A Systematic Search for Short-term Variability of EGRET Sources

P. M. Wallace, N. J. Griffis[1]

Department of Physics & Astronomy, Berry College, Mt. Berry, GA 30149

D. L. Bertsch, R. C. Hartman, D. J. Thompson

Code 661, NASA Goddard Space Flight Center, Greenbelt, MD 20771

D. A. Kniffen[2]

Department of Physics & Astronomy, Hampden-Sydney College, Hampden-Sydney, VA 23943

and

S. D. Bloom[3]

IPAC, JPL/Caltech, MS 100-22, Pasadena, CA 91125

Received ____________; accepted ____________

To appear in The Astrophysical Journal

---

[1]present address: Dept. of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

[2]present address: NASA HQ, Washington, DC 20546

[3]present address: Dept. of Physics & Astronomy, Hampden-Sydney College, Hampden-Sydney, VA 23943

ABSTRACT

The 3rd EGRET Catalog of High-energy Gamma-ray Sources contains 170 unidentified sources, and there is great interest in the nature of these sources. One means of determining source class is the study of flux variability on time scales of days; pulsars are believed to be stable on these time scales while blazars are known to be highly variable. In addition, previous work has demonstrated that 3EG J0241-6103 and 3EG J1837-0606 are candidates for a new gamma-ray source class. These sources near the Galactic plane display transient behavior but cannot be associated with any known blazars. Although many instances of flaring AGN have been reported, the EGRET database has not been systematically searched for occurrences of short-timescale ($\sim$ 1 day) variability. These considerations have led us to conduct a systematic search for short-term variability in EGRET data, covering all viewing periods through proposal cycle 4. Six 3EG catalog sources are reported here to display variability on short time scales; four of them are unidentified. In addition, three non-catalog variable sources are discussed.

Subject headings: gamma rays: observations

1. Introduction

The Energetic Gamma-Ray Experiment Telescope (EGRET) on board the *Compton Gamma-Ray Observatory* (*CGRO*) began observing the high-energy gamma-ray sky in 1991. Since that time, EGRET has contributed enormously to the list of gamma-ray point sources; the third EGRET catalog (Hartman et al. 1999, hereafter H99) contains 271 point sources exhibiting significant flux above 100 MeV. Besides a single solar flare, the Large Magellanic Cloud (LMC), and a probable association with a radio galaxy (Cen A), the identified sources are distributed among two established classes of high-energy gamma-ray emitters: pulsars and radio-loud blazars. 170 sources remain unassociated with known objects. There is great interest in the nature of the unidentified sources, whether they be pulsars, blazars, or representatives of new classes of gamma-ray sources.

The limited spatial resolution of EGRET often hampers source identification based solely on position; an alternate means of determining source class is the study of flux variability. In particular, pulsars are believed to be stable on short ($\sim$ 1 day) time scales (Ramanamurthy et al. 1997) while blazars are known to be strongly variable (e.g., Mattox et al. 1997a). Short-term and long-term variability studies have also led to the discovery of two candidates for a new gamma-ray source class: 3EG J1837-0606 (GRO J1838-04) (Tavani et al. 1997) and 3EG J0241-6103 (2CG 135+01) (Kniffen et al. 1997, Tavani et al. 1998). These sources display transient behavior but cannot be associated with any known radio-loud blazars.

There are many instances of gamma-ray flares of AGN on short time scales. For example, 3C 279 (Kniffen et al. 1973, Wehrle et al. 1998), PKS 0528+134 (Hunter et al. 1993), 3C 454.3 (Hartman et al. 1993), PKS 1633+382 (Mattox et al. 1993), PKS 1406-076 (Wagner et al. 1995), PKS 1622-297 (Mattox et al. 1997a), and CTA 26 (Mattox et al. 1995, Hallum et al. 1997, Mattox et al. 2000) all show strong evidence of variability on time scales of 1-3 days. Many other AGN show variations on time scales of weeks to months (von Montigney et al. 1995, McLaughlin et al. 1996, Mukherjee et al. 1997). Although these many instances of short-term variability have been noted, no exhaustive survey of the EGRET database has been performed.

It is the purpose of this study to conduct a systematic and comprehensive survey of EGRET data from proposal cycles 1-4 in search of evidence of short-term flux variability above 100 MeV. The standard method of EGRET data analysis, maximum likelihood, was applied to short-duration (one-day and two-day) maps of gamma-ray intensity. The variability statistic V was used as a guide for singling out those light curves which deviate appreciably from constant flux. For the unidentified sources that display evidence of flaring, Monte Carlo simulations were performed to determine the probability of such fluctuations assuming intrinsically nonvariable sources. Six catalog sources were found to exhibit variability on one- and two-day time scales: four are unidentified, one is a flat-spectrum radio quasars (FSRQ), and one is a BL Lac object. In addition, two transient non-catalog excesses and one non-catalog sub-threshold repeating source are discussed. The limitations of this study are then considered; a summary and concluding remarks follow.

2. EGRET Data and Preliminary Analysis

The data used for the present analysis are those from Phase 1 through Cycle 4 of the CRGO mission (1991 April - 1995 October), matching the time span of the third EGRET catalog (H99). The CGRO timeline is divided into observation (viewing) periods at fixed attitudes that range in duration from one day to several weeks. Each of the 144 viewing periods longer than 3 days was first divided into two-day intervals (for viewing periods with an odd number of days, the last interval has three days). For each interval, a sky map was generated for $E > 100$ MeV using the same criteria used to generate standard EGRET maps. In addition, for each instrument pointing within 20° of the Galactic plane (where the sources typically are brighter), a series of one-day maps was generated. Each of these maps was analyzed with the EGRET maximum likelihood program (Mattox et al. 1996) using the following procedure: (1) All sources from H99 within 30° of the pointing direction were modeled. Sources beyond 30° for these short intervals have too little exposure to be useful and would require separate analysis, because the EGRET Point Spread Function (PSF) is broader at wide angles (Esposito et al. 1999). (2) Fluxes for all the sources and the EGRET diffuse radiation model (Hunter et al. 1997, Sreekumar et al. 1998) within the map were optimized simultaneously, producing a table with statistical significance and flux for each source. (3) A search was made for any statistically-significant source in the map not found in the EGRET catalog.

The statistics of the data are very limiting, especially for the one-day light curves. In order to isolate the curves for which the flux uncertainty is not overwhelming, the significance of each of the short-duration detections were examined. An excess of 4σ is the minimum requirement for inclusion of a source in H99, and this threshold was applied here so that only those light curves which contain at least one 4σ short-duration detection were considered for further analysis.

Even with this requirement, much of the data suffers from large statistical uncertainty. This leads us to the conclusion that for all but the strongest sources, EGRET is sensitive to only the most dramatic short-term variations in flux. In order to single out the most variable light curves, the variability statistic V (McLaughlin et al. 1996) was used. For the remaining light curves the χ^2 statistic was calculated from

$$\chi^2 = \sum_{i=1}^{N} \frac{(F_i - \bar{F})^2}{\sigma_i^2} \tag{1}$$

where N is the number of observations, F_i is the detected flux during the ith observation, $\bar{F}$ is the mean flux for the viewing period, and σ_i is the 1-σ flux uncertainty of the ith observation. If Q is the probability of obtaining a value of χ^2 equal to or greater than the empirical χ^2 from an intrinsically nonvariable source, then $V \equiv -\log Q$. For this work, light curves with $V \geq 3.0$ ($Q \leq 10^{-3}$) are considered to manifest source variability. Light curves displaying one or more consecutive strong two-day detections or two or more consecutive strong one-day detections against a background of weak detections and/or upper limits are considered to show evidence of flaring. In such situations, the value of V is depressed by the high number of weak detections and/or upper limits; for this reason these curves were retained for further study if they had variability indexes at or above 1.0.

