Bayesian Mixture Modeling of the High-Energy Photon Counts collected by the Fermi Large Area Telescope

Denise Costantin [1 2 3], Andrea Sottosanti [3], Alessandra R. Brazzale [3], Denis Bastieri [1 4 5] and JunHui Fan [1 2]

[1] Center for Astrophysics, Guangzhou University, Guangzhou 510006 China

[2] Department of Education, Astronomical Science and Technology Research Laboratory, Guangdong Province, PRC

[3] Department of Statistical Sciences, University of Padova, via Cesare Battisti 241, Padova, Italy

[4] Department of Physics and Astronomy "G. Galilei", University of Padova, via F. Marzolo 8, Padova, Italy

[5] National Institute for Nuclear Physics, Padova Division, Padova, Italy

---

Address for correspondence: Denise Costantin, Center for Astrophysics, Guangzhou University, Guangzhou 510006, China.

E-mail: denise.costantin@gmail.com.

Phone: .

Fax: .

Abstract: Identifying as yet undetected high-energy sources in the γ-ray sky is one

of the declared objectives of the *Fermi* LAT Collaboration. We develop a Bayesian mixture model which is capable of disentangling the high-energy extra-galactic sources present in a given sky region from the pervasive background radiation. We achieve this by combining two model components. The first component models the emission activity of the single sources and incorporates the instrument response function of the *Fermi* γ-ray space telescope. The second component reliably reflects the current knowledge of the physical phenomena which underly the γ-ray background. The model parameters are estimated using a reversible jump MCMC algorithm, which simultaneously returns the number of detected sources, their locations and relative intensities, and the background component. Our proposal is illustrated using a sample of the *Fermi* LAT data. In the analyzed sky region, our model correctly identifies 116 sources out of the 132 present. The detection rate and the estimated directions and intensities of the identified sources are largely unaffected by the number of detected sources.

Key words: bivariate exponential distribution; γ-ray photon, instrument response function; mixture model, reversible jump MCMC

Supplementary Material

Table 1 reports the complete list of the 118 sources detected by our model within the analyzed sky region which can be associated with confirmed sources present in the 3FHL catalog. Columns 2 and 3 report the longitude (l_{alg}) and the latitude (b_{alg}) of the detected source together with its mixing proportion ω (Column 4). Columns 6 and

7 report the longitude (l_{3FHL}) and the latitude (b_{3FHL}) of the associated catalog source together with its angular distance from the potential source (Column 8). Multiple matches are reported. The less likely associations are struck through. In the end, 116 components were uniquely associated with known sources within an angular distance of 1° with respect to the catalog direction.

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
1	-79.213	17.062	1.27e-04	1	-79.214	17.071	0.010
2	-79.431	21.486	1.76e-04	2	-79.424	21.503	0.019
3	-79.339	28.077	1.65e-04	3	-79.333	28.090	0.014
4	-75.963	23.756	2.08e-04	4	-75.954	23.754	0.009
5	-74.738	21.444	1.17e-04	5	-74.759	21.463	0.028
6	-76.516	28.177	3.01e-04	6	-76.512	28.177	0.003
7	-70.647	13.130	4.38e-04	7	-70.624	13.160	0.037
8	-70.732	22.939	3.21e-04	8	-70.744	22.951	0.016
9	-78.489	46.552	2.43e-04	9	-78.463	46.580	0.034
10	-73.005	35.191	2.40e-04	10	-72.991	35.182	0.014
11	-70.815	28.609	2.36e-04	11	-70.794	28.617	0.020
12	-69.992	27.158	3.49e-04	12	-70.019	27.154	0.025
13	-73.220	38.422	8.69e-05	13	-73.242	38.352	0.072
14	-72.896	39.584	1.51e-04	14	-72.893	39.582	0.004
15	-78.941	53.207	7.66e-05	15	-78.905	53.248	0.046
16	-67.124	22.513	3.04e-04	16	-67.106	22.525	0.020
17	-77.186	53.853	3.33e-04	17	-77.173	53.867	0.017

Table 1: Complete list of the sources detected by our model in the analyzed sky region which can be associated with confirmed sources present in the 3FHL catalog. Multiple matches are reported. The less likely associations are struck through. (Continues on the next page.)

