A variability and localization study of 3EG J1746-2851

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ABSTRACT

I have studied the variability properties and localization of 3EG J1746-2851 based on EGRET data of the observing periods 1–4. Using corrections for known systematic problems and performing various consistency checks I find no evidence of variability with an amplitude exceeding 30% with the possible exception of viewing period 429, for which a strong soft excess is observed. 3EG J1746-2851 is displaced from the exact Galactic Center towards positive Galactic longitudes. Sgr A∗, the center of Sgr A East, the pulsar J1747-2958, and the TeV γ-ray source observed with HESS seem to be excluded as possible counterparts at the > 95% level.

1. Introduction

The Galactic Center region contains many potential sources of high-energy γ-ray emission (Melia & Falcke 2001). A point source of GeV-scale γ-ray emission, 3EG J1746-2851, has been detected with EGRET (Mayer-Hasselwander et al. 1998), but no firm identification with sources known in other frequency bands has been made to date. Many models have been published to explain 3EG J1746-2851, e.g. invoking an advection-dominated accretion flow onto the supermassive black hole known as Sgr A∗ (Mahadevan et al. 1997; Markoff, Melia and Sarcevic 1997), the decay of neutralinos (Berezinsky et al. 1992), the acceleration of quasi-monoenergetic electrons in the radio arc (Pohl 1997), or a pulsar located on the line-of-sight to the Galactic Center (McLaughlin & Cordes 2003).

Very high-energy γ-rays have also been detected from the Galactic Center region with the Whipple 10m telescope (Kosack et al. 2004), the CANGAROO telescope (Tsuchiya et al. 2004), and the HESS array (Aharonian et al. 2004). The HESS data indicate a power-law spectrum with photon index $\alpha = 2.21 \pm 0.09$, an extrapolation of which does not fit the GeV-scale flux measured with EGRET. The source of TeV-scale γ-ray emission shows no evidence of variability and is coincident with Sgr A∗ to within about 0.02°. The lack of a cut-off in the γ-ray spectrum seems to disfavor models involving the annihilation of dark-matter particles (Bergström et al. 1998;
Ellis et al. 2002; Gnedin & Primack 2004), for a very high mass \( m_x \gtrsim 12 \text{ TeV} \) of the hypothetical neutralino would be required.

More conventional models for the high-energy emission from the Galactic Center region have also been proposed. Electron acceleration by plasma turbulence near the supermassive black hole (Schödel et al. 2002) may be a very efficient process (Liu et al. 2003). Atoyan & Dermer (2004) argue that the combination of ADAF-type accretion with a subrelativistic MHD outflow can explain the TeV-scale emission as well as that at X-rays and lower frequencies, but 3EG J1746-2851 would be a separate source. Fattuzzo & Melia (2003) discuss Sgr A East, a nonthermal radio source with a supernova-like morphology located near the Galactic center, as a possible counterpart of 3EG J1746-2851, and Crocker et al. (2004) attempt to relate 3EG J1746-2851, the TeV-scale \( \gamma \)-ray source, and anisotropies in the UHE cosmic-ray intensity to Sgr A East.

One of the fundamental questions is whether or not the sources seen in the GeV and TeV bands are identical. The analysis of EGRET data for the Galactic Center region is known to be affected by systematic problems, some of which have been understood since the detection of 3EG J1746-2851 was announced in 1998. In this paper I re-analyze the available EGRET data with a view to infer the variability properties and the localization as accurately as reasonably possible. For that purpose I introduce corrections in the way the diffuse foreground model is treated in the likelihood analysis, which are outlined in Sec. 2. I do not change the foreground model per se. Various consistency checks are performed using data for different energy bands and from different observing dates.

2. Modeling the galactic foreground emission

I have first analyzed the combined data sets of the EGRET observing periods 1–4 in an area of \( \pm 60^\circ \) in latitude and longitude around the Galactic Center. Using all 80 sources, that are listed in the Third EGRET Catalogue (Hartman et al. 1999) to be located in an area of \( \pm 40^\circ \) in latitude and longitude around the Galactic Center, I have run the LIKE software (Mattox et al. 1996) to simultaneously determine the multipliers \( G_{\text{Mult}} \) and \( G_{\text{Bias}} \) for the standard model of galactic diffuse \( \gamma \)-ray emission (Hunter et al. 1997) and isotropic emission, respectively, and the fluxes of these 80 sources while keeping their positions fixed. The multipliers \( G_{\text{Mult}} \) and \( G_{\text{Bias}} \) were allowed to vary freely. The purpose of the exercise was two-fold:

- to test whether or not the combination of the eighty 3EG sources and the foreground model is an acceptable fit to the entire data set. If there are \( \gamma \)-ray excesses with test statistic \( TS \geq 16 \) within \( 30^\circ \) of the Galactic Center, we may need to incorporate them in the analysis of individual viewing periods.

- to derive an appropriate range of parameter values for the foreground model. The galactic diffuse emission cannot be variable, and therefore the same model, i.e. the same values for \( G_{\text{Mult}} \) and \( G_{\text{Bias}} \) that we obtain from analyzing the combined data set, should be used in
the likelihood analysis of individual viewing periods. However, $G_{\text{Mult}}$ and $G_{\text{Bias}}$ must be allowed to vary within the range of statistical uncertainty of their best-fit values and within the uncertainty range of the spark-chamber efficiency correction (Esposito et al. 1999).