Seven light curves of six sources displayed one or two-day variability indexes greater than 3.0 and/or 1.0 with evidence of flaring. With one exception, the one-day analysis turned up a final list of variable light curves identical to that of the (independently performed) two-day analysis. Four of the seven sources are listed as unidentified in H99.

For the unidentified sources that display evidence of flaring behavior, Monte Carlo simulations of the data were performed. The data in question were simulated using the current models of the diffuse isotropic radiation (Sreekumar et al. 1998) and the diffuse Galactic emission (Hunter et al. 1997) in conjunction with the source flux. In some cases, the source in question was not isolated and a number of nearby sources were included in the simulation; all sources were assumed to be intrinsically nonvariable. Mean fluxes for each source and short-duration exposures representative of the viewing period are input into the model. For a given source, the simulation consisted of distributing the flux as the EGRET PSF and adding Poisson-distributed deviates pixel-by-pixel. In this way 1000 counts maps were generated; these maps were analyzed using maximum likelihood, resulting in a distribution of the significance for the source of interest. The probability of finding a single detection and subsequently a "flare" of given overall significance or greater from an intrinsically nonvariable source was then determined from this distribution. See Mattox et al. (1996) for more details about the Monte Carlo simulation.

3. Discussion of Individual Catalog Sources

The following sources are listed in H99 and display evidence for variable output. To be listed in H99, sources with $|b| < 10^\circ$ must be detected with a significance of at least 5σ and sources with $|b| > 10^\circ$ must be detected at a significance of at least 4σ. Four of the sources have not been previously known to display short-term variability. The variability of the other two has been reported and for these we present additional work.

3.1. New Reports of Short-term Variability

3.1.1. 3EG J0222+4253 (3C 66A/PSR J0218+4232?)

Source 3EG J0222+4253 exhibits a strong two-day flare in VP 15.0 [4]; virtually all of the detection in this 14-day interval came on days 11 and 12. The peak flux value on day 12, $(8.1 \pm 2.4) \times 10^{-7}$ photons cm^{-2} s^{-1}, is over four times the mean flux for this source, either in the full viewing period or averaged over all observations in H99. The source was 12°5 off-axis and the two-day light curve (see Figure 1) registers a variability index of 2.6. Monte Carlo simulation of this source indicates that one should expect only about 5 in 10^4 such viewing periods to display an equivalent or stronger "flare" if the source is intrinsically nonvariable. Source 3EG J0222+4253 was also observed within 20° of the instrument axis in VP's 211.0, 325.0, and 427.0, but was found in all three cases to be nonvariable and consistent with the lower-level flux observed in VP 15.0.

[4]The preliminary version of this result appeared in Bloom et al. 1997.

At energies above 1 GeV, the spatial analysis (H99) strongly supports an association of this source with the BL Lac object 3C66A ($z = 0.444$). This identification would place this source among the more than 60 blazar-class objects seen by EGRET, many of which show short-term time variability, as noted above.

Verbunt et al. (1996) and Hermsen et al. (1999) suggest that much of the sub-GeV gamma-ray flux may have its origin in a second source, the binary millisecond pulsar PSR J0218+4232, located less than 1 degree from 3C66A. Their argument is based on three lines of evidence: (1) the 100-1000 MeV data show a 3.5 sigma evidence of pulsation at the radio period; (2) the gamma-ray light curve resembles the one seen in hard X-rays; and (3) the spatial analysis shows that the source position moves from the BL Lac position toward the pulsar position with decreasing gamma-ray energy.

For the two-day flare, the EGRET data do not have good enough statistics or resolution to determine which of the two candidate sources is responsible for the flare. Modeling both the AGN and the pulsar at their known positions, the likelihood analysis assigns some photons to each source. The flare does have many more photons at lower energies than higher energies, as indicated in Table 2. Also listed in Table 2 are the number of photons expected from a single 2-day interval given the average flux of 3EG J0222+4253 in VP 15.0. From the numbers it is clear that the flare is seen at all energies, including the 100-300 and 300-1000 MeV bands. The energy distribution of the flare can also be seen in the source spectrum for all of VP 15.0, shown in Figure 2. The photon number index is 2.37 ± 0.29 for this viewing period, compared to 2.01 ± 0.14 for the sum of phases 1-4 for this source. Because most of the photons that make up the flare are of lower energy, they would be associated with the pulsar and not the AGN in the two-source model. Flaring behavior is not seen, however, in the other EGRET-detected pulsars. We cannot rule out the possibility that the AGN spectrum extended to lower energies during the flare, although other EGRET AGN spectra tend to flatten rather than steepen during flares (Sreekumar et al. 1996, Hartman et al. 2000).

3.1.2. 3EG J1410-6147

In the first four days of VP 14.0, this unidentified source decayed from a flux of almost $(5.4 \pm 1.5) \times 10^{-6}$ photons cm^{-2} s^{-1} to below EGRET's sensitivity, where it remained for the rest of the 14-day period (see Figure 3). This is suggestive of flaring behavior. The one-day variability index is 1.5 and Monte Carlo simulation gives a probability of about 0.0006 that the fluctuation found in VP 14.0 is produced by a nonvariable source. Although the source is 27°1 off-axis during VP 14.0, this was an early observation, when EGRET's sensitivity was high.

It has been suggested that 3EG J1410-6147 (l = 312.18, b = −0.35) is associated with SNR G312.4-0.4 (Sturner, S. J. & Dermer, C. D. 1995), which falls just outside the 68% error contour; this association is not well-confirmed. Flaring behavior would not be expected if the origin of the gamma rays was either cosmic rays from the SNR interacting with the surrounding material or a radio-quiet pulsar in the SNR. No association with any point radio source can be made (Mattox et al. 2000). Sources 3EG J0241-6103 (2CG 135+01; see below) and 3EG J1837-0606 (GRO J1838-04) share this characteristic (Kniffen et al. 1997, Tavani et al. 1998) of low Galactic latitude, variability, and lack of a strong radio counterpart. It may be that along with these sources, 3EG J1410-6147 represents a new class of gamma-ray emitter. This suggestion should be considered with caution in light of the high aspect during VP 14.0.

3.1.3. 3EG J1746-2851

As this source is unidentified, strong, and coincident with the Galactic Center, it has been studied in some detail (Mayer-Hasselwander et al. 1998). However, until now its short-term time history has not been examined. There is some evidence of fluctuation in VP's 16.0 and 429.0. It should be stated first that 3EG J1746-2851 sits in the center of the most densely-packed region of the gamma-ray sky; there are 10 sources listed in H99 within 10° of the Galactic Center. Given the broad EGRET PSF, source confusion is a serious problem. In addition, EGRET's sensitivity was high during this early observation but the source was 20°3 off-axis, leading to increased statistical uncertainty. However, while 3EG J1746-2851 appears to fluctuate during two different viewing periods, no other sources in highly congested regions display any evidence of short-term variability.

In VP 16.0 the three strongest one-day detections fall on days 7-9 of the 14-day period, exhibiting a peak flux of $(3.40 \pm 0.92) \times 10^{-6}$ photons cm^{-2} s^{-1} on day 8 (see Figure 4). This is only a 4.3σ detection, but it is flanked on days 7 and 9 by detections of 3.9σ and 3.1σ respectively and there is no detection stronger than 2.3σ within 5 days of the peak. The one-day variability index for VP 16.0 is 2.1, corresponding to a probability of 0.008 that these data are consistent with a nonvariable source. Monte Carlo analysis is more restrictive. This source and the seven others within a 7° radius were modeled and there is a probability of 0.0011 that a fluctuation of this (or greater) significance will occur in a 14-day period given intrinsically nonvariable sources.