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
18	-70.094	39.286	3.34e-04	18	-70.125	39.282	0.024
19	-68.612	38.488	7.28e-05	19	-68.617	38.511	0.024
20	-67.647	35.762	1.76e-04	20	-67.625	35.785	0.029
21	-74.392	58.994	6.79e-05	21	-74.390	58.964	0.030
22	-74.632	61.261	1.03e-04	22	-74.620	61.252	0.012
~~22~~	~~-74.632~~	~~61.261~~	~~1.03e-04~~	~~23~~	~~-73.808~~	~~60.449~~	~~0.906~~
~~23~~	~~-73.789~~	~~60.438~~	~~8.24e-05~~	~~22~~	~~-74.620~~	~~61.252~~	~~0.908~~
23	-73.789	60.438	8.24e-05	23	-73.808	60.449	0.014
24	-72.350	58.730	7.71e-05	24	-72.452	58.708	0.057
25	-65.974	37.340	1.99e-04	25	-65.984	37.345	0.009
26	-63.854	25.248	1.34e-04	26	-63.884	25.219	0.040
29	-63.089	27.760	2.29e-04	28	-63.092	27.773	0.013
30	-74.132	68.629	1.57e-04	29	-74.129	68.647	0.018
31	-66.154	48.970	2.90e-04	30	-66.148	48.973	0.005
32	-61.595	18.017	2.78e-04	31	-61.601	18.044	0.028
33	-61.034	13.843	4.92e-04	32	-61.013	13.831	0.023
34	-69.981	64.385	1.90e-04	33	-69.978	64.338	0.046
35	-76.224	74.491	2.00e-04	34	-76.229	74.488	0.003
36	-64.457	48.374	3.59e-04	35	-64.490	48.395	0.030
37	-78.126	76.419	1.31e-04	36	-78.108	76.417	0.005
38	-61.220	25.382	3.04e-04	37	-61.225	25.381	0.005

Table 1: (Continues on the next page.)

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
39	-66.189	60.828	2.88e-04	38	-66.174	60.807	0.022
40	-64.907	58.055	3.64e-05	39	-64.899	58.033	0.022
41	-64.731	67.405	1.70e-04	40	-64.743	67.416	0.012
43	-60.344	48.000	1.57e-04	41	-60.541	47.887	0.174
44	-58.416	37.028	4.22e-04	42	-58.407	37.052	0.025
45	-57.667	34.692	1.52e-04	43	-57.662	34.709	0.018
48	-56.610	23.306	3.23e-04	45	-56.596	23.297	0.016
49	-55.634	66.304	2.22e-04	46	-55.606	66.338	0.036
50	-54.900	57.032	8.05e-04	47	-54.900	57.057	0.025
51	-55.213	51.083	3.58e-04	48	-55.191	51.074	0.016
52	-54.811	40.512	3.79e-05	49	-54.813	40.525	0.013
~~52~~	~~-54.811~~	~~40.512~~	~~3.79e-05~~	~~50~~	~~-54.793~~	~~39.648~~	~~0.864~~
~~53~~	~~-54.786~~	~~39.655~~	~~1.31e-04~~	~~49~~	~~-54.813~~	~~40.525~~	~~0.871~~
53	-54.786	39.655	1.31e-04	50	-54.793	39.648	0.009
54	-55.219	25.021	1.89e-04	51	-55.217	25.014	0.007
55	-53.673	38.548	1.71e-04	52	-53.340	38.556	0.261
56	-54.591	18.911	3.09e-04	53	-54.614	18.912	0.021
57	-54.692	13.354	5.25e-04	54	-54.732	13.347	0.039
58	-53.965	19.784	2.81e-04	55	-53.923	19.779	0.040
59	-49.783	50.604	1.73e-04	56	-49.776	50.633	0.029
60	-46.241	63.092	4.06e-04	57	-46.216	63.019	0.074

Table 1: (Continues on the next page.)

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
63	-50.586	40.696	3.08e-04	59	-50.622	40.670	0.038
64	-50.800	38.829	2.54e-04	60	-50.809	38.777	0.053
65	-52.412	20.042	2.58e-04	61	-52.440	20.037	0.027
66	-35.884	73.425	1.66e-04	62	-35.842	73.443	0.021
67	-46.496	54.825	3.98e-04	63	-46.491	54.823	0.004
70	-46.691	49.734	9.51e-05	65	-46.686	49.738	0.005
71	-28.974	75.402	7.94e-05	66	-28.974	75.385	0.017
72	-25.295	74.932	3.33e-04	67	-25.268	74.925	0.010
73	-50.429	19.428	6.65e-04	68	-50.474	19.422	0.043
74	-50.604	14.947	1.05e-03	69	-50.586	14.933	0.021
76	-38.519	56.244	2.37e-04	71	-38.636	56.237	0.065
77	-41.767	48.671	3.65e-04	72	-41.785	48.708	0.038
78	-45.799	32.060	4.12e-04	73	-45.820	32.063	0.017
79	-39.817	48.350	3.91e-05	74	-39.943	48.371	0.086
80	-18.567	71.103	2.63e-04	75	-18.607	71.123	0.024
81	-43.303	37.603	4.12e-04	76	-43.310	37.601	0.006
82	-39.959	46.222	2.79e-04	77	-39.970	46.219	0.008
83	-39.499	43.692	2.51e-04	78	-39.541	43.676	0.035
84	-44.386	27.604	2.12e-04	79	-44.419	27.591	0.032
85	-42.981	31.353	2.76e-04	80	-42.954	31.343	0.025
86	-12.644	68.760	2.53e-04	81	-12.600	68.775	0.022

Table 1: (Continues on the next page.)