In contrast to the procedure used to derive the Third EGRET Catalogue, I did not include below-threshold excesses with $TS \geq 9$ in the analysis. The source fluxes obtained for the combined data set of the EGRET observing periods 1–4 are generally very similar to those listed in Hartman et al. (1999). The most prominent exception is 3EG J1744-3011, located at $l = -1.15^\circ$ and $b = -0.52^\circ$, with

$$3 \text{EG} \quad S = 9.4 \sigma \quad F(>100 \text{MeV}) = (63.9 \pm 7.1) \times 10^{-8} \text{ph./cm}^2/\text{sec}$$

This analysis

$$S = 7.6 \sigma \quad F(>100 \text{MeV}) = (50.5 \pm 6.9) \times 10^{-8} \text{ph./cm}^2/\text{sec}$$

(1)

For the Galactic Center source, 3EG J1746-2851, the flux and source significance determined with the combined data set are virtually identical to those listed in the catalogue.

$$3 \text{EG} \quad S = 17.5 \sigma \quad F(>100 \text{MeV}) = (119.9 \pm 7.4) \times 10^{-8} \text{ph./cm}^2/\text{sec}$$

This analysis

$$S = 17.5 \sigma \quad F(>100 \text{MeV}) = (118.6 \pm 7.3) \times 10^{-8} \text{ph./cm}^2/\text{sec}$$

(2)

At the position of the Galactic Center source the best-fit parameters of the foreground model are

$$G_{\text{Mult}} = 0.948 \quad G_{\text{Bias}} = 3.405$$

(3)

In the entire area of $\pm 20^\circ$ in latitude and longitude around the Galactic center these parameters have values not exceeding the range $[0.93, 1.18]$ for $G_{\text{Mult}}$ and $[2.3, 4.7]$ for $G_{\text{Bias}}$. The high value for the multiplier of isotropic emission, $G_{\text{Bias}}$, is possibly related to inverse-Compton emission not accounted for in the standard model of galactic diffuse $\gamma$-ray emission.

The highest intensity of diffuse galactic $\gamma$-rays is observed in direction of the Galactic Center. Any systematic errors associated with a mismodeling of the galactic emission will therefore be most severe in this region of sky. Systematic effects will also be more important at low $\gamma$-ray energies than at high energies on account of the strong energy dependence of EGRET’s point-spread function (PSF). Given the average photon flux above 100 MeV (Eq.2) and the similarity between the apparent $\gamma$-ray spectrum of 3EG J1746-2851 (Merck et al. 1996) and that of the diffuse emission, we can infer that the mean measured intensity (or count density) associated with 3EG J1746-2851 within the solid angle element containing $68\%$ of the photons, $\Omega(68\%)$, is approximately

$$I_{\text{GC}}(68\%) \simeq 0.68 \frac{F(>100 \text{MeV})}{\Omega(68\%)} \simeq 1.8 \times 10^{-4} \text{ph./cm}^2/\text{sec}/\text{sr}$$

(4)

which is small compared with the mean intensity of diffuse emission in that solid angle element. In the energy band above 1 GeV the mean intensity associated with 3EG J1746-2851 is actually more than a factor of two higher than that of the diffuse emission, solely on account of the narrower PSF. We must therefore expect that the high-energy band above 1 GeV is relatively clean of systematic
problems, as far as the determination of flux and position of 3EG J1746-2851 are concerned, and that the low-energy bands and the very wide bands, e.g. > 100 MeV, are subject to possibly serious systematic uncertainties.

One such systematic uncertainty arises from a simplification in the EGRET standard data analysis chain. There one uses allsky maps of modeled galactic diffuse $\gamma$-ray emission, in which the effect of the PSF is already incorporated. These maps are then multiplied with the exposure map (the time integral of the effective area) of the viewing period in question to produce a map of the expected event distribution that can be compared with the data. So the PSF is applied before the exposure, whereas it should be the other way around. Unpublished earlier Monte-Carlo studies by the author have indicated that this simplification may be problematic for 3EG J1746-2851, if the pointing direction is in the Galactic Plane at galactic longitude $l \approx \pm 20^\circ$, so that the Galactic Plane is radially oriented in the EGRET field-of-view, and the effective area of the instrument is rapidly decreasing with off-axis angle at the location of the point source in question.

For each viewing period I have created customized maps of diffuse galactic $\gamma$-ray emission, that are corrected for this simplification. Using a simple analytical representation of the spectrum of the diffuse galactic $\gamma$-ray emission,

\[
I_{\text{diff}} \propto \begin{cases} 
E^{-1.6} & \text{for } E < 1 \text{ GeV} \\
E^{-2.3} & \text{for } E > 1 \text{ GeV}
\end{cases} \tag{5}
\]
as well as the effective area distribution, the energy dispersion function, and the tabulated PSF data from the pre-launch calibration files for the dominant EGRET observing mode 74, I have calculated a mean PSF for each energy interval, for which data analysis would be performed. The mean PSF thus derived was then applied to the expected true count distribution, i.e. the product of the model of galactic emission, GALDIF, and the exposure map, EX, to derive the expected count distribution in the data,

\[
C(\theta, \phi) = \int d\alpha d\beta \text{ PSF}(\theta, \phi, \alpha, \beta) \text{ EX}(\alpha, \beta) \text{ GALDIF}(\alpha, \beta) \tag{6}
\]

where $\alpha$ and $\beta$ denote the true angular coordinates of the incoming $\gamma$-rays, whereas $\theta$ and $\phi$ are the measured angular coordinates of the $\gamma$-rays. The standard maps of diffuse galactic $\gamma$-ray emission, that can be obtained from the CGRO Science Support Center, are calculated assuming a single power-law spectrum with index 2.1, thus implying a PSF of different width that used in my analysis.

