Spectral Modeling of the EGRET 3EG Gamma Ray Sources Near the Galactic Plane

D.L. Bertsch[1], R.C. Hartman[1], S.D.Hunter[1], D.J. Thompson[1], Y.C. Lin[2], D.A. Kniffen[3], G. Kanbach[4], H.A. Mayer-Hasselwander[4], O. Reimer[4], and P. Sreekumar[5]

1. *Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA*
2. *W. W. Hansen Exp. Phys. Lab., Stanford Univ., Stanford, CA 94305 USA*
3. *Code S, NASA Headquarters, 300 E. St. SW, Washington, DC 20024*
4. *Max-Planck Institut fur Extraterrestrische Physik, Giessenbachstr. D-85748, Garching, Germany*
5. *ISRO Satellite Center, Bangalore, India*

Abstract. The third EGRET catalog lists 84 sources within 10° of the Galactic Plane. Five of these are well-known spin-powered pulsars, 2 and possibly 3 others are blazars, and the remaining 74 are classified as unidentified, although 6 of these are likely to be artifacts of nearby strong sources. Several of the remaining 68 unidentified sources have been noted as having positional agreement with supernovae remnants and OB associations. Others may be radio-quiet pulsars like Geminga, and still others may belong to a totally new class of sources. The question of the energy spectral distributions of these sources is an important clue to their identification. In this paper, the spectra of the sources within 10° of Galactic Plane are fit with three different functional forms; a single power law, two power laws, and a power law with an exponential cutoff. Where possible, the best fit is selected with statistical tests. Twelve, and possibly an additional 5 sources, are found to have spectra that are fit by a breaking power law or by the power law with exponential cutoff function.

INTRODUCTION

The gamma ray sources near the Galactic Plane are likely to be from a more than one class of objects that are associated with our Galaxy. The spectral properties of these sources may offer a distinction between different source mechanisms. The five known pulsars for example exhibit relatively hard spectra and all except the Crab break at high energies. This paper examines the spectral properties of the EGRET third catalog (Hartman et al. 1999) sources within ±10° of the Galactic plane.

ANALYSIS

Each source in the EGRET Third Catalog (Hartman et al., 1999) was fitted with three functional forms, a single power law, two matching power laws, and a power law, modified by an exponential cut-off as shown in the following equations;

$$\frac{\partial J}{\partial E}(E, K, E_0, \lambda) = K\left(\frac{E}{E_0}\right)^{-\lambda} \qquad (1)$$

$$\frac{\partial J}{\partial E}(E, K, \lambda_1, \lambda_2) = K\left(\frac{E}{1000\ MeV}\right)^{-\lambda_1} \qquad for \quad E \le 1000\ MeV$$
$$= K\left(\frac{E}{1000\ MeV}\right)^{-\lambda_2} \qquad for \quad E \ge 1000\ MeV \tag{2}$$

$$\frac{\partial J}{\partial E}(E, K, \lambda, E_f) = K\left(\frac{E}{300\ MeV}\right)^{-\lambda} \exp(-E / E_f) \tag{3}$$

In eq. 1, E_0 was set to the value determined by the EGRET Spectral program to minimize the correlation between the two other fit parameters. The location of the break energy in eq. 2 was set to 1000 MeV to keep the number of parameters at a minimum since at best, there are only 10 energy points available. With each fit, a reduced χ^2 was obtained, and an F-Test was done to see if there is statistical justification in using either of the forms in eqs. 2 or 3 rather than a simple power law to fit the observed spectral data. In the F-Test, a value of $P < 0.05$ is generally taken as the point where the more complicated fit is warranted. Summed data sets for Phases 1 through 4 of the CGRO (Compton Gamma Ray Observatory) mission were used to maximize the statistics since the sources in the Galactic plane region of the sky do not show strong variability.

RESULTS

Six sources that are listed in the third EGRET catalog are thought to be artifacts from residual emission in the wings of the PSF (Point Spread Function) from Vela (see Hartman et al., 1999). These were removed from consideration, and just the remaining 78 sources were modeled. The photon energy spectra of the majority of these 78 sources were found to be best represented by a simple power law whose index is given in the catalog paper (Hartman et al., 1999). However, 28 of these were judged to be too limited statistically at the extremes of EGRET's energy range to have a meaningful measure of a departure from a simple power law spectrum.

