2014). Its spectrum in SDSS, however, presents a clear dominance of the host galaxy emission with a well evident Ca H&K break. There is also a very close γ -ray source in the 2FHL catalogue at energies above 50 GeV (The Fermi-LAT Collaboration 2015).

5.3.2 5BZG J1105+3946

This source is in the compact group of galaxies Shk 007 (Shakhbazyan 1973; Stoll et al. 1996, see also Figure 3). It is a CLASS source reported as a blazar by Marchã et al. (2001) and is also in the Low-frequency Radio catalogue of Flat-spectrum Sources by Massaro et al. (2014). The SDSS optical spectrum is typical of an elliptical galaxy with some narrow emission lines. No X-ray detection is reported. WISE colours ($W1 - W2 = 0.41$, $W2 - W3 = 2.27$) are marginally compatible with the *locus* occupied by γ -ray blazars in the colour space (D’Abrusco et al. 2014). There is a Planck source at about $2'2$ (Planck Collaboration et al. 2014). This source appears likely as an active radio galaxy rather than a typical BL Lac object.

5.3.3 5BZG J1215+0732

This source, also known as 1ES 1212+078, is apparently located inside the galaxy cluster GMBCG J183.79574+07.53462, whose spectroscopic redshift is not known but the photometric estimate is 0.227, that if confirmed is about 70% higher than the one of the 5BZG source. It is generally reported in the literature as a BL Lac object, but the optical emission in the SDSS spectrum appears dominated by the host galaxy component. A VLA radio image (Rector et al. 2003) shows a jet elongating for about 50 pc and in Massaro et al. (2013) it was proposed as a TeV emitter candidate on the basis of ROSAT and WISE data. The present detection above 10 GeV confirms the BL Lac properties of this source.

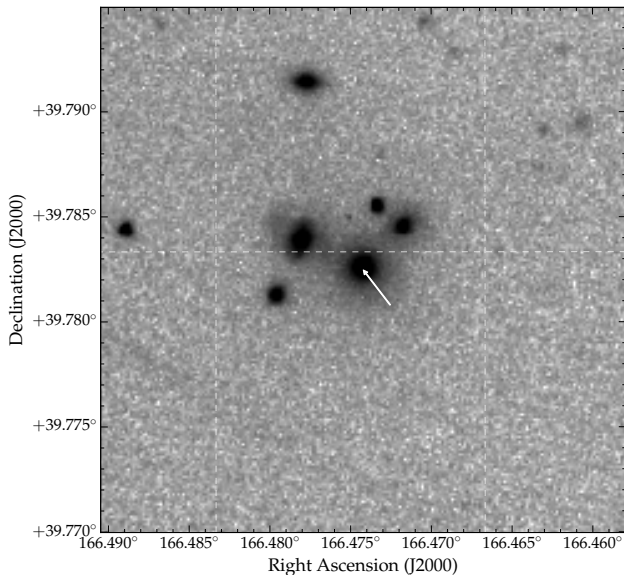


Fig. 3 Image of the compact group of galaxies Shk 007 with 5BZG J1105+3946 indicated by the arrow (adapted from SDSS *r*-band image). The image side is 1'.5.

5.3.4 5BZG J1449+2746

This BZG object is the closest to the MST cluster centroid position. It is a good candidate as high energy source because it was identified as the counterpart to a ROSAT source and is classified as a HBL. However, this is a case of possible confusion because there is another object that could be also associated with the γ -ray emission. The closer and brighter galaxy MCG +05-35-018 ($z = 0.030$) is at only 1'.20; it is also reported in the CRATES catalogue because of its flat radio spectrum and is considered variable by Thyagarajan et al. (2011). Moreover, there is the galaxy cluster MSPM 00116 ($z = 0.031$), that could be partially responsible for X and radio emission.

5.3.5 5BZG J1515+2426

This radio source was classified as a BL Lac object by Brinkmann et al. (2000), but in SDSS it appears a red galaxy ($u - r = 1.88$). No other interesting possible counterpart to the γ -ray cluster can be found up to a 12' radius.

5.3.6 5BZG J1518+4045

This flat spectrum radio source was identified as the counterpart of a ROSAT source (Laurent-Muehleisen et al. 1997; Brinkmann et al. 2000) and reported as a weak line AGN in the CLASS BL Lac sample (Marchã and Caccianiga 2013). The SDSS spectrum of this galaxy presents several emission lines ($H\alpha$, NI , SI , OII), the high Ca H&K break and the colour $u - r = 2.60$ that justify its classification as a BZG source in the 5BZCAT, while in the previous editions it was named as BZU. Moreover, the WISE colours are largely outside the *locus* occupied by γ -ray blazars in the colour space (D'Abrusco et al. 2014) and close to the regions of stars and normal galaxies. This source, therefore, could be a transition object between a radio galaxy and a blazar.