3. Analysis

Table 1 displays a list of all viewing periods considered in this study. For each viewing period the data have been analyzed in the energy bands 100-300 MeV, 300-1.000 MeV, >100 MeV, >300 MeV, and >1.000 MeV. I have also constructed a combined data set for all viewing periods with a view to derive a detailed spectrum and to pinpoint the localization of the source.
Table 1. A list of all viewing periods considered in this study. The table also shows the pointing direction in galactic coordinates and the observing time.

| VP | l   | b   | t [10^5 sec] |
|----|-----|-----|-------------|
| 5  | 0.0 | -4.0| 11.9        |
| 16 | 0.0 | 20.3| 12.9        |
| 210| -4.4| 6.3 | 2.4         |
| 214| -4.4| 6.3 | 2.5         |
| 219| -9.9| 15.9| 1.1         |
| 223| -0.9| -0.1| 2.6         |
| 226| -5.0| 5.0 | 8.6         |
| 2295| 5.0| 5.0 | 4.2         |
| 231| 22.2| -13.1| 5.7      |
| 232| -12.5| 0.0 | 12.1        |
| 3023| 1.4| 9.3 | 10.3        |
| 323| -3.2| -11.3| 11.9       |
| 324| 15.0| 5.6 | 5.9         |
| 330| 18.0| 0.0 | 3.4         |
| 332| 18.0| 0.0 | 14.6        |
| 334| 9.0| -8.4 | 5.9         |
| 3365| -19.6| 2.9 | 4.5         |
| 421| -4.7| 0.4 | 5.8         |
| 422| -4.6| -0.4| 6.1         |
| 423| 2.6| -0.2 | 8.5         |
| 4235| -14.3| 13.5| 8.5         |
| 429| 18.3| 4.0 | 6.0         |
| 508| 6.5| -0.2 | 5.1         |
| 625| 1.5| 0.8 | 11.1        |
3.1. Consistency checks and the spectrum

The spectra of EGRET sources are usually determined on the basis of a likelihood analysis in ten standard energy ranges. Table 2 lists the integrated photon flux and the $\nu F_\nu$ flux in the ten narrow energy bands and five wide energy bands based on a likelihood analysis of the combined data set. The spectrum depends very weakly on the assumed position of the source, if that is varied by $|\delta l| \lesssim 0.1^\circ$ in the Galactic Plane. Figure 1 shows the $\nu F_\nu$ spectrum above 70 MeV. The parameters of the diffuse foreground model, $G_{\text{Mult}}$ and $G_{\text{Bias}}$, were allowed to vary freely. Table 2 also lists the integrated photon flux for all energy bands that one obtains using the standard maps of diffuse foreground emission. The combined data set has an exposure distribution that peaks within $2^\circ$ of the Galactic Center and is fairly symmetric. The standard maps and the modified maps of galactic diffuse emission differ only marginally.

The photon flux for the energy bands below 100 MeV is strongly dependent on the particulars of the likelihood run, e.g. on the analysis parameter RANAL, and thus discredited. An anticorrelation between the multiplier $G_{\text{Mult}}$ of the diffuse emission model and the photon flux attributed to 3EG J1746-2851 can be observed, which indicates a similarity of the expected angular distributions of events for the diffuse emission and 3EG J1746-2851, respectively. The results of the likelihood analysis at energies below 100 MeV do therefore not merit our consideration in the variability and localization study.

One also notes that the integrated flux above 100 MeV is significantly higher than derived in the allsky analysis (Eq.2). The only difference between the two likelihood analyses was the inclusion in the allsky analysis of all viewing periods not listed in table 1, which leads to a significantly more homogeneous distribution of exposure across the sky. However, the exposure distribution for the combined data set as listed in table 1 is wider than that of any individual viewing period. So if the likelihood analysis of the combined data set is apparently inaccurate at low $\gamma$-ray energies for which the PSF is wide, there is no reason to assume it would fare better for any individual viewing period.

Another consistency check would be a comparison of the integrated flux obtained for a wide energy band with the sum of the fluxes in the corresponding narrow energy bands. While the high-energy bands are consistent with each other, we note that for the wide band 100–10.000 MeV the flux is about twice the sum of fluxes obtained in the corresponding narrow energy bands. The flux determined for the 300–10.000 MeV band is about 14% higher than the sum of the fluxes for the corresponding narrow energy bands. The chance probability of that deviation is about 15%, so given the number of trials we have to expect one deviation of that amplitude on statistical grounds. Significant problems can thus only be noted for the energy band 100–10.000 MeV.
Table 2. The spectrum of 3EG J1746-2851 as derived using the combined data set. The integrated photon flux in each energy band is given in units of $10^{-8} \text{ cm}^{-2} \text{s}^{-1}$. The $\nu F_\nu$ flux is in units of $10^{-6} \text{ MeV cm}^{-2} \text{s}^{-1}$ and derived assuming a photon spectrum $\propto E^{-2}$. The results of the likelihood analysis at energies below 70 MeV should be considered as upper limits for systematic reasons. Upper limits are given for a $2\sigma$ confidence level. For comparison the fourth column gives the integrated photon flux derived using the standard maps of diffuse emission.