The F-Test analysis of the change in χ^2 between a simple power law and the more complex forms (eqs. 2 and 3) indicated that 12 sources have complex spectra. Another 5 sources that are weak statistically also may exhibit a curving or breaking form. Table 1 lists the results of the two-power law modeling of these 17 sources. The column labeled "Spectral Category" indicates by the "2P" designation the 5 sources that are best fit by a breaking power law. These are also shown in bold in Table 1. The spectra of sources designated by "PE" are better described by power-law with an exponential cutoff. The sources labeled "SL" (italicized) are statistically limited and either model fits them reasonably well. The parameters of eq. 2 and their

Table 1. Two-Power-Law Fits to the EGRET Sources Within 10° of the Galactic Plane

Name	Type	Galactic Long. deg.	Galactic Lat. deg.	Spectral Sigif. σ	Spectral Cat.	Coefficient 10^{-11} cm^{-2} s^{-1}	Index-1	Index-2	Red. χ^2
3EG_J0617+2238	**U**	**189.00**	**3.05**	**17.4**	**2P**	**5.89 ± 0.70**	**-1.79± 0.09**	**-2.65 ± 0.24**	**0.91**
3EG_J1710-4439	**P**	**343.10**	**-2.69**	**21.4**	**2P**	**16.71 ± 9.08**	**-1.69 ± 0.07**	**-2.26 ± 0.13**	**0.73**
3EG_J1736-2908	**U**	**358.79**	**1.56**	**5.8**	**2P**	**7.15 ± 1.67**	**-1.49 ± 0.23**	**-5.80 ± 1.39**	**0.92**
3EG_J1746-2851	**U**	**0.11**	**-0.04**	**17.5**	**2P**	**13.29 ± 2.83**	**-1.20 ± 0.27**	**-2.31 ± 0.26**	**2.64**
3EG_J2021+3716	**U**	**75.58**	**0.33**	**10.3**	**2P**	**10.19 ± 1.44**	**-1.23 ± 0.15**	**-3.39 ± 0.36**	**0.55**
3EG_J0633+1751	P	195.13	4.27	76.4	PE	49.3 ± 14.1	-1.38 ± 0.07	-2.54 ± 0.16	7.51
3EG_J0834-4511	P	263.55	-2.79	73.8	PE	107.6 ± 40.2	-1.48 ± 0.08	-2.50 ± 0.19	13.46
3EG_J1655-4554	U	340.48	-1.61	5.2	PE	5.23 ± 1.37	-1.44 ± 0.26	-6.41 ± 1.96	0.38
3EG_J1741-2050	U	6.44	5.00	6.6	PE	3.68 ± 0.67	-1.71 ± 0.16	-3.77 ± 0.59	0.62
3EG_J2020+4017	U	78.05	2.08	21.0	PE	13.63 ± 2.16	-1.87 ± 0.10	-2.71 ± 0.34	2.60
3EG_J2027+3429	U	74.08	-2.36	5.8	PE	2.55 ± 0.75	-2.02 ± 0.18	-20 ± 20	0.73
3EG_J2033+4118	U	80.27	0.73	11.8	PE	7.72 ± 2.50	-1.60 ± 0.26	-3.85 ± 1.29	2.12
3EG_J0634+0521	*U*	*206.18*	*-1.41*	*4.6*	*SL*	*1.80 ± 0.67*	*-1.56 ± 0.37*	*-3.74 ± 1.54*	*0.55*
3EG_J0747-3412	*U*	*249.35*	*-4.48*	*3.5*	*SL*	*2.23 ± 0.66*	*-1.77 ± 0.23*	*-21 ± 21*	*0.29*
3EG_J1316-5244	*U*	*306.85*	*9.93*	*5.7*	*SL*	*1.43 ± 0.34*	*-2.26 ± 0.14*	*-19 ± 19*	*0.50*
3EG_J1810-1032	*U*	*18.81*	*4.23*	*4.9*	*SL*	*2.69 ± 0.57*	*-1.98 ± 0.15*	*-4.85 ± 1.36*	*0.42*
3EG_J2206+6602	*a*	*107.23*	*8.34*	*5.2*	*SL*	*2.04 ± 0.58*	*-1.99 ± 0.20*	*-5.66 ± 2.29*	*0.34*

