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EGRET GAMMA-RAY SOURCES: GRO J0744+54 AND GRO J0957+65 (=BL LACERTAE OBJECT 0954+658)

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ABSTRACT

EGRET detected an unidentified source, GRO J0744+54, at a significance of 6.5 σ, during its observations from 1993 June 28 to July 12. The source was seen again in the following 2 week viewing period and was weakly evident in the earlier phase 1 of the EGRET observations. Considering the variability of its gamma-ray flux, and its location at high Galactic latitude, GRO J0744+54 is likely to be a previously undetected blazar. Its most likely identification is with the radio source 87GB 073840.5+545138. A second source, GRO J0957+65, was seen by EGRET during the same two viewing periods at a combined significance of 5.7 σ. The most probable counterpart of GRO J0957+65 is the BL Lacertae object 0954+658. The spectra, time variability, and positions of the two sources are presented. Multiwavelength observations of 0954+658 are also presented.

Subject headings: BL Lacertae objects: individual (0954+658) — gamma rays: observations

1. INTRODUCTION

The observations by the Energetic Gamma-Ray Experiment Telescope (EGRET) on the *Compton Gamma-Ray Observatory* (*CGRO*) have led to the discovery of a large number of point sources of gamma-rays. A catalog of the sources detected during the first 18 months of operation (phase 1) may be found in Fichtel et al. (1994). Several of these gamma-ray sources have been identified with counterparts in other wavelength bands. Among the detected sources are 25 active galactic nuclei (AGNs) detected with high confidence and an additional 13 AGNs marginally detected. Many of the sources detected by EGRET, however, remain unidentified. This paper describes two sources, GRO J0744+54 and GRO J0957+65, that were detected with high significance in viewing period (VP) 227 and VP 228, during phase 2 of the EGRET observations. Neither of the sources is in the EGRET phase I catalog.

2. EGRET OBSERVATIONS

EGRET is sensitive to gamma rays in the energy range of about 30 MeV to 30 GeV. It has the standard components of a high-energy gamma-ray telescope: an anticoincidence dome to discriminate against charged particles, a spark chamber particle track detector with interspersed high-Z material to convert the gamma rays into electron-positron pairs, a triggering telescope to detect the presence of the pair with the correct direction of motion, and an energy measurement system, which in the case of EGRET is a NaI(Tl) crystal. EGRET has an effective area of 1.5×10^3 cm^2 in the energy range 0.2 GeV to 1 GeV, decreasing to about one-half the on-axis value at 18° off-axis and to one-sixth at 30°. Details of the instrument design are discussed in Hughes et al. (1980) and Kanbach et al. (1988, 1989), and the preflight and postflight calibrations are described by Thompson et al. (1993a).

The energies and directions of individual photons are determined using standard EGRET data processing as described in Bertsch et al. (1989). Maps of photons and intensity are generated for the entire field of view (FOV) using a grid of 0°.5 × 0°.5. Photons with angles greater than 30° from the center of the FOV are not used here in order to restrict the analysis to photons with the best direction and energy determinations. The method of maximum likelihood (Mattox et al. 1995) is used to analyze the data and to optimize the number of source photons, distributed according to the instrument point-spread function (PSF), in excess of that expected from the diffuse background. The background diffuse radiation is taken to be a combination of isotropic diffuse radiation and a component due to cosmic-ray interactions in Galactic atomic and molecular hydrogen gas, as well as inverse-Compton interactions of cosmic-ray electrons with photons (Bertsch et al. 1993). As explained by Mattox et al. (1995), a likelihood test statistic (TS) map is generated and this is used to determine the best estimate of the gamma-ray source location, its uncertainty, and its flux. The significance of a source detection in sigma is given approximately by the square root of TS (Mattox et al. 1995).

This paper describes two sources, GRO J0744+54 and GRO J0957+65, detected by EGRET during two consecutive observations of the region around SN 1993J ($l = 149°$, $b = 42°$), made during 1993 June 28–July 12 and July 13–26 in VP 227 and VP 228, respectively. The greatest fluxes from the

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TABLE 1

EGRET OBSERVATIONS OF GRO J0744+54

Viewing Period	Observation Dates	Flux ($\times 10^{-7}$ photons cm^{-2} s^{-1} MeV^{-1})	Inclination Angle of Source
0.6......	1991 May 07–May 10	<1.6[a]	25°.7
18.0......	1992 Jan 10–Jan 23	1.4 ± 0.6	23.7
31.0......	1992 Jun 11–Jun 25	<1.6[a]	17.2
40.0......	1992 Sep 17–Oct 08	2.0 ± 1.2	30.0
216.0......	1993 Apr 06–Apr 12	<2.3[a]	20.5
227.0......	1993 Jun 29–Jul 13	4.0 ± 0.8	17.1
228.0......	1993 Jul 13–Jul 27	2.0 ± 0.6	17.2
319.0......	1994 Mar 01–Mar 08	<5.0[a]	16.7
319.5......	1994 Mar 15–Mar 22	<0.9[a]	15.0