6 Summary and discussion

Our application of MST for searching localized photon clusters in the LAT Pass 8 sky confirmed the good performances of this method. We verified also the consistency of the Paper I (Pass 7) sources with the Pass 8 sky: 15 of the 19 detected clusters in the older data were confirmed with a comparable or higher significance; in some cases a reduced number of photons was overcompensated by a higher clustering parameter. Two the remaining 4 clusters (MST 0932+1042 and MST 1005+6443) were found with a low photon number but with $g > 3$, while the significance of other two (MST 1311+3951 and MST 1423+1414) decreased because both n and g resulted lower than in Pass 7. To gain more confidence on the cluster significance in the present work we applied a secondary selection using higher values of the parameters, as already done in Paper II.

In the present paper we reported 25 new clusters to be associated with known BL Lac or similar objects (3 of them are in the new 2FHL catalogue). No association with FSRQ sources was found, supporting the picture of a GeV to TeV sky preferentially dominated by BL Lacs. This result can be understood on the basis that BL Lac objects, and particularly HBLs, have gamma ray spectra much harder than FSRQs, as clearly apparent in the photon index plot by Singal et al. (2012). In the

3LAC population (Ackermann et al. 2015) the mean photon index of BL Lacs is 2.01 ± 0.25 , and the one of HBLs is 1.87 ± 0.20 , while FSRQs have 2.44 ± 0.20 . Therefore it can reasonably be expected that above 10 GeV the new and weaker sources, not already detected at lower energies, are mostly HBL objects, and this is also supported by the values of the photon indices in Table 2.

Our detections were generally confirmed by the standard maximum likelihood analysis. Considering also the 19 BL Lacs previously discovered in the Pass 7 sky (Paper I) and the other 16 sources (Paper II) in the 1WHSP catalogue (Arsioli et al. 2015), the use of our method based on the MST clustering has provided up to now several tens of new possible γ -ray blazars. It should be emphasized, however, that these discoveries are mainly due to the improvement of instrumental response functions used for producing the Pass 8 sky and to an exposure with a duration of about twice the one considered at the epoch of 3FGL catalogue.

We acknowledge use of archival Fermi data. We made large use of the online version of the Roma-BZCAT and of the scientific tools developed at the ASI Science Data Center (ASDC), of the Sloan Digital Sky Survey (SDSS) archive, of the NED database and other astronomical catalogues distributed in digital form (VizieR and Simbad) at Centre de Données astronomiques de Strasbourg (CDS) at the Louis Pasteur University.