Table 2. Power-Law-With-Exponential-Cutoff Fits to Sources Within 10° of the Galactic Plane

Name	Type	Galactic Long. deg.	Galactic Lat. deg.	Spectral Sigif. σ	Spectral Cat.	Coefficient 10^{-11} cm^{-2} s^{-1}	Index	*e*-Folding Energy MeV	Red. χ^2
3EG_J0633+1751	**P**	**195.13**	**4.27**	**76.4**	**PE**	**37.14 ± 1.69**	**-1.29 ± 0.06**	**2770 ± 472**	**4.24**
3EG_J0834-4511	**P**	**263.55**	**-2.79**	**73.8**	**PE**	**80.61 ± 4.14**	**-1.45 ± 0.06**	**3807 ± 925**	**7.92**
3EG_J1655-4554	**U**	**340.48**	**-1.61**	**5.2**	**PE**	**10.10 ± 4.36**	**-0.27 ± 0.63**	**299 ± 111**	**0.30**
3EG_J1741-2050	**U**	**6.44**	**5.00**	**6.6**	**PE**	**4.97 ± 0.80**	**-1.19 ± 0.24**	**692 ± 187**	**0.36**
3EG_J2020+4017	**U**	**78.05**	**2.08**	**21.0**	**PE**	**14.70 ± 1.69**	**-1.78 ± 0.13**	**2804 ± 1428**	**2.28**
3EG_J2027+3429	**U**	**74.08**	**-2.36**	**5.8**	**PE**	**14.08 ± 7.73**	**-0.81 ± 0.47**	**234 ± 85**	**0.33**
3EG_J2033+4118	**U**	**80.27**	**0.73**	**11.8**	**PE**	**15.07 ± 6.87**	**-0.56 ± 0.62**	**370 ± 172**	**1.69**
3EG_J0617+2238	U	189.00	3.05	17.4	2P	5.97 ± 0.70	-1.68 ± 0.15	2226 ± 1003	1.27
3EG_J1710-4439	P	343.10	-2.69	21.4	2P	12.14 ± 0.78	-1.75 ± 0.07	8320 ± 3914	1.20
3EG_J1736-2908	U	358.79	1.56	5.8	2P	10.42 ± 3.90	-0.69 ± 0.58	407 ± 172	1.02
3EG_J1746-2851	U	0.11	-0.04	17.5	2P	7.02 ± 1.74	-1.12 ± 0.37	629 ± 154	0.61
3EG_J2021+3716	U	75.58	0.33	10.3	2P	7.94 ± 1.28	-0.63 ± 0.30		
3EG_J0634+0521	*U*	*206.18*	*-1.41*	*4.6*	*SL*	*23.3 ± 11.3*	*-0.85 ± 0.78*	*550 ± 385*	*0.48*
3EG_J0747-3412	*U*	*249.35*	*-4.48*	*3.5*	*SL*	*60.7 ± 46.5*	*-0.71 ± 0.86*	*300 ± 193*	*0.36*
3EG_J1316-5244	*U*	*306.85*	*9.93*	*5.7*	*SL*	*26.5 ± 12.4*	*2.20 ± 0.38*	*1201 ± 1635*	*0.91*
3EG_J1810-1032	*U*	*18.81*	*4.23*	*4.9*	*SL*	*65.5 ± 16.3*	*-1.30 ± 0.27*	*473 ± 139*	*0.22*
3EG_J2206+6602	*a*	*107.23*	*8.34*	*5.2*	*SL*	*67.6 ± 28.8*	*-1.10 ± 0.43*	*341 ± 135*	*0.19*

uncertainties along with the reduced χ^2 value of the fit are given in Table 1.