Source 3EG J1746-2851 also shows evidence of variability in VP 429.0. During this pointing the aspect is only 6° and the one-day variability index has a value of 3.0. The peak flux is very high $(6.4 \pm 1.7) \times 10^{-6}$ photons cm^{-2} s^{-1} and on two days the source is not detected at all, but there is no evidence of flaring. The light curve is shown in Figure 5.

Time variability would indicate a compact object as the gamma-ray source. Models such as advection-dominated accretion flow onto a massive black hole (Mahadevan et al. 1997) would be favored rather than a collection of pulsars or a cosmic ray enhancement. See Mayer-Hasselwander et al. (1998) for further discussion of possible models.

3.1.4. 3EG J2006-2321

During VP 13.1 (1991 October 31 - November 7), this source ($l = 18^\circ 8, b = -26^\circ 3$) exhibited transient behavior on time scales of 12 hours. During this VP the source was 13°6 from the instrument axis and the overall significance of the detection is 4.8σ. A light curve of 3EG J2006-2321 in VP 13.1 is shown in Figure 6. The first two days of observation are broken down into four 12-hour periods; the remaining points represent full days. Breakdown of the data into smaller time intervals is not useful as poor statistics become overwhelming. EGRET appears to have caught 3EG J2006-2321 on the leading edge of an intense flare, although this is not known with high confidence. The peak flux, centered on MJD 48560.25, is $(1.75 \pm 0.53) \times 10^{-6}$ photons cm^{-2} s^{-1}; this 12-hour detection has a significance of 5.4σ. The source then decays monotonically on this time scale; less than two days later it is not detected by EGRET at all. The flux never rises above 3.9×10^{-7} photons cm^{-2} s^{-1} for the rest of VP 13.1. The ratio of peak to average flux for the VP is 5:1. The gamma-ray spectrum of 3EG J2006-2321 for VP 13.1 is consistent with a power law with exponent -2.13 ± 0.31.

Applying a χ^2 test to the light curve yielded a probability of 0.0006 that these data are consistent with an intrinsically nonvariable source. Results from Monte Carlo simulations of the source are consistent with these analyses. From the simulated data it was determined that the probability of finding such a deviation in a 7-day viewing period is 0.0005.

The combination of high Galactic latitude and short-term transient behavior suggests an association with the blazar class of AGN. While this source may well be a blazar, its radio flux at 5 GHz is significantly lower than blazars with similar peak gamma-ray flux values. The best candidate for association with 3EG J2006-2321 is the radio source PMN J2005-2310 (260 mJy at 5 GHz, α_r not known at this frequency; (Griffith, M. R. & Wright, A. E. 1993)). Of the 10 high-confidence blazars listed by Mattox et al. (1997) with peak gamma-ray flux above 10^-6 photons cm^{-2} s^{-1}, all are associated with flat-spectrum radio sources having a 5 GHz intensity above 1.0 Jy. The analysis of Mattox et al. (2000b) has determined that the *a priori* probability of EGRET detecting such a weak radio source is 0.0006. This low probability ensures that even though PMN J2005-2310 falls only 11.0 arcmin from the EGRET-determined position of 3EG J2006-2321, well within the 50% confidence countour, the probability of association is only 0.015 (Mattox et al. 2000). However, the variability presented in the present study bolsters the possibility of the source being a blazar. In addition, while PMN J2005-2310 is not bright, there is strong evidence that it is a flat-spectrum source; it is listed with a flux of 260 mJy in the Texas 365 MHz survey (Douglas, J. N. et al. 1996) where it is listed as TXS 2002-233. The spectral index around 365 MHz is 0.7 ± 0.2. The radio source also appears as NVSS J200556-231028 in the NRAO VLA Sky Survey (Condon et al. 1998) at 1.4 GHz with a strength of 302 mJy.

A multi-wavelength investigation of PMN J2005-2310 is encouraged in order to determine its nature. VLBI measurements may resolve a compact core, and optical observations may aid in determining redshift and polarization. Finally, an X-ray detection of this source will help to establish its spectral energy distribution.

3.2. Follow-up Reports of Short-term Variability

3.2.1. 3EG J0241+6103 (2CG 135+01)

Source 3EG J0241+6103 is unidentified and has been the subject of several papers because of evidence of short-term variability and lack of radio-loud blazar counterparts (Kniffen et al. 1997, Tavani et al. 1998). The short-term data have been re-analyzed in light of indications that another source (3EG J0229+6151, H99) exists only 1°68 away with about half the intensity of 3EG J0241+6103. The results still indicate evidence of variability in VP 211.0 (1993 25 February - 9 March) with a two-day variability index of 3.1 (see Figure 7). Although this source is near the galactic plane ($b = +0°99$), there are no EGRET-detected sources other than 3EG J0229+6151 within 10°. Source 3EG J0241+6103 and the nearby source were modeled using Monte Carlo methods and the probability of finding a fluctuation this strong or stronger from steady sources in a 14-day period is about 5.9×10^{-4}. During no viewing period other than 211.0 was the source found to be variable.

3.2.2. 3EG J0530+1323 (PKS 0528+134)

Previous analyses of this quasar, located near the Galactic anticenter, found it to be strongly variable on two-day time scales during early EGRET observations (Hunter et al. 1993, Thompson et al. 1997). PKS 0528+134 was observed in 1993 March to have a peak flux of 3.5×10^{-6} photons cm^{-2} s^{-1}; by 1993 May it had decreased by a factor of 2.5. The two-day variability index of 4.6 for VP's 0.2 through 2.1 corresponds to a probability of 0.0002 that these data are consistent with an intrinsically nonvariable source. This is in stark contrast to the results of almost three weeks of continuous observations of the Galactic Anticenter in 1995 February - March (VP's 412.0 and 413.0). During this time PKS 0528+134 displayed virtually constant flux in its two-day light curve (see

Figure 8); there is no evidence of variability from this strong, previously erratic source. The χ^2 analysis indicates that the probability that these late-period data are consistent with a constant source is 0.97. Therefore one must be careful when using flux histories to determine source class; while strongly variable data might be used to rule out identification of pulsars, measurements of constant flux do not rule out identification of AGN.

4. Discussion of Non-catalog Sources

The thresholds for inclusion in H99 (5σ for $|b| < 10°$ and 4σ for $|b| > 10°$) apply to any single viewing period or combination of viewing periods; however, it is possible for a source to display a short-duration significance well above that of the entire viewing period. This is almost always true of flaring sources, and is true of the following two sources. Their overall detections during the viewing periods in question fall below the catalog thresholds, but have short-duration excesses above these values.

4.1. GRO J0927-41

This source appears near $l = 266.68$, $b = 7.03$ with a 95% confidence radius of 1°01 during the third and fourth days of VP 338.5. On these days the source displays excesses of 3.3σ and 4.0σ respectively (see Figure 11). The combined significance for these two days is 5.2σ. The very strong Vela pulsar is 10°4 away; Monte Carlo simulation of GRO J0927-41 and Vela indicates that the probability of such transient behavior from an intrinsically nonvariable source is 0.0013. A search for counterparts revealed PKS 0920-397, a FSRQ 1°33 away near the 99% confidence contour. This quasar ($z = 0.591$) has a flat radio spectrum above 1.4 GHz, with a flux of 1.5 Jy at 4.85 GHz. It may be that EGRET has detected the tip of a flare from this source. There are not enough counts in the data to produce a spectrum of this source.

