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Exploring the Universe above 1 GeV

D.J. Macomb[1, 2] **and R.C. Lamb**[3]

[1] *Astronomy Programs, Universities Space Research Association, USA*

[2] *Laboratory for High Energy Astrophysics, NASA/GSFC, Greenbelt, MD 20771, USA*

[3] *Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*

Abstract

The first 4.5 years of observations by the EGRET instrument on the Compton Gamma Ray Observatory have been used to construct a catalog of 57 sources of cosmic gamma rays at energies above 1 GeV. These sources are identified as: blazars (21), pulsars (5), the LMC, and 30 unidentified sources whose latitude distribution argues for a galactic origin. In this paper, we report on the preliminary extension of this work to approximately 7 years of observations with special emphasis on a search for transient sources. Sixteen new steady GeV sources are also detected, 3 of which have never been reported as gamma-ray sources. The search method and significance levels are presented. Our initial result on 22 possible transients indicates that 12 of them are new gamma-ray sources.

1 Introduction

The gamma-ray sources detected above 100 MeV have been described in an impressive series of EGRET catalogs culminating in the 3rd EGRET catalog (Hartman et al. 1999). There are several TeV sources which are not represented in the EGRET catalogs such as MRK 501(Bradbury et al. 1997; Catanese et al. 1997) 1ES 2344+514 (Catanese et al. 1998) and SN 1006 (Tanimori et al. 1998). Both gamma-ray blazars and supernova remnants can therefore have spectral shapes which make them preferentially detected in certain parts of a very broad gamma-ray energy range (the high-energy portion of which extends from 100 MeV to at least 10 TeV – five orders of magnitude). This leads us to fully investigate the EGRET database above 1 GeV, an order of magnitude above the threshold for the standard EGRET catalogs.

We divide our search into two separate parts; a search for new steady sources and a search for GeV transients. Note that steady in this context means detectable in the full all-sky data, not showing a lack of variability. Our data consists of 99000 photons with energies above 1 GeV spread over 217 publicly available EGRET datasets taken over 71/2 years. Section 2 below describes our new steady sources of GeV emission beyond the catalog of Lamb and Macomb (1997, hereafter LM97). These sources form the basis of our search for transients, which is described in Section 3. Section 4 summarizes our preliminary findings.

2 Newly Discovered Steady Sources

To find transient GeV sources, we must understand steady sources. Although the GeV database is only approximately 10% large than in LM97, there is evidence for several new sources. In addition, the publication of the 3rd EGRET Catalog (Hartman et al. 1999) provides new insight into weak candidate sources. We prepared a database of nearly 99000 photons in maps that represent the full EGRET database through the early CGRO cycle 7 (Viewing period 710.0). The data preparation and treatment is as described in LM97. Briefly, photons above 1 GeV are binned in 0.5x0.5 degree all-sky maps that are analyzed using Maximum Likelihood (Mattox et al. 1996) and the diffuse model of Bertsch et al. 1993:

Simulations of twelve all-sky maps using actual EGRET exposure maps indicate that a threshold of 4.5σ is adequate to ensure that sources found in the full EGRET database are real. The number of spurious sources at this significance level is expected to be less than one. Five sources beyond those in LM97 now exceed this threshold. Supporting evidence, such as detection in another energy range, can make subthreshold sources more likely. In addition to sources detected above 4.5σ, we include sources with significance above 4.0σ that have a 100 MeV counterpart in the 3rd EGRET catalog. This counterpart is defined by having the 95% GeV and 100 MeV error circles overlapping. Nine new GeV sources are in this category. A third category of source are those whose significance is above 4.0σ, and are detected at a significance of at least 3σ in the 300-1000 MeV energy band. Two such cases exist. This allows us to include those sources too weak to be 100 MeV sources, but with enough corroborating evidence to make the GeV flux believable. With these rules in mind, Table 1 shows the list of steady GeV gamma-ray sources beyond that of LM97.

Table 1. New GeV sources found in the full EGRET database. For sources below 4.5σ, the qualifying characteristic is noted (either a 3EG counterpart or probable 100-300 MeV detection).