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
89	-44.186	21.687	1.13e-04	83	-44.192	21.691	0.007
92	-16.649	60.996	5.16e-04	86	-16.644	60.994	0.003
93	-33.683	40.560	3.51e-04	87	-33.648	40.558	0.027
94	-36.402	34.710	4.49e-04	88	-36.397	34.718	0.009
~~98~~	~~-24.894~~	~~50.420~~	~~2.82e-04~~	~~90~~	~~-26.110~~	~~50.288~~	~~0.787~~
98	-24.894	50.420	2.82e-04	91	-24.883	50.397	0.024
99	-33.466	34.666	2.14e-04	92	-33.475	34.670	0.009
100	-18.395	53.657	7.91e-04	93	-18.419	53.652	0.015
101	-23.187	48.363	3.23e-04	94	-23.209	48.340	0.027
102	-10.044	59.321	1.78e-04	95	-10.021	59.320	0.011
103	-28.125	40.787	1.54e-04	96	-28.085	40.832	0.054
104	-27.335	38.843	1.33e-04	97	-27.358	38.869	0.032
~~106~~	~~-34.425~~	~~26.338~~	~~4.13e-04~~	~~98~~	~~-34.811~~	~~25.584~~	~~0.830~~
106	-34.425	26.338	4.13e-04	99	-34.431	26.335	0.006
107	-38.564	17.260	2.96e-03	100	-38.556	17.269	0.012
109	-33.109	26.590	1.38e-04	101	-33.277	26.865	0.313
110	-28.356	31.372	1.48e-04	102	-28.355	31.362	0.010
113	-35.444	18.347	9.51e-05	104	-35.443	18.342	0.005
115	-34.814	19.327	3.21e-04	106	-34.804	19.325	0.009
116	-24.411	36.235	5.26e-04	107	-24.451	36.243	0.033
~~115~~	~~-34.814~~	~~19.327~~	~~3.21e-04~~	~~109~~	~~-34.354~~	~~18.713~~	~~0.752~~

Table 1: (Continues on the next page.)

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
117	-37.862	12.311	6.31e-04	108	-37.845	12.323	0.020
~~118~~	~~-34.364~~	~~18.702~~	~~1.01e-03~~	~~106~~	~~-34.804~~	~~19.325~~	~~0.750~~
118	-34.364	18.702	1.01e-03	109	-34.354	18.713	0.015
119	-10.747	48.881	4.28e-04	110	-10.775	48.937	0.059
121	-34.207	15.710	2.78e-04	112	-34.206	15.704	0.006
122	-30.071	20.483	1.10e-04	113	-30.088	20.533	0.052
123	-35.599	10.837	3.40e-04	114	-35.605	10.827	0.012
124	-16.249	36.461	7.74e-04	115	-16.267	36.493	0.035
125	-19.494	29.499	2.76e-04	116	-19.496	29.503	0.005
129	-28.878	17.963	3.59e-04	117	-28.131	17.402	0.907
131	-19.307	27.574	7.94e-04	118	-19.319	27.584	0.015
132	-21.352	24.977	3.99e-04	119	-21.336	24.986	0.017
133	-20.429	24.405	3.60e-04	120	-20.427	24.391	0.015
134	-17.951	20.397	1.17e-04	121	-17.964	20.372	0.027
135	-13.307	24.073	2.18e-04	122	-13.302	24.067	0.008
138	-12.147	24.202	2.43e-04	124	-12.159	24.174	0.031
~~140~~	~~-18.869~~	~~20.649~~	~~3.45e-04~~	~~121~~	~~-17.964~~	~~20.372~~	~~0.891~~
~~141~~	~~-17.398~~	~~17.190~~	~~2.50e-04~~	~~125~~	~~-17.656~~	~~18.153~~	~~0.993~~
141	-17.398	17.190	2.50e-04	126	-17.410	17.177	0.018
142	-12.483	22.281	1.40e-04	127	-12.413	22.238	0.078
143	-12.112	20.526	3.65e-04	128	-12.087	20.538	0.026

Table 1: (Continues on the next page.)

Detected source				Confirmed source			
ID_{alg}	l_{alg}	b_{alg}	ω	ID_{3FHL}	l_{3FHL}	b_{3FHL}	distance (°)
144	-15.849	16.456	5.44e-05	129	-15.872	16.444	0.026
145	-14.149	14.635	2.02e-04	130	-14.150	14.648	0.012
146	-11.226	13.320	6.82e-04	131	-11.200	13.332	0.028
147	-13.763	10.320	6.79e-04	132	-13.756	10.349	0.030
~~183~~	~~-58.190~~	~~34.996~~	~~5.55e-05~~	~~43~~	~~-57.662~~	~~34.709~~	~~0.520~~

Table 1: (Continues from the previous page.)