4.2. GRO J1547-39

In VP 226.0, an excess of 4.7σ appears near $l = 336.17$, $b = 11.78$ 95% with a confidence radius of 0°97. The source is given the name GRO J1547-39 and is seen most clearly in the third of four two-day maps. The light curve is shown in Figure 10. When broken down into one-day intervals, the significance falls to 4.0σ and 3.1σ. The overall detection for this source in VP 226.0 is 3.6σ; in no other viewing periods that include the source position does the overall significance rise above 3.0σ. No flat-spectrum radio loud blazars or other candidate objects appeared as candidates for association with this source, and there are not enough counts to provide a spectrum. Monte Carlo simulation of this source indicates that there is a probability of 0.010 of finding a "flare" of equal or greater strength from an intrinsically nonvariable source. With such a high probability we make only a weak claim for variability of GRO J1547-39.

4.3. Sub-threshold Repeating Sources

In the region $-40 < b < 40$, 148 two-day non-catalog excesses with significance $\geq 3.5\sigma$ are found. Among these are seven spatially coincident pairs and one spatially coincident triplet. For each set, the data are combined; in six of these combined maps the significance exceeds the standard thresholds. These pairs are considered for further analysis, with the hypothesis that each one represents the same transient source at high flux values.

This hypothesis is almost certainly not true. The probability of finding six such coincident pairs from 148 excesses is not negligible; assuming that the sources are randomly scattered and that each source has an error circle with radius ~1°0, the probability of finding six or more spatially coincident pairs is nearly 0.03. Beyond this simple analysis, the individual excesses are below threshold and most are close to the Galactic plane, and may not represent real sources. However, of these six pairs one is worthy of mention for its high combined significance.

During VP 423.5, a source appeared near $l = 334.78$, $b = -0.28$, prompting a report to the IAU (Kanbach et al. 1995). The source, GRO J1627-49, has a 95% confidence radius of 0°42 and was found to be coincident with an H II region. However, it was not seen in any other band and faded during the viewing period; it was not strong enough for the viewing period as a whole to be included in H99. The present analyses reveal that during VP 23.0 a sub-threshold excess appeared for two days at a coincident position. The data from these viewing periods combine to yield an excess with significance 5.7σ. The spectrum of these combined data is shown in Figure 11 and is rather flat, with a spectral index of 1.78 ± 0.31.

5. Limitations of this Study

EGRET's sensitivity, while higher than any previous gamma-ray telescope, is low enough to severely limit the present analyses when combined with the intrinsically low gamma-ray flux. Often there are simply not enough counts to break t he data down into smaller divisions and retain any meaningful information. For much of the data, low counts translate into statistical errors of ~40-50%. In these cases, an intrinsic flux increase of 100% is barely detected with any significance; changes of ~200-300% are required for higher-confidence claims of variability. Thus only the most dramatic changes in flux are measured with any confidence. For all but the strongest sources, the estimated 10% systematic uncertainty (Thompson et al. 1995) adds insignificantly to statistical error.

Interpretations of the variability index V are rendered problematic by the low EGRET count rate. A low value of V may have its origin in constant source output; it may also be due to poor statistics. There is no way to distinguish between these two cases. Again, this means that only very large values of V are meaningful, and that only strong variations from constant flux are detected.

Also, the high short-duration errors lead to uncertainties in mean fluxes for given viewing periods; the shorter the duration of the detection, the higher the uncertainty of the mean. This may result not only in misleading values of V but also Monte Carlo probabilities, as these calculations assume the averages for the viewing period in question.

6. Summary and Conclusions

The results of this work are summarized in Table 1. The first column indicates the source name by increasing Right Ascension; sources found in H99 are given the 3EG designation and non-catalog sources are given the GRO designation. The second column indicates alternate names, and the third column indicates source identification as FSRQ, BL Lac, or unidentified (UID). Column four indicates those viewing periods in which the source is found to be variable, column five gives the variability index for that viewing period, and column six indicates whether the source flared in that viewing period. The Monte Carlo probability for unidentified flaring sources is given in the seventh column.

The detections of short flares in 3EG J0222+4253 and 3EG J2006-2321 demonstrate that EGRET can detect short, intense flares in relatively weak catalog sources (3.9σ and 4.8σ in the viewing periods in which the flares were seen) as well as in strong blazars. Therefore most EGRET sources, except bright AGN, are not characterized by strong variability on one- and two-day time scales. If intense flares from sources like 3EG J0222+4253 and 3EG J2006-2321 were common, this survey would have detected more of them.

The same conclusion is reached for sub-threshold sources. The detections of GRO J0927-41 and GRO J1547-39, plus the repeating sources, demonstrate that EGRET can find very weak transients from sub-threshold sources with this sort of systematic analysis. The fact that few such intense flares are seen in this study indicates that the gamma-ray sky is not filled with these kind of flares from sub-threshold sources.

The flaring behavior seen in 3EG J0222+4253 adds another puzzle to the issue of identification of this source. The flaring is seen at energies between 100 MeV and 1 GeV, where the emission may be dominated by PSR J0218+4232. This would make this source unusual in two ways; it would be the only ms pulsar seen by EGRET and the only pulsar to show strong flaring.

The long observation of steady emission from PKS 0528+134 shows that, as seen by EGRET, blazars are not always variable even on time scales of three weeks. Therefore long episodes, free of intense flares from a given source, do not rule out the identification of that source as a blazar.

The observation of clear short-term variability in 3EG J2006-2321 indicates that this source may be a blazar, although its radio flux at 5 GHz is significantly less than other EGRET-detected blazars with similar peak gamma-ray brightness. The suggestion of variability of 3EG J1410-6147 may place it alongside 3EG J0241-6103 and 3EG J1837-0606 as a third candidate for a new gamma-ray class of variable Galactic sources.

In summary, the results of this study suggest that EGRET reached the threshold of an important new feature of gamma-ray astrophysics: the ability to measure short-term time variability. The few examples found by EGRET show that such sources do exist and are not restricted to the blazar class. Variability offers an effective tool for matching gamma-ray sources to objects seen at other wavelengths. With its ability to detect much fainter sources, measure variability on time scales of hours, and detect smaller flux variations that EGRET, the proposed Gamma-ray Large Area Space Telescope (GLAST) should be able to take full advantage of gamma-ray source time variability to extend the results of the present study.

The authors wish to thank J. R. Mattox and J. P. Halpern for their helpful comments and suggestions. P. W. gratefully acknowledges support from the NASA/ASEE Summer Faculty Fellowship Program.

REFERENCES

Bloom, S. D. et al. 1997, Proc. 4th Comp. Symp., ed. C. D. Dermer, M. S. Strickman, & J. D. Kurfess, AIP Conf. Proc. 410, 1262

Condon, J. J. et al. 1998, AJ, 115, 1693

Douglas, J. N. et al. 1996, AJ, 111, 1945

Esposito, J. A. et al. 1999, ApJS, 123, 203

Griffith, M. R. & Wright, A. E. 1993, AJ, 105, 1666

Hallum, J. C. et al. BAAS, 191, 103.15

Hallum, J. C. et al. ApJ, submitted

Hartman, R. C. et al. 1993, ApJ, 461, 698

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

Hartman, R. C. et al. 2000, ApJ, submitted

Hermsen, W. et al. Proc. 5th Comp. Symp., AIP Conf. Proc., in press.