| Energy [MeV] | $\bar{F}$  | $\nu F_\nu$ | $F_{\text{strd}}$ |
|--------------|-------------|--------------|-------------------|
| 30–50        | 565.3±73.1  | 424.0±54.8   | 344.9±71.6        |
| 50–70        | 101.8±16.9  | 178.2±29.6   | 73.4±16.7         |
| 70–100       | <14.1       | <32.6        | <15.4             |
| 100–150      | <8.92       | <26.3        | <9.1              |
| 150–300      | 20.7±4.1    | 59.7±12.3    | 16.1±4.1          |
| 300–500      | 18.5±2.1    | 136.±15.8    | 17.9±2.1          |
| 500–1.000    | 10.1±1.6    | 97.±16.      | 9.7±1.6           |
| 1.000–2000   | 9.4±1.1     | 181.±22.     | 9.1±1.1           |
| 2000–4000    | 3.3±0.67    | 127.±26.8    | 3.2±0.67          |
| 4000–10.000  | 1.1±0.42    | 68.±28.      | 1.1±0.42          |
| 100–300      | 22.4±6.5    | 33.6±9.8     | 12.6±6.5          |
| 100–1.000    | 143.7±7.0   | 145.±7.1     | 122.1±7.3         |
| 300–1.000    | 27.5±2.6    | 118.±11.1    | 25.8±2.6          |
| 300–10.000   | 48.5±3.1    | 150.±9.6     | 45.7±3.1          |
| 1.000–10.000 | 14.5±1.5    | 161.±16.7    | 13.7±1.5          |
Fig. 1.— The $\nu F_\nu$ spectrum of 3EG J1746-2851 as derived from an analysis of the combined data as listed in table 1. The spectrum is similar to that of the galactic diffuse emission.
3.2. Search for variability

In the preceding subsection we have reported on a number of inconsistencies in the results of a likelihood analysis of the combined data set, which indicate systematic problems. The affected data in the energy bands 100–10,000 MeV and below 100 MeV will therefore be excluded from the following analysis.

We now want to analyze the data for individual viewing periods with a view to infer the variability properties of 3EG J1746-2851. Earlier publications (e.g. Nolan et al. 2003) reported some evidence for variability based on a likelihood analysis of EGRET data in the energy band 100–10,000 MeV that we found affected by systematic problems. Here we use only data for energy bands, for which we see no clear evidence for systematic errors.

In the search for variability we therefore analyze EGRET data in the energy bands 100–300 MeV, 300–1,000 MeV, 1,000–10,000 MeV, and 300–10,000 MeV. In the narrow energy bands that we have used to derive the spectrum of 3EG J1746-2851 the statistical significance of detection is so low that an analysis of data of individual viewing periods does not provide meaningful results. We keep the position of the source fixed, for that cannot vary. Our analysis of the combined data set yielded $l = 0.11^\circ$ and $b = -0.04^\circ$ as best-fit position of 3EG J1746-2851, which we henceforth use as fixed location in the search for variability. Small changes in the assumed position by $\delta l \lesssim 0.1^\circ$ have virtually no impact on the results of the variability analysis.

The intensity of diffuse emission should be constant over time, and so should be the values of its scaling factors in the likelihood analysis, $G_{\text{Mult}}$ and $G_{\text{Bias}}$. The uncertainty of the spark-chamber efficiency correction introduces some variations in the best-fit values of the scaling factors, that should have an amplitude around 10% (Esposito et al. 1999). For each data set we ran the likelihood analysis twice, first with the scaling factors fixed to the values found in the allsky analysis (Eq. 3), and then allowing the scaling factor to freely vary. Variable scaling factors should provide a better representation of the diffuse galactic emission, for they can balance errors in the spark-chamber efficiency correction and they can correct inappropriate large-scale structure in the model of diffuse emission. On the other hand, one may expect an anti-correlation between the best-fit flux from 3EG J1746-2851 and the best-fit value of $G_{\text{Mult}}$, which is the dominant parameter for the intensity of the expected diffuse $\gamma$-ray emission from the inner galaxy. Therefore the mean relative amplitude of variations in $G_{\text{Mult}}$ over $N$ viewing periods

$$
\sigma_{G_{\text{Mult}}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \frac{(G_{\text{Mult}} - \bar{G}_{\text{Mult}})^2}{\bar{G}_{\text{Mult}}^2}}
$$

(7)

should not significantly exceed 10%. We thus monitor the variations in the best-fit values of $G_{\text{Mult}}$ to ensure that variations in the measured flux from 3EG J1746-2851 are not caused by an unrealistically extreme value of $G_{\text{Mult}}$. 
3.2.1. The energy band 300–10,000 MeV

The results of the likelihood analysis runs for the individual viewing periods as well as for the combined data set are summarized in table 3. The scaling parameter of diffuse emission, $G_{\text{Mult}}$, has best-fit values that are characterized by

$$G_{\text{Mult}} = 1.021 \quad \sigma G_{\text{Mult}} = 0.106$$

so the scatter in $G_{\text{Mult}}$ is at a level commensurate with the systematic error in the absolute determination of EGRET’s effective area at the time of measurement, thus not indicating any additional systematic problem.