NAME	LII	BII	SIG	FLUX[A]	RAD[B]	COUNTERPART NOTES
GEV J2159-3024	17.45	-52.32	6.3	1.8±0.5	33	3EG J2158-3023, PKS 2155-304
GEV J2257-2755	24.45	-64.68	5.4	1.8±0.6	36	PKS 2255-282
GEV J1745-3014	358.86	-0.63	5.2	6.1±1.3	23[C]	3EG J1744-3011
GEV J1228+0159	289.89	64.30	5.2	0.9±0.3	33[C]	3EG J1229+0210, 3C 273
GEV J1824-1511	16.36	-1.03	5.1	5.6±1.3	32[C]	3EG J1824-1514
GEV J1017-5845	284.14	-1.60	4.9	4.0±1.0	33[C]	3EG J1013-5915
GEV J2204+4225	92.89	-10.48	4.9	2.2±0.7	41	3EG J2202+4217, BL Lacertae
GEV J1306-5920	304.81	3.47	4.6	2.9±0.8	29	---
GEV J1230-4839	299.39	14.07	4.5	1.6±0.5	44	---
GEV J0526-6515	275.12	-33.32	4.5	1.2±0.4	41	LMC extended?
GEV J2057-4702	352.86	-40.58	4.4	2.1±0.8	52	3EG J2055-4716, QSO 2052-474
GEV J0911+6548	148.38	38.74	4.3	1.1±0.4	59	3EG J0910+6556, 4C 66.08?
GEV J2055+2548	70.69	-12.30	4.3	1.6±0.5	41	3σ (300-1000), 4C +26.58?
GEV J1742-2039	6.70	4.91	4.2	2.0±0.6	24	3EG J1741-2050
GEV J1952+3251	68.67	2.94	4.1	2.6±0.8	28	3σ (300-1000), PSR 1951+32
GEV J0614-3331	240.56	-21.74	4.1	2.0±0.8	57	3EG J0616-3310

[A] Units of 10^{-8} cm^{-2} s^{-1} , [B] Units of arcminutes, [C] larger of the radii for a fit to an ellipse is quoted

The majority of these new steady sources are in the third EGRET catalog. Of the six sources without a 3EG counterpart, GEV J2257-2755 has been detected above 100 MeV (Macomb et al. 1999) but fell outside the time frame of the 3rd EGRET catalog. The LMC source, GEV J0526-6515, may be an artifact. Above 1 GeV, the EGRET point spread may be small enough that the LMC size becomes wider than the typical extent of a point source. The LMC is in LM97, and this new source may be more diffuse emission. This is being studied further. The source GEV J1952+3251 is consistent with PSR 1951+32. This source was previously been detected through pulsar analysis (Ramanamurthy et al. 1995). Three of our new sources have no 100 MeV counterparts. The sources GEV J1306-5920, GEV J1230-4839 and GEV J2055+2548 are all previously unreported sources, two of the three being high latitude (|bii| > 10 degrees).

3 Search for Transient Sources:

Combining the sources listed in Table 1 with those of LM97 gives us a basis for searching for transient emission. Our approach is to look for sources of week-scale transient emission by analyzing all 217 public EGRET viewing periods. For each viewing period, the sources in LM97 and Table 1 present in the observation are modeled as part of the background. Then a map of the residual maximum likelihood statistic is calculated. This gives the likelihood of a source being present at each point of the 0.5 degree binned map. There are typically 25000 likelihood points per map and a total of 5.6 million likelihood values in the total resulting database. The search for transients proceeds by listing points in any map which exceed a 3.0σ significance level. This is approximately 3400 bins representing a single point on the sky in a single viewing period. Finally, we correlate all of these features to find instances of 3.0σ excesses within 1 degree of each other (a typical weak point source location radius) in separate viewing periods.

Figure 1 shows the distribution of the resulting 53 pairs as a function of the maximum likelihood value in the two viewing periods. The probability of getting any likelihood value comes from the full distribution of the 5.6 million likelihood values. The resulting probability for a pair is given as

$$P = P1 \bullet P2 \bullet \mathrm{BINOMIAL}(N,2) \bullet 20$$

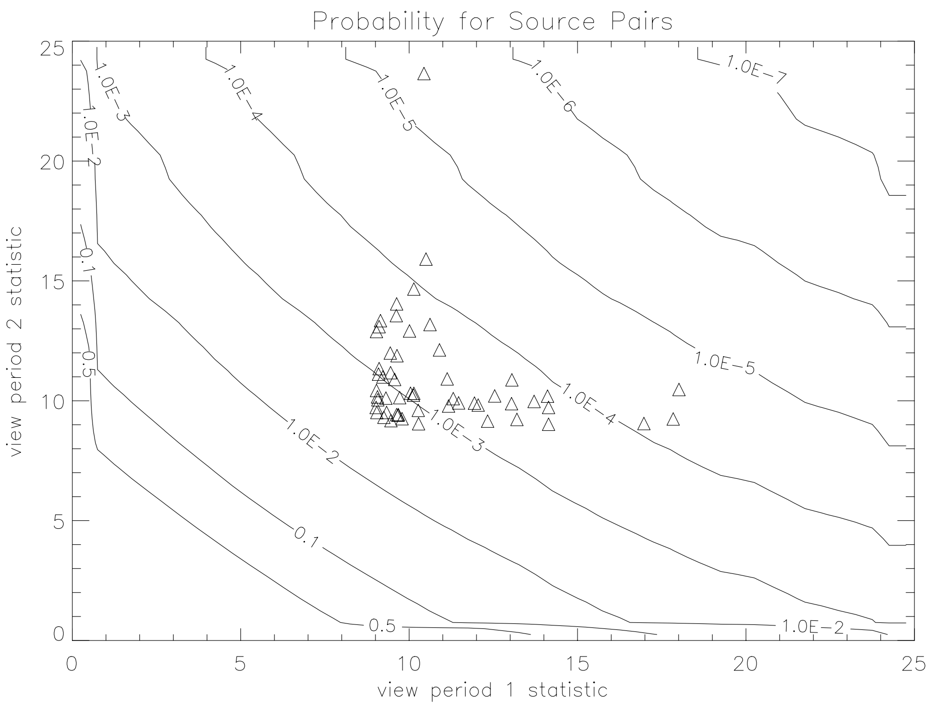
where P1 and P2 are the probabilities of the two likelihoods, BINOMIAL(N,2) is the number of ways we could pick 2 viewing periods out of N periods which contain the sky point, and 20 is approximately the number of bins within the 1 degree search range for 0.5 degree binning. In Figure 1, contours of total probability are included with the points for our 53 pairs assuming N = 25. For these sources, we combine the maps containing the paired points and analyzed the combined data. At this time, we restrict further analysis to those pairs that are detected at the 4.0σ level in the combined data. These sources are listed in Table 2 along with any overlapping 3rd EGRET catalog sources or other bright counterpart candidate.