Hunter, S. D. et al. 1993, ApJ, 409, 134

Hunter, S. D. et al. 1997, ApJ, 481, 205

Kanbach, G. et al. 1995, IAU Circular 6182

Kniffen, D. A. et al. 1993, ApJ, 411, 133

Kniffen, D. A. et al. 1997, ApJ, 486, 126

Mahadevan, R. et al. 1997, ApJ, 486, 268

Mattox, J. R. et al. 1993, ApJ, 410, 609

Mattox, J. R. et al. 1995, IAU Circular 6161

Mattox, J. R. et al. 1996, ApJ, 461, 396

Mattox, J. R. et al. 1997a, ApJ, 476, 692

Mattox, J. R. et al. 1997b, ApJ, 481, 95

Mattox, J. R. et al. 2000a, ApJ, submitted

Mattox, J. R. et al. 2000b, ApJS, submitted

Mayer-Hasselwander, H. A. et al. 1998, A&A 335, 161

McLaughlin, M. A. et al. 1996, ApJ, 473, 763

Mukherjee, R. et al. 1996, ApJ, 470, 831

Mukherjee, R. et al. 1997, ApJ, 490, 116

Ramanamurthy, P. V. et al. 1995, ApJ, 450, 791

Sreekumar, P. et al. 1996, ApJS, 464,628

Sreekumar, P. et al. 1998, ApJ, 494, 523

Sturner, S. J. & Dermer, C. D. 1995, A&A, 293, L17

Tavani, M. et al. 1997, ApJ, 479, L109

Tavani, M. et al. 1998, ApJ, 497, L89

Thompson, D. J. et al. 1995, ApJS, 101, 259

Thompson, D. J. et al. 1997, Proc. 4th Comp. Symp., ed. C. D. Dermer, M. S. Strickman, & J. D. Kurfess, AIP Conf. Proc. 410, 1257

Verbunt, F. et al. 1996, A&A, 311, L9

von Montigney, C. et al. 1995, ApJ, 440, 525

Wagner, S. et al. 1995, ApJ, 454, L97

Wherle, A. et al. 1998, ApJ, 497, 178

This manuscript was prepared with the AAS LaTeX macros v4.0.

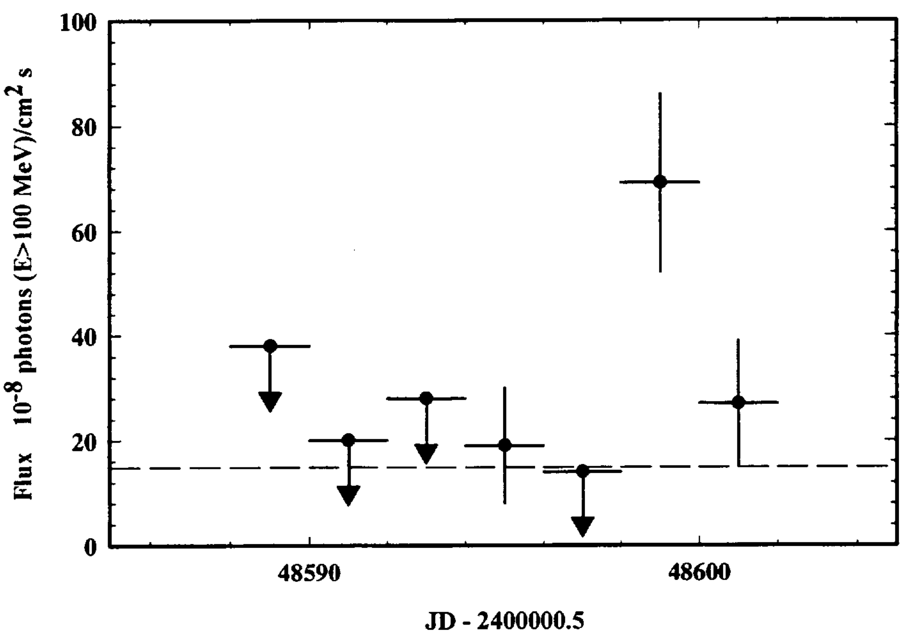

Fig. 1.— Light curve of 3EG J0222+4253 (3C 66A) during VP 15.0. The points represent 48-hour integration times. The variability index $V = 2.6$.

For all light curves, the dashed line indicates the average flux for the viewing period.

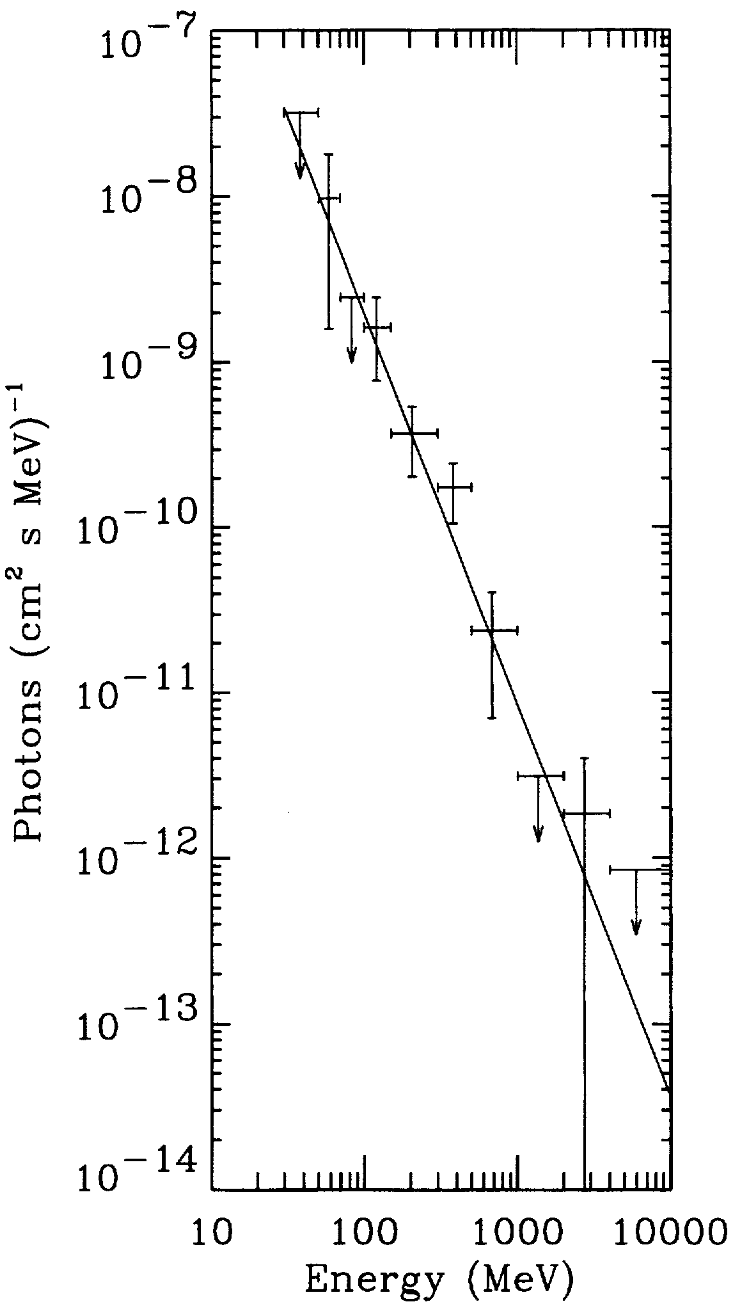

Fig. 2.— Spectrum of 3EG J0222+4253 (3C 66A) during VP 15.0. The spectral index is 2.37 ± 0.29.