We can perform a $\chi^2$-test to determine how well the measured fluxes in the 24 viewing periods are compatible with a constant flux. The best-fit constant flux would be

$$\overline{F}(>300 \text{MeV}) = 45.74 \times 10^{-8} \text{cm}^{-2} \text{s}^{-1}$$

for which the minimal value of the $\chi^2$-sum and the chance probability of drawing the measured distribution given a constant flux, the goodness-of-fit, would be

$$\chi^2_{\text{min}} = 30.0 \quad P_{\text{chance}} = 15\%$$

This indicates some scatter in the distribution of flux values beyond what must be expected on statistical grounds. We can estimate the amplitude of that scatter by Gaussian adding of a systematic uncertainty $\delta = y\overline{F}$ to the flux measurement error. The amplitude of scatter is then approximately given by the value of $y$, for which the minimal value of the $\chi^2$-sum equals the number of degrees of freedom (22 in this test). The resulting estimate for the amplitude of variations is

$$y_{\text{best fit}} = 0.197$$

which is just twice the expected level of absolute calibration error.

3.2.2. The energy band 300–1,000 MeV

This energy band is part of the energy band, the results for which we have just discussed. It is thus not statistically independent. The scaling parameter of diffuse emission, $G_{\text{Mult}}$, has best-fit values that are characterized by

$$G_{\text{Mult}} = 0.875 \quad \sigma G_{\text{Mult}} = 0.118$$

so the scatter in $G_{\text{Mult}}$ is again at a level commensurate with the systematic error in the absolute calibration.

The best-fit constant flux would be

$$\overline{F}(300 – 1,000 \text{MeV}) = 25.08 \times 10^{-8} \text{cm}^{-2} \text{s}^{-1}$$
Table 3. Results of the likelihood analysis in the energy band $> 300$ MeV. The position of 3EG J1746-2851 was held fixed at $l = 0.11$ deg and $b = -0.04$ deg. The integrated photon flux $F$ is given in units of $10^{-8}$ cm$^{-2}$ s$^{-1}$. Upper limits correspond to 95% confidence or $2\sigma$.

| VP | $G_{\text{Mult}}$ fixed | $G_{\text{Mult}}$ variable |
|----|--------------------------|-----------------------------|
|    | $\sigma$ | $F$ | $\sigma$ | $F$ | $G_{\text{Mult}}$ | $\sigma$ | $F$ | $G_{\text{Mult}}$ |
| 5  | 5.2     | 28.9±6.2 | 7.3     | 44.9±7.0 | 0.889 |
| 16 | 8.9     | 85.5±11.7 | 7.3     | 76.4±12.3 | 1.129 |
| 210| 2.5     | 58.4±27.4 | 1.9     | 49.0±28.6 | 1.129 |
| 214| 1.6     | 29.3±20.1 | 1.5     | 28.8±21.3 | 1.059 |
| 219| 0.7     | $<125.7$ | 0.8     | $<136.6$ | 0.988 |
| 223| 2.3     | 41.8±20.9 | 1.9     | 37.7±22.0 | 1.117 |
| 226| 1.9     | 19.9±11.5 | 2.2     | 25.9±12.6 | 0.969 |
| 2295| 2.1     | 32.8±17.6 | 2.1     | 37.1±19.4 | 1.015 |
| 231| 2.4     | 56.6±29.0 | 2.4     | 62.6±31.2 | 0.980 |
| 232| 5.6     | 61.8±13.0 | 5.4     | 64.5±14.0 | 1.029 |
| 3023| 2.4     | 29.7±13.4 | 1.9     | 24.7±14.3 | 1.068 |
| 323| 4.9     | 45.9±10.7 | 3.9     | 39.4±11.3 | 1.122 |
| 324| 3.6     | 54.0±17.5 | 3.2     | 52.0±18.5 | 1.069 |
| 330| 5.0     | 118.2±29.6 | 4.3     | 110.5±31.1 | 1.086 |
| 332| 6.8     | 69.1±12.1 | 6.6     | 72.2±12.9 | 1.022 |
| 334| 2.0     | 27.7±14.9 | 1.9     | 27.5±16.0 | 1.053 |
| 3365| 2.4     | 55.2±26.9 | 1.9     | 46.3±27.9 | 1.120 |
| 421| 1.8     | 20.5±12.7 | 2.5     | 32.2±14.5 | 0.938 |
| 422| 1.2     | 12.9±11.2 | 3.2     | 38.1±13.5 | 0.822 |
| 423| 1.9     | 17.3±9.8  | 3.7     | 38.1±11.6 | 0.897 |
| 4235| 0.3     | $<37.2$   | 2.2     | 34.2±18.0 | 0.773 |
| 429| 3.2     | 56.7±20.7 | 4.0     | 77.8±23.3 | 0.883 |
| 508| 5.6     | 88.7±19.7 | 4.0     | 69.5±20.2 | 1.235 |
| 625| 4.2     | 43.1±11.7 | 3.2     | 36.4±12.6 | 1.107 |
| all| 17.9    | 44.7±2.9  | 17.8    | 48.5±3.1  | 1.011 |
for which the minimal value of the $\chi^2$-sum and the chance probability of drawing the measured distribution given a constant flux, the goodness-of-fit, would be

$$\chi^2_{\text{min}} = 31.0 \quad P_{\text{chance}} = 12.3\% ,$$

(14)

very similar to the results obtained for the wide energy band 300–10,000 MeV.

The resulting estimate for the amplitude of variations is

$$y_{\text{best fit}} = 0.346 ,$$

(15)

which is nearly twice as much as in the wide energy band.

### 3.2.3. The energy band 1,000–10,000 MeV

At these very high energies we expect the model of diffuse galactic emission to play a small role in the likelihood analysis. On the other hand, the small number of photons will reduce the statistical accuracy of the results.