References

- Abdo, A.A., Ackermann, M., Ajello, M., Atwood, W.B., Axelsson, M., Baldini, L., Ballet, J., Barbiellini, G., *et al.*: *Astrophys. J.* **707**, 1310 (2009)
- Ajero, F., Ackermann, M., Ajello, M., Albert, A., Atwood, W.B., Axelsson, M., Baldini, L., Ballet, J., *et al.*: *Astrophys. J. Suppl. Ser.* **218**, 23 (2015)
- Ackermann, M., Ajello, M., Allafort, A., Asano, K., Atwood, W.B., Baldini, L., Ballet, J., Barbiellini, G., *et al.*: *Astrophys. J.* **765**, 54 (2013)
- Ackermann, M., Ajello, M., Allafort, A., Atwood, W.B., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., *et al.*: *The Astrophysical Journal Supplement Series* **209**(2), 34 (2013)
- Ackermann, M., Ajello, M., Asano, K., Atwood, W.B., Axelsson, M., Baldini, L., Ballet, J., Barbiellini, G., *et al.*: *Science* **343**, 42 (2014)
- Ackermann, M., Ajello, M., Atwood, W.B., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., *et al.*: *Astrophys. J.* **810**, 14 (2015)
- Antonucci, R.R.J., Ulvestad, J.S.: *Astrophys. J.* **294**, 158 (1985)
- Arsioli, B., Fraga, B., Giommi, P., Padovani, P., Marrese, P.M.: *Astron. Astrophys.* **579**, 34 (2015)
- Atwood, W., Albert, A., Baldini, L., Tinivella, M., Bregeon, J., Pesce-Rollins, M., Sgrò, C., Bruel, P., Charles, E., *et al.*: *ArXiv e-prints* (2013). 1303.3514
- Brinkmann, W., Laurent-Muehleisen, S.A., Voges, W., Siebert, J., Becker, R.H., Brotherton, M.S., White, R.L., Gregg, M.D.: *Astron. Astrophys.* **356**, 445 (2000)
- Campana, R., Massaro, E., Bernieri, E.: *Astrophys. Space Sci.* **in press**, (2016). doi:10.1007/s10509-016-2772-6
- Campana, R., Massaro, E., Gasparrini, D., Cutini, S., Tramacere, A.: *Mon. Not. R. Astron. Soc.* **383**, 1166 (2008)
- Campana, R., Bernieri, E., Massaro, E., Tinebra, F., Tosti, G.: *Astrophys. Space Sci.* **347**, 169 (2013)
- Campana, R., Massaro, E., Bernieri, E., D'Amato, Q.: *Astrophys. Space Sci.* **360**, 65 (2015)
- Collinge, M.J., Strauss, M.A., Hall, P.B., Ivezić, Ž., Munn, J.A., Schlegel, D.J., Zakamska, N.L., Anderson, S.F., Harris, H.C., Richards, G.T., Schneider, D.P., Voges, W., York, D.G., Margon, B., Brinkmann, J.: *Astron. J.* **129**, 2542 (2005)
- D'Abrusco, R., Massaro, F., Paggi, A., Smith, H.A., Masetti, N., Landoni, M., Tosti, G.: *Astrophys. J. Suppl. Ser.* **215**, 14 (2014)
- Falomo, R., Scarpa, R., Bersanelli, M.: *Astrophys. J. Suppl. Ser.* **93**, 125 (1994)
- Hook, I.M., Shaver, P.A., Jackson, C.A., Wall, J.V., Kellermann, K.I.: *Astron. Astrophys.* **399**, 469 (2003)
- Jackson, C.A., Wall, J.V., Shaver, P.A., Kellermann, K.I., Hook, I.M., Hawkins, M.R.S.: *Astron. Astrophys.* **386**, 97 (2002)
- Laurent-Muehleisen, S.A., Kollgaard, R.I., Ryan, P.J., Feigelson, E.D., Brinkmann, W., Siebert, J.: *Astron. Astrophys. Suppl. Ser.* **122**, 235 (1997)
- Marchã, M.J.M., Caccianiga, A.: *Mon. Not. R. Astron. Soc.* **430**, 2464 (2013)
- Marchã, M.J., Caccianiga, A., Browne, I.W.A., Jackson, N.: *Mon. Not. R. Astron. Soc.* **326**, 1455 (2001)
- Maselli, A., Melandri, A., Nava, L., Mundell, C.G., Kawai, N., Campana, S., Covino, S., Cummings, J.R., *et al.*: *Science* **343**, 48 (2014)
- Massaro, F., Thompson, D.J., Ferrara, E.C.: *Astron. Astrophys. Rev.* **24**, 2 (2016)
- Massaro, F., Paggi, A., Errando, M., D'Abrusco, R., Masetti, N., Tosti, G., Funk, S.: *Astrophys. J. Suppl. Ser.* **207**, 16 (2013)
- Massaro, F., Giroletti, M., D'Abrusco, R., Masetti, N., Paggi, A., Cowperthwaite, P.S., Tosti, G., Funk, S.: *Astrophys. J. Suppl. Ser.* **213**, 3 (2014)
- Nolan, P.L., Abdo, A.A., Ackermann, M., Ajello, M., Allafort, A., Antolini, E., Atwood, W.B., Axelsson, M., Baldini, L., Ballet, J., *et al.*: *Astrophys. J. Suppl. Ser.* **199**, 31 (2012)
- Planck Collaboration, Ade, P.A.R., Aghanim, N., Argüeso, F., Armitage-Caplan, C., Arnaud, M., Ashdown, M., Atrio-Barandela, F., Aumont, J., Baccigalupi, C., *et al.*: *Astron. Astrophys.* **571**, 28 (2014)
- Rector, T.A., Gabuzda, D.C., Stocke, J.T.: *Astron. J.* **125**, 1060 (2003)
- Selig, M., Vacca, V., Oppermann, N., Enßlin, T.A.: *ArXiv e-prints* (2014). 1410.4562
- Shakhbazyan, R.K.: *Astrofizika* **9**, 495 (1973)

- Singal, J., Petrosian, V., Ajello, M.: *Astrophys. J.* **753**, 45 (2012)
- Stoll, D., Tiersch, H., Braun, M.: *Astronom. Nach.* **317**, 239 (1996)
- The Fermi-LAT Collaboration: ArXiv e-prints (2015). [1508.04449](https://arxiv.org/abs/1508.04449)
- Thyagarajan, N., Helfand, D.J., White, R.L., Becker, R.H.: *Astrophys. J.* **742**, 49 (2011)