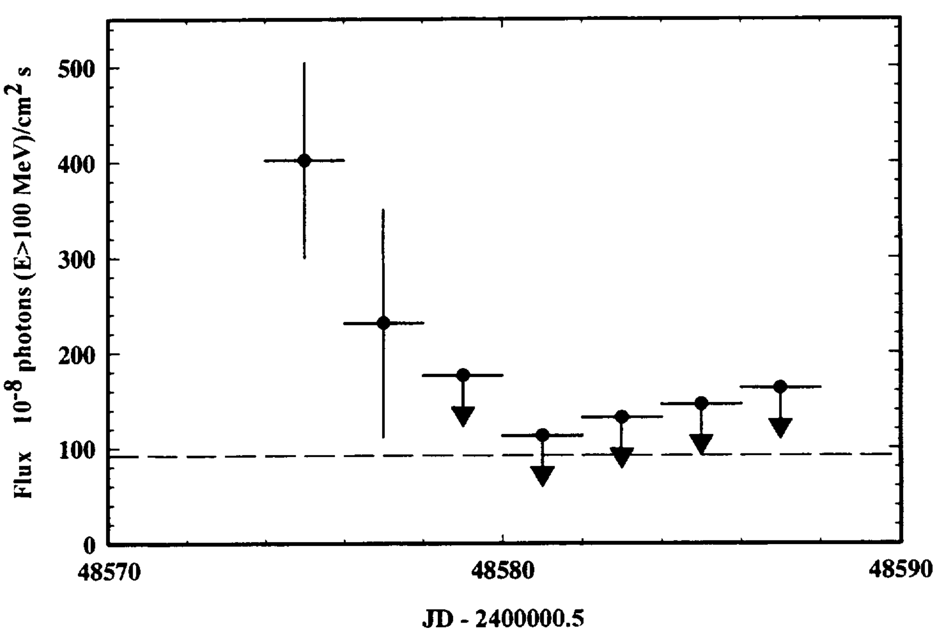

Fig. 3.— Light curve of 3EG J1410-6147 during VP 14.0. The points represent 48-hour integration times. The variability index $V = 2.4$.

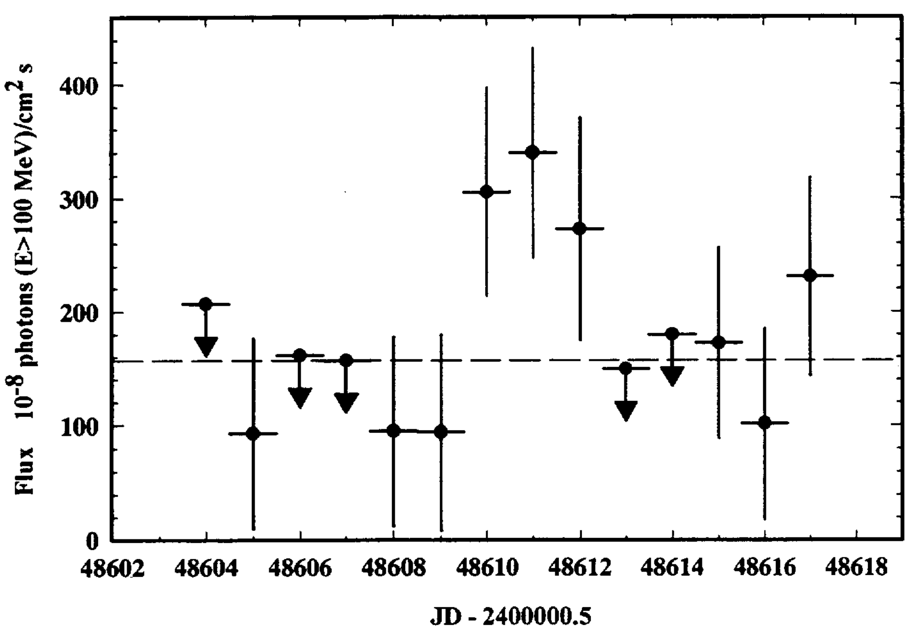

Fig. 4.— Light curve of 3EG J1746-2851 during VP 16.0. The points represent 24-hour integration times. The variability index $V = 2.1$.

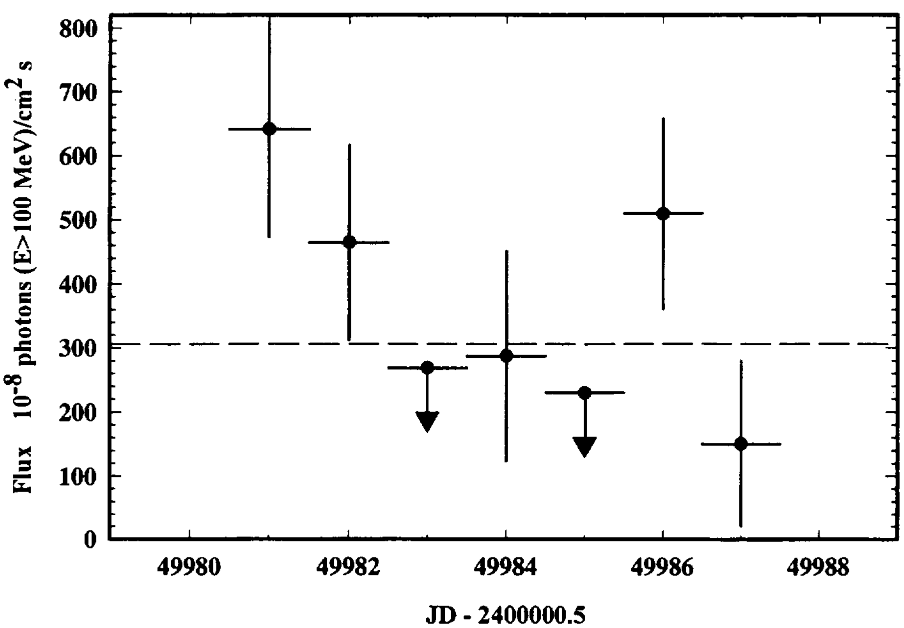

Fig. 5.— Light curve of 3EG J1746-2851 during VP 429.0. The points represent 24-hour integration times. The variability index $V = 3.0$.