The scaling parameter of diffuse emission, $G_{\text{Mult}}$, has best-fit values that are characterized by

$$\overline{G_{\text{Mult}}} = 1.46 \quad \sigma G_{\text{Mult}} = 0.154$$

(16)

so the scatter in $G_{\text{Mult}}$ is slightly larger than the systematic error in the absolute calibration. The large value of $\overline{G_{\text{Mult}}}$ reflects the GeV excess in the diffuse galactic $\gamma$-ray emission (Hunter et al. 1997).

The best-fit constant flux would be

$$\overline{F}(>1,000\text{MeV}) = 12.9 \cdot 10^{-8} \text{ cm}^{-2}\text{ s}^{-1}$$

(17)

for which the minimal value of the $\chi^2$-sum and the chance probability of drawing the measured distribution given a constant flux, the goodness-of-fit, would be

$$\chi^2_{\text{min}} = 25.3 \quad P_{\text{chance}} = 33.5\% ,$$

(18)

indicating no evidence for variability at energies higher than 1 GeV.

The resulting estimate for the amplitude of variations is

$$y_{\text{best fit}} = 0.182 ,$$

(19)

which here is more an estimate for the sensitivity of the method used in the search for variability, for additional fluctuations with an amplitude much higher than this value would be required to significantly increase the minimum $\chi^2$-sum in Eq. 18.
3.2.4. The energy range 100–300 MeV

This data in this energy range should contain a large number of γ-ray events, but are potentially problematic because of the large width of the PSF. Systematic problems were evident at lower energies, and we do not know very well to what extent the data at 100–300 MeV are affected.

The scaling parameter of diffuse emission, $G_{\text{Mult}}$, has best-fit values that are characterized by

$$G_{\text{Mult}} = 0.897 \quad \sigma_{G_{\text{Mult}}} = 0.132$$

so the scatter in $G_{\text{Mult}}$ is marginally larger than the systematic error in the absolute calibration.

The best-fit constant flux would be

$$F(100−300 \text{ MeV}) = 29.9 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$$

for which the minimal value of the $\chi^2$ sum and the chance probability of drawing the measured distribution given a constant flux, the goodness-of-fit, would be

$$\chi^2_{\text{min}} = 43.58 \quad P_{\text{chance}} = 0.6\%.$$  

The resulting estimate for the amplitude of variations is

$$y_{\text{best fit}} = 0.71.$$  

A close inspection of the flux distribution reveals that all this evidence of variability is caused by one data point, that for viewing period 429. If we neglected that measurement, our results would be

$$F(\text{excl. VP429}) = 26.1 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$$

and

$$\chi^2_{\text{min}} = 21.92 \quad P_{\text{chance}} = 46.5\% \quad \text{excl. VP429},$$

i.e. no evidence for any variability. So the question is whether or not the measurement of a high flux during VP429 is realistic.

The measured flux from 3EG J1746-2851 during VP429 is

$$F_{\text{VP429}}(100−300 \text{ MeV}) = (242.6 \pm 46.1) \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$$

What was the flux in the other energy bands? In all cases it was around 60% above average with the statistical significance of the excess being around 1σ. Equation 26 indicates that in the energy band 100–300 MeV the flux was a factor of 8 above average with a statistical significance of 4.6σ. If the outburst were real, the source must have an soft flare spectrum, as shown in figure 2.

What was the best-fit value of the scaling factor of diffuse emission, $G_{\text{Mult}}$, for VP429? It is $G_{\text{Mult}}(\text{VP429}) = 0.66$, actually the lowest value of all viewing periods, which mandates a view at the results of the likelihood analysis for fixed $G_{\text{Mult}}$,

$$F_{\text{VP429}}(G_{\text{Mult}} = 0.948) = (104.1 \pm 39.9) \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$$

which is still more than three times the average flux with a statistical significance of 2σ.
Fig. 2.— The $\nu F_{\nu}$ spectrum of 3EG J1746-2851 during viewing period 429. Data shown with dotted or dashed error bars refer to wide energy bands and are not statistically independent of the data points plotted with solid error bars. The spectrum is much softer than the time-averaged spectrum shown in Fig. 1.
3.3. The localization of 3EG J1746-2851

The likelihood ratio test, that is used to determine the flux and detection significance of point sources, can also provide an estimate of the source position and its uncertainty. For that purpose one calculates the point source test statistic

\[ TS = -2 \ln L_0 - \ln L_1(\alpha, \beta) \] (28)

for a finely sampled array of test positions \((\alpha, \beta)\) (Mattox et al. 1996). Here \(L_0\) is the likelihood function for the null hypothesis and \(L_1\) is the likelihood function assuming a point source at the position \((\alpha, \beta)\). The increase in TS at the location of its maximum over TS at the true position is expected to follow a \(\chi^2\) distribution, for the two angular coordinates are two additional degrees of freedom (Wilks 1938). Decrements from max(TS) by 2.3, 6.0, and 9.1 delineate the boundaries of regions in which the source is located with a confidence level of 68%, 95%, and 99%.

Obviously the localization analysis can provide meaningful results only if max(TS) is not too small. We have therefore first analyzed the combined data set, which should provide the best statistical accuracy. As in our search for variability (Sec. 3.2), we exclude data at energies below 100 MeV and in the wide energy band 100-10,000 MeV, because they appear to be affected by systematic problems.