Table 2 summarizes the fits using a power-law with an exponential cutoff form to the same 17 sources. There are 7 sources that are fitted best by this model. The fit parameters of eq. 3 are tabulated here.

Figure 1 compares the F-Test probability with the source significance. It is evident that most of the sources are near the significance threshold of 5σ required of sources near the plane for inclusion in the third EGRET catalog. Some of the sources here are below the cutoff. They exceeded the Catalog threshold in either one viewing period or in some combination of viewing periods, but are not as strong in the Phase 1 through 4 data used here. Three pulsars, Vela, Geminga, and PSR 1706-44 (3EG-J1710-4439) below the dotted line and the Crab pulsar above the dotted line have the four highest significance levels in figure 1. Discounting these four sources, the remaining points have a source significance distribution that is similar to the points above the line (power-law spectra). In other words, there is not a significant bias for strong sources to have non-power law spectra.

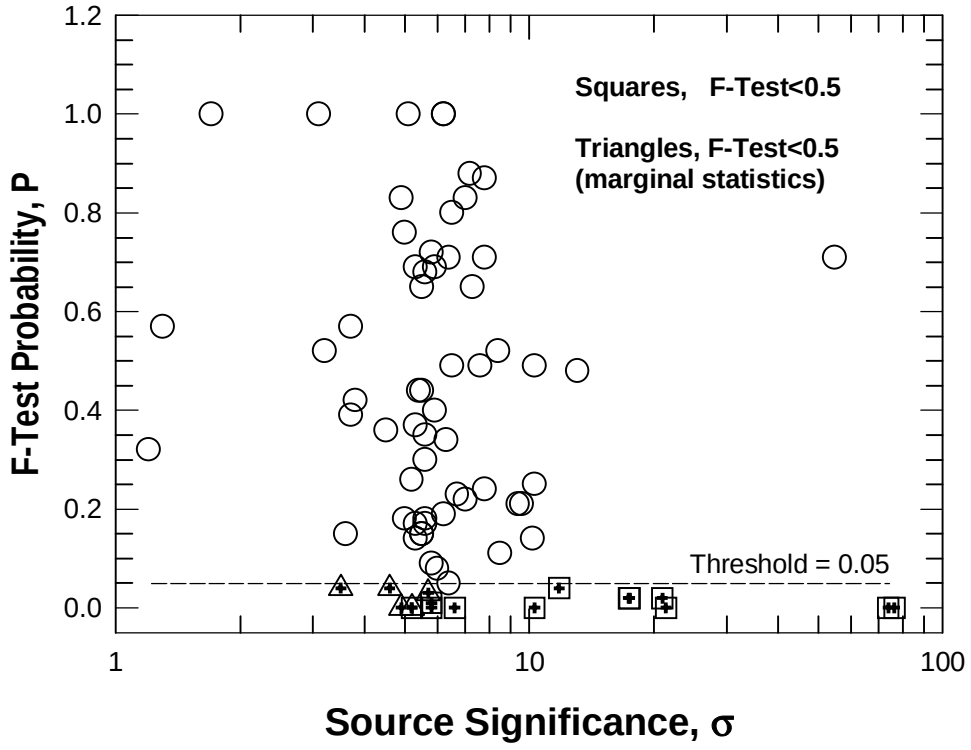

FIGURE 1. F-Test probability as a function of source significance. Points below the threshold line of P = 0.05 are the sources that have spectra that are modeled best by a breaking power law or a power law with an exponential cutoff. The distribution with significance is similar for the sources above and below the dotted line if the four highest points (pulsars) are ignored.

CONCLUSIONS

Among the sources within 10° of the Galactic Plane, at least 12 have spectral features that break at high energies. Three of these are known pulsars as noted above. The remaining 9 may be from a distinct class and perhaps are pulsar candidates themselves. EGRET will not be able to add significantly to the statistics on any of these sources, and it remains for the next generation gamma ray telescope, GLAST, to better determine their spectral features.

REFERENCES

Hartman et al., 1999, ApJS, 123, 79.