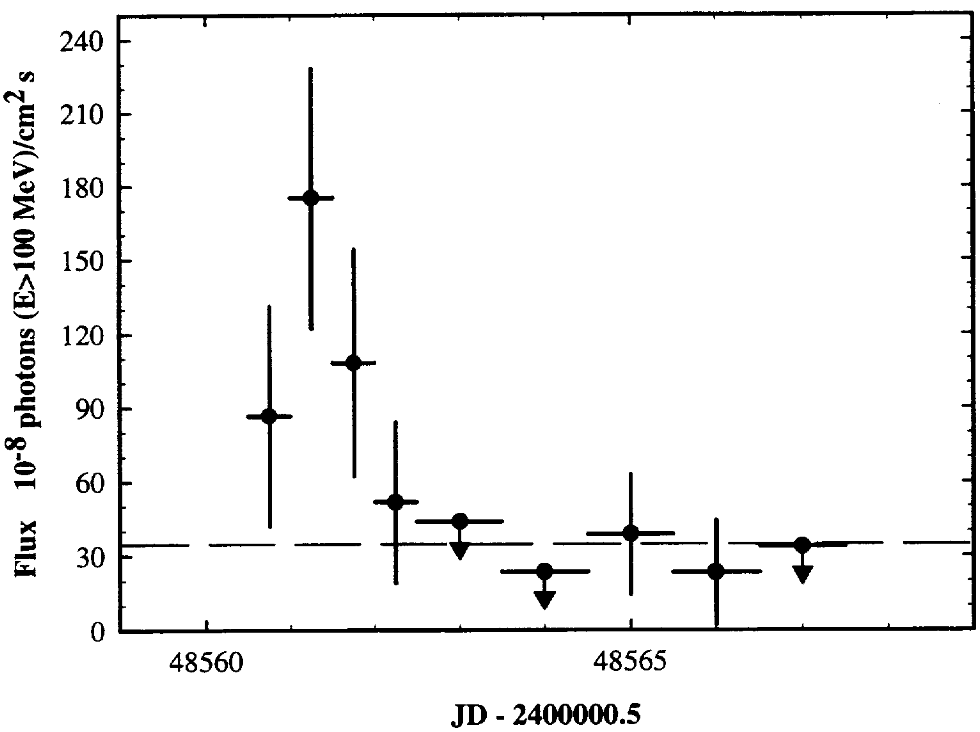

Fig. 6.— Light curve of 3EG J2006-2321 during VP 13.1. The first four points represent 12-hour integration times and the last five points represent 24-hour integration times. The dashed line indicates the average flux for the viewing period. The variability index $V = 3.2$.

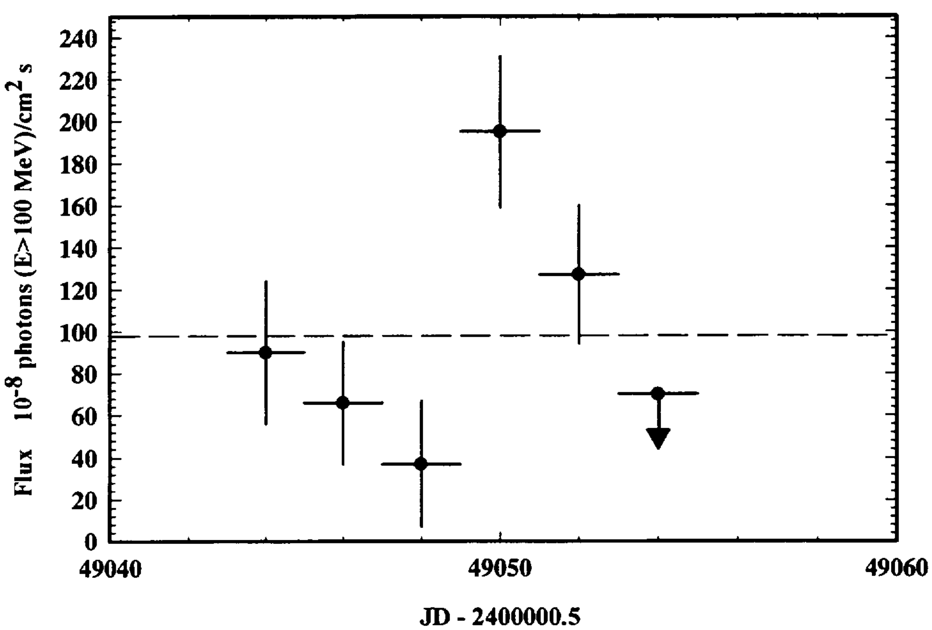

Fig. 7.— Light curve of 3EG J0241+6103 (2CG 135+01) during VP 211.0. The points represent 48-hour integration times. The variability index $V = 3.1$.

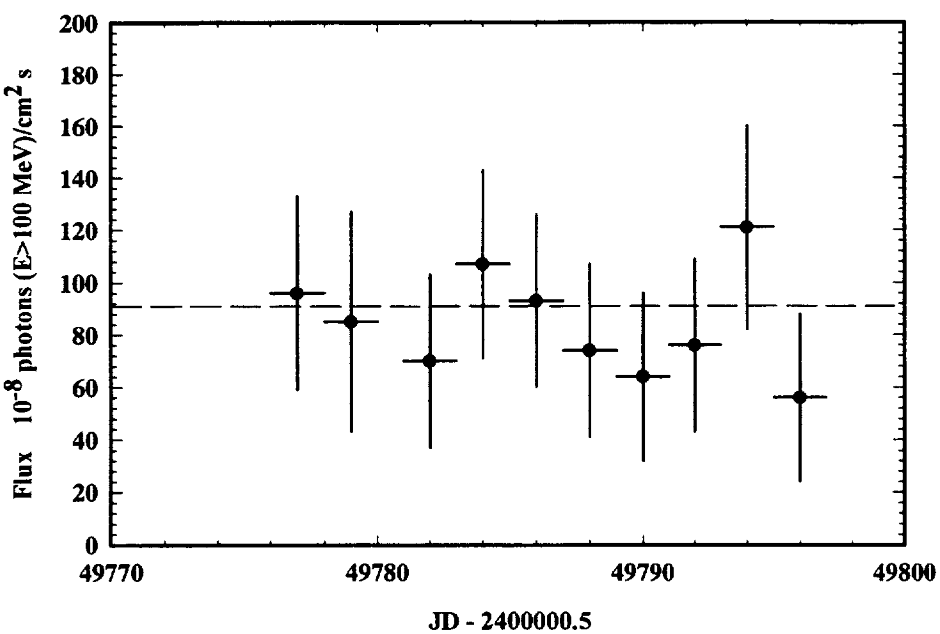

Fig. 8.— Light curve of 3EG J0530+1323 (PKS 0528+134) during VP's 412.0 and 413.0. The points represent 48-hour integration times. The variability index $V = 0.013$.

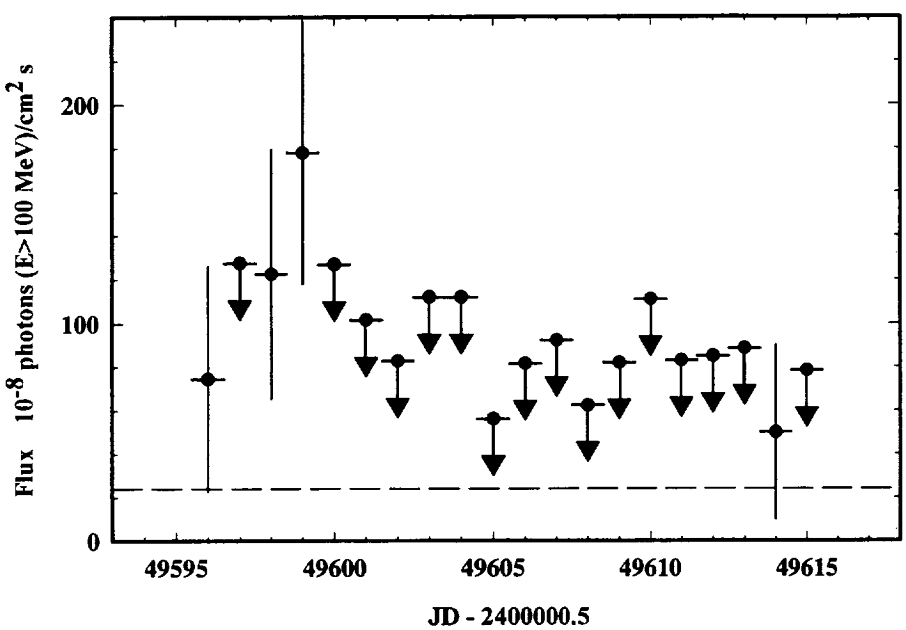

Fig. 9.— Light curve of GRO J0927-41 during VP 338.5. The points represent 24-hour integration times.