In the energy band 100–300 MeV 3EG J1746-2851 is detected with a significance of only 3.5\(\sigma\), too low to provide constraining results, so here we only report that the localization estimate for that energy band is compatible with those obtained using data at higher photon energies.

In the figures 3 and 4 we show source localization confidence contours for the energy bands 300–1,000 MeV and > 1,000 MeV, respectively, in comparison with the position of the central part of the galactic center arc and that of Sgr A* . To be noted from the figures is that in the two independent energy bands the likelihood analysis indicates a source position that is significantly displaced from the exact Galactic Center, or Sgr A*, or the position of the TeV \(\gamma\)-ray source (Aharonian et al. 2004), that coincides with Sgr A* to within 1.2 minutes of arc.

The best-fit positions determined for the two energy bands are moderately well compatible with each other. However, both are within the 68% confidence contour as determined for the 100–300 MeV band. The 68% confidence contours for the energy bands 300–1,000 MeV and > 1,000 MeV just touch each other, but there is a substantial overlap of the 95% confidence regions. The localization analysis of these two statistically independent data sets thus provides a much more consistent result than did the original study by the EGRET team (Mayer-Hasselwander et al. 1998), where even the 99% confidence contours for the 1–30 GeV and the 100–300 MeV bands didn’t come close to each other.

We can further test for systematic errors in two ways, which we discuss in turn.
Fig. 3.— Source localization confidence contours for the energy band 300–1,000 MeV. The square indicates the position of the central part of the Galactic Center arc and the asterisk denotes Sgr A*. The triangle and the diamond indicate the best-fit position in the energy bands 300–1,000 MeV and > 1,000 MeV, respectively.
Fig. 4.— The results of the source localization analysis for the energy band > 1.000 MeV. The symbols indicate the positions of the same systems as in Fig. 3.
3.3.1. Consistency of localization in different energy bands

The test statistic, TS, of two statistically independent data sets is additive. We can therefore co-add the TS fine maps for the energy bands 300–1.000 MeV and > 1.000 MeV to obtain a TS fine map for the total energy range > 300 MeV. The localization information thus derived should be compatible with the results of a likelihood analysis of the data in the band > 300 MeV, which is systematically different for two reasons. First it lacks the information which photons have a high energy and thus a narrow PSF, and therefore there is less information available. Second, the source spectrum may be different from the simple power law that is assumed to construct a band-averaged PSF, and therefore the PSF used in the likelihood analysis is the more likely to be inaccurate the wider the energy band. In Fig. 5 we compare the confidence contours derived from a likelihood analysis of the data in the > 300 MeV band with those obtained by adding the TS fine maps for the two narrower bands. There is a substantial overlap of the confidence regions, and the differences can be attributed to the displacement of the source localization at energies > 1.000 MeV relative to that at lower energies, an information that is preserved in the co-added TS fine map but not available to the likelihood analysis for the energy band > 300 MeV. We do not note any systematic problem that might arise from a possibly inaccurate PSF in the analysis of the wide energy band. Again, the position of Sgr A* and the position of the TeV γ-ray source seem to be excluded, and the GeV γ-ray source 3EG J1746-2851 appears to be located a fraction of a degree away from the exact Galactic Center.

3.3.2. Consistency of localization in individual viewing periods

The localization accuracy obtained from the analysis of data for individual viewing periods will be worse than that derived using the combined data set, and the best-fit positions of 3EG J1746-2851 will be scattered over an area much larger than the confidence regions shown in Figs. 3–5. We can test whether or not the observed scatter in the best-fit source position is compatible with a common true position and the measured localization uncertainties. The confidence contours can usually be accurately fitted with an ellipse that is specified by a semimajor axis $p$, semiminor axis $q$, and position angle of the major axis $\phi$ (Thompson et al. 1995). The ellipse is centered on the centroid of the confidence location region, which thus serves as a position estimate. Mattox et al. (1997) noted that for strong sources the dependence of the logarithm of the likelihood of EGRET data upon the assumed source position closely follows a paraboloid, indicating a Gaussian error distribution and thus justifying the use of the $\chi^2$-test. In contrast to Thompson et al. (1995) and Mattox et al. (1997) we use a fit to the 68% confidence contour. The displacement of the assumed (or measured) position from the true position is described by the distance $r$ and the position angle $\theta$. Then the $\chi^2$-sum is defined by

$$
\chi^2 = \sum_{i=1}^{N} r_i^2 \left[ \left( \frac{\cos(\phi_i - \theta_i)}{p_i} \right)^2 + \left( \frac{\sin(\phi_i - \theta_i)}{q_i} \right)^2 \right] \quad (29)
$$
Fig. 5.— The results of the source localization analysis for the energy band $> 300$ MeV. The solid lines denote the confidence contours derived from a likelihood analysis of the data in the $> 300$ MeV band, whereas the dotted lines are obtained by adding the TS fine maps that result from likelihood analysis of the statistically independent data in the $300–1,000$ MeV and $> 1,000$ MeV bands. The meaning of the symbols is the same as in Fig. 3.
A certain minimum in detection significance is necessary to provide a meaningful localization. Here we only consider data from viewing periods for which 3EG J1746-2851 was detected with at least $\sqrt{T S} = 3$.