Table 2. Sources of GeV gamma rays based upon the search for repeating, weak outbursts.

NAME	LII	BII	SIG	FLUX[A]	RAD[B]	COUNTERPART NOTES
GEV J1323+2206	359.91	81.20	5.8	10.1±3.8	22	3EG J1323+2200
GEV J0339-0137	187.93	-42.27	5.6	12.0±4.3	51	3EG J0340-0201, CTA 26
GEV J1409-6126	312.13	0.02	5.1	15.6±4.0	26	3EG J1410-6147
GEV J2009-4827	350.84	-32.87	5.1	4.5±1.6	54	PKS 2005-489?
GEV J0424-0113	195.36	-32.81	5.1	5.7±2.0	27	3EG J0422-0102, PKS 0420-01
GEV J1223+2121	253.72	81.43	5.1	6.5±2.7	26	3EG J1224+2118, 4C +21.35
GEV J1645-4605	339.17	-0.33	5.1	27.0±7.0	26	---
GEV J1653+3945	63.58	38.97	5.0	2.8±1.0	52	MRK 501
GEV J0612+2910	182.68	5.16	4.9	12.9±4.5	56	4C +29.22?, 4C +29.21?
GEV J1808-2814	3.07	-3.91	4.8	8.7±2.6	38	---
GEV J1317-4002	308.25	22.56	4.7	3.9±1.4	56	---
GEV J0310-7141	289.10	-41.50	4.7	4.8±1.9	51	---
GEV J1838+4745	76.63	21.83	4.5	4.6±1.9	57	3C 381?, 4C +47.50?
GEV J1515-4555	327.43	9.99	4.5	8.0±3.2	59	---
GEV J0448+1054	187.76	-21.09	4.3	8.0±3.4	57	3EG J0450+1105, PKS 0446+11
GEV J0638+0446	207.19	-0.74	4.2	9.2±3.1	43	3EG J0634+0521
GEV J2225-4935	344.17	-54.18	4.2	14.6±6.9	65[C]	PKS 2220-50?
GEV J1305-8232	303.42	-19.68	4.1	5.8±2.5	56[C]	3EG J1249-8330
GEV J1622+1340	28.71	39.05	4.1	7.6±3.7	52	4C +14.65?
GEV J0408+5724	147.07	4.08	4.1	11.4±4.6	84[C]	4C +56.08?
GEV J1743-0457	20.57	12.62	4.0	5.4±2.0	59[C]	4C –05.72?, 4C -04.66?, 4C 14.64?, 3C 335?
GEV J0441+2648	173.39	-12.85	4.0	7.6±2.8	53	---

[A] Units of 10^{-8} cm^{-2} s^{-1} , [B] Units of arcminutes, [C] larger of the radii for a fit to an ellipse is quoted

Eight of these sources have counterparts in the 3rd EGRET catalog. We consider this further verification of the technique. Of the other 14 sources, all but GEV J2009-4827 and MRK 501 are new sources. The source GEV J2009-4827 was in LM97 but was not included in the sources that were modeled as the background because its significance had dropped below the threshold. The TeV detected MRK 501 has only recently been discovered to emit in the EGRET energy range (Sreekumar et al. 1999



4 Discussion

A preliminary analysis of data above 1 GeV finds 38 sources of GeV gamma-ray emission, 22 of which are found in a search for transient emission. Fifteen of these sources are previously unreported. Of the 22 sources detected in the transient search, seven are low latitude, with four of these having no hypothetical AGN counterpart. These could be high-energy analogs to the 100 MeV transient GRO J1838-04 (Tavani et al. 1997). Many of the new sources have bright radio sources in their error circles, although most of the radio sources have 4.8 GHz fluxes below 1 Jy. Future work will emphasize other candidates, class studies, extending our work to lower energy, and quantifying the variability for the sources found by our transient search.

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