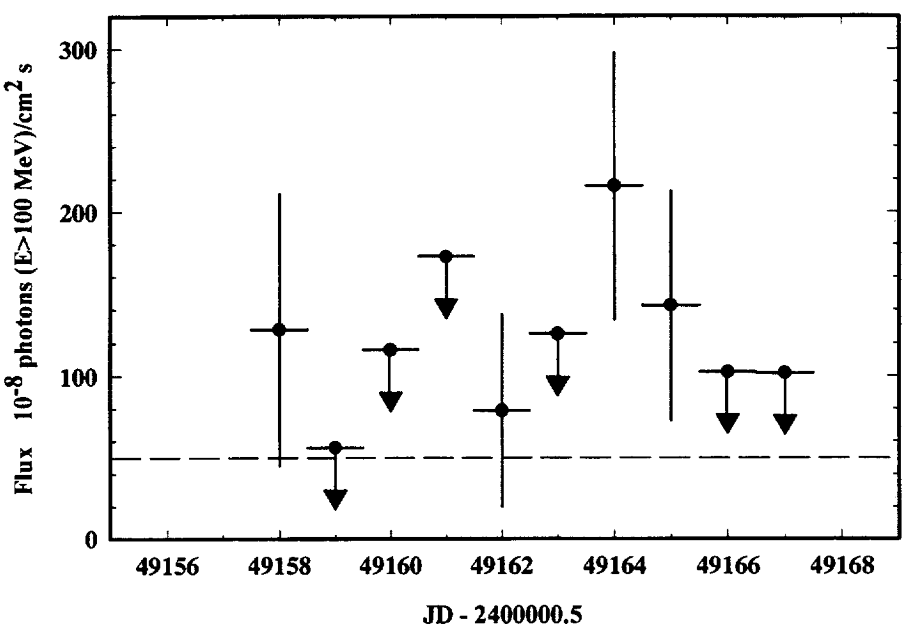

Fig. 10.— Light curve of GRO J1547+42 during VP 226.0. The points represent 48-hour integration times.

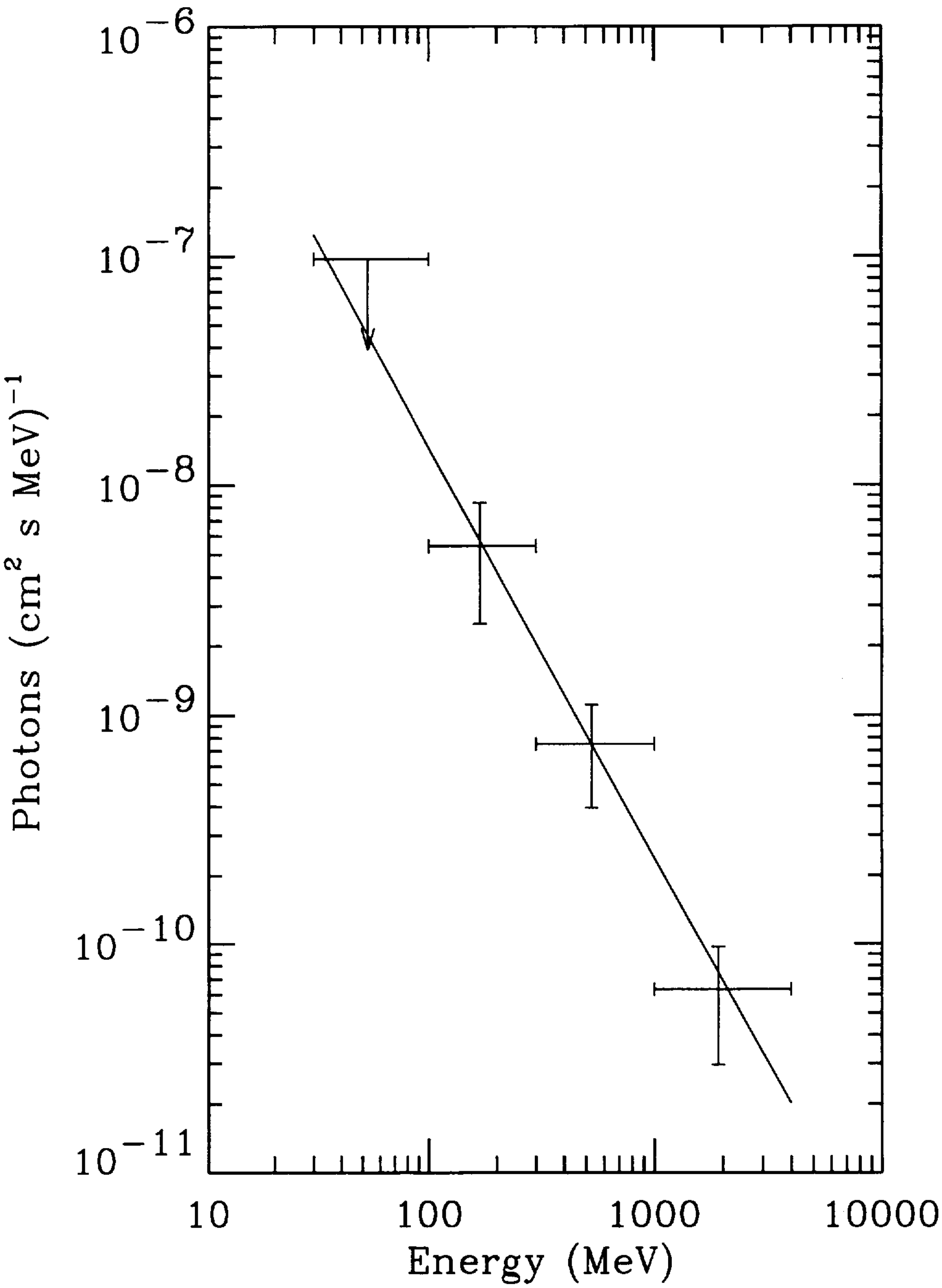

Fig. 11.— Combined spectrum of GRO J1627-49 from VP's 23.0 and 423.5. The spectral index is 1.78 ± 0.31.

Table 1. Sources Reported in this Study.

Source	Alt Name	ID	VP's	V	Single Flare	P_{mc}
3EG J0222+4253	3C 66A/	BL Lac/	15.0	2.6	yes	0.0005
	PSR J0218+4232	PSR				
3EG J0241+6103	2CG 135+01	UID	211.0	3.1	yes	0.0006
3EG J0530+1323	PKS 0528+134	FSRQ	0.2-2.1	4.6	no	n/a
GRO J0624-02[a]	none	UID	1.0,413.0	n/a	yes	n/a
GRO J0927-41	none	UID	338.5	0.5	n/a	0.001
3EG J1410-6147	none	UID	14.0	2.4	yes	0.0006
GRO J1547-39	none	UID	226.0	1.4	yes	0.010
GRO J1627-49[a]	none	UID	23.0,423.5	n/a	n/a	n/a
3EG J1746-2851	none	UID	16.0	2.2	yes	0.001
			429.0	3.0	no	n/a
3EG J2006-2321	none	UID	13.1	3.2	yes	0.0002

[a]Sub-threshold repeating source. Light curves were not generated for this source since it did not display any short-duration excess greater than 4σ.

Table 2. Fluxes for the Two-day Flare of 3EG J0222+4253.

Energy Range	Significance	Flux	Photons	Expected Photons
100-300 MeV	3.2σ	35 ± 14	18 ± 7	6 ± 2
300-1000 MeV	4.4σ	22 ± 8	13 ± 5	3 ± 1
>1000 MeV	1.8σ	4 ± 3	1.5 ± 1.4	0.2 ± 0.2