Table 4 lists the results of the location analysis in the energy range $> 300$ MeV for the 12 viewing periods, for which the detection significance exceeded the required threshold. By minimizing the $\chi^2$-sum as given in Eq. 29 we obtain for that energy range

$$\chi^2_{\text{min}} = 8.876 \quad N_{\text{d.o.f.}} = 10 \quad P_{\text{chance}} = 54.4\%$$

(30)

The coordinates, for which the $\chi^2$-sum is minimized, and their marginalized $1\sigma$-errors are

$$l = 0.38^\circ \pm 0.09^\circ \quad b = -0.007^\circ \pm 0.075^\circ$$

(31)

which is right inside the 68% localization contour derived from the combined data set for the same energy band (Fig. 5). The scatter in the position estimates for the 12 viewing periods and the best-fit position thus determined are therefore entirely consistent with the statistical uncertainties. There is no evidence for an additional systematic error in the localization.

4. Summary and discussion

In this paper I have re-analyzed EGRET data of the observing periods 1–4 to derive the variability properties and localization of 3EG J1746-2851. For that purpose I have introduced corrections in the way the diffuse foreground model is used treated in the likelihood analysis, and I have also performed various consistency checks using data for different energy bands and from different observing dates. Using only data for which I found no evidence of systematic problems, e.g. excluding the wide energy band 100–10,000 MeV and other low-energy bands, I obtained the following results:

- There is little evidence of variability. The chance probability of drawing the measured distribution of photon fluxes given a constant flux is always higher than 10%, corresponding to a $\chi^2$/d.o.f. smaller than 1.35. The observed scatter in the measured flux values may correspond to variability at a level of 20–30%, if it were real. Thus I find an upper limit of $\lesssim 30\%$ to the relative amplitude of stochastic variability in the lightcurve above 300 MeV of 3EG J1746-2851. This conclusion would be corroborated by the data in the energy range 100–300 MeV, if I neglected viewing period 429, for which one notes an apparently intense flare with a soft spectrum. I find some indications of systematic problems in the data of VP429 for the 100–300 MeV band, but no substantial indication that the observed high flux may be an artifact.

- The data indicate that 3EG J1746-2851 is displaced from the exact Galactic Center towards positive Galactic longitudes, in qualitative agreement with the findings of Hooper & Dingus
Table 4. Results of the localization analysis in individual viewing periods and the energy band $> 300$ MeV. The position angle $\phi = 0$ and $\phi = \pi/2$ correspond to the direction of the galactic-longitude axis and the negative galactic-latitude axis, respectively. We only list viewing periods for which 3EG J1746-2851 was detected with at least $\sqrt{TS} = 3$. The best-fit positions are in degrees, the ellipse axes are in arcmin, and the major-axis position angle is in degrees.

| VP | position | 68% error ellipse |
|----|----------|-------------------|
|    | $l$   | $b$   | $p$   | $q$   | $\phi$ |
| 5  | 0.05  | 0.21  | 22.2  | 7.9   | 93.0   |
| 16 | 0.39  | -0.04 | 9.5   | 9.5   | 0.0    |
| 232| 0.11  | 0.17  | 15.8  | 14.9  | 140.7  |
| 323| 0.58  | -0.04 | 15.9  | 15.9  | 0.0    |
| 324| 0.48  | -0.04 | 39.2  | 26.7  | 93.3   |
| 330| 0.79  | -0.38 | 26.6  | 21.1  | 120.9  |
| 332| 0.27  | -0.04 | 25.0  | 14.2  | 109.1  |
| 422| 0.11  | 0.33  | 39.7  | 28.4  | 177.2  |
| 423| 0.40  | -0.33 | 47.8  | 23.0  | 13.1   |
| 429| 0.81  | -0.04 | 23.8  | 23.8  | 0.0    |
| 508| 0.11  | -0.04 | 22.4  | 22.4  | 0.0    |
| 625| 0.31  | -0.24 | 43.2  | 20.8  | 132.7  |
| all| 0.31  | -0.01 | 7.3   | 3.5   | 176.3  |
This displacement is consistently found in maximum likelihood analyses of all energy bands above 300 MeV and also using data of individual viewing periods and the energy range 300–10,000 MeV, in contrast to the contradictory results of Mayer-Hasselwander et al. (1998). The position of Sgr A*, the center of Sgr A East, the pulsar J1747-2958, and the position of the TeV γ-ray source seem to be incompatible at the > 95% level with the results of the localization analysis of 3EG J1746-2851. The Galactic Center arc or any other source located in the Galactic plane at longitudes $0.1^\circ \lesssim l \lesssim 0.4^\circ$ are possible counterparts to the GeV γ-ray source. On account of the similarity of the spectra of 3EG J1746-2851 and that of the diffuse Galactic γ-ray emission it is possible, though very unlikely, that a compact, dense complex of interstellar gas, that is unaccounted for in the standard foreground model, is responsible for 3EG J1746-2851. The total mass of the gas cloud would have to be $M_{\text{gas}} \simeq 5 \cdot 10^7 M_\odot$ if located at the Galactic Center, and the cloud should have an apparent extent of $\theta_{\text{gas}} \lesssim 0.3^\circ$, lest it doesn’t appear point-like at high γ-ray energies. Such a massive gas complex should have been seen in the atomic fine-structure lines (Ojha et al. 2001; Rodríguez-Fernández et al. 2004) or in CO lines (Kime et al. 2002; Martin et al. 2004). A somewhat smaller mass of unaccounted gas is required to shift the apparent position of a true point source, but even at the 20% level, i.e. $M_{\text{gas}} \simeq 10^7 M_\odot$, the radio and infrared data do not indicate the existence of a previously unknown gas of the appropriate localization and compactness.

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