[a] Two sigma upper limit.

two sources were observed in these viewing periods. GRO J0744+54 was detected at a statistical significance of 7 σ in VP 227 and at 4.6 σ in VP 228. GRO J0957+65 was detected marginally (significance of about 4 σ) in both VP 227 and VP 228 separately. Stronger detections were obtained by combining the two viewing periods, 227 and 228. In the combined analysis, GRO J0744+54 was observed at 7.8 σ and GRO J0957+65 at 5.7 σ. GRO J0744+54 was also weakly detected in phase 1, during VP 18 and VP 40. GRO J0957+65, however, was not detected previously. Tables 1 and 2 list the viewing periods to date during which the viewing angles for the two sources were within 30° of the instrument axis.

3. POSITION DETERMINATION

The positions of the sources were derived from the maximum likelihood analysis (Mattox et al. 1995) performed on the combined viewing periods VP 227 and VP 228. Because the EGRET PSF varies strongly with energy (Thompson et al. 1993a), data binned into three separate energy ranges of 0.1–0.3 GeV, 0.3–1 GeV, and 1–10 GeV were used for the source position estimation, to take better advantage of the smaller effective PSF at greater energies. Using the appropriate PSF, maps of the liklihood TS were made for each of the energy ranges for GRO J0744+54 and GRO J0957+65. The TS maps for the three energy ranges were then added together. Mattox et al. (1995) note that in such maps, for the estimation of positions of sources, TS is distributed as χ^2 with 2 degrees of freedom.

The likelihood TS map for GRO J0744+54 indicates the most likely position of the source to be $l = 162°.86$, $b = 29°.3$, or (J2000) $\alpha = 7^h43^m59^s$, $\delta = 54°55'04''$. The 68% and 95% confidence contours are approximately circular and have radii of 17′ and 28′, respectively. A search of the NASA/IPAC Extragalactic Database (NED) indicates eight extragalactic sources (four radio sources and four normal galaxies) within the 95% confidence contour as possible sources of the gamma-ray emission. Of these, the most likely to be identified with GRO J0744+54 is the radio source 87GB 073840.5+545138 (Gregory & Condon 1991) which is the brightest of the four radio sources and nearest to the gamma-ray source. Located at $l = 163°.04$, $b = 29°.09$, its distance is 15′.7 from GRO J0744+54, and it is within the 68% confidence contour. 87GB 073840.5+545138 has a flux of 269 mJy at 4.85 GHz and has a flat radio spectrum, with a spectral index of 0.0 (NED). The quality of an identification can be judged by applying the method of Mattox et al. (1994). Using this method, for each radio source found at a certain angular distance relative to the center of the EGRET error ellipse, the probability that it is the radio counterpart to the EGRET source compared to the probability that is a confusing source at that distance, can be obtained. This method is similar to the method of de Ruiter, Willis, & Arp (1977). Five gigahertz surveys of radio sources were used to identify the EGRET sources, as most of the radio sources identified by EGRET are flat-spectrum sources. The surveys used were the 4.85 GHz Greenbank survey (Condon, Broderick, & Seielstad 1989) and the 4.85 GHz Parkes-MIT-NRAO (PMN) survey (Griffith & Wright 1993). The threshold for both surveys was approximately 30 mJy. Using this method, the probability of the identification of GRO J0744+54 with 87GB 073840.5+545138 being the correct association is estimated to be about 11%.

Three other weak (<50 mJy) radio sources from the 4.85 GHz survey of Gregory & Condon (1991) within the 95% confidence contour are 87GB 0737+5443 at $l = 163°.17$, $b = 28°.92$, 073935.5+542901 at $l = 163°.48$, $b = 29°.18$, and 87GB 074110.5 + 551150 at $l = 162°.70$, $b = 29°.49$. Owing to the large number of such weak sources, these are not inconsistent with chance coincidences and are not considered as likely identifications. The other four sources yielded by the search of the NED database are all normal galaxies and are unlikely to be strong sources of gamma rays.

The likelihood TS map for GRO J0957+65 indicates the most likely position of the source to be $l = 145°.75$, $b = 43°.16$ or (J2000) $\alpha = 9^h59^m$, $\delta = 65°32'50''$. The 68% and 95% confidence contours are approximately circular and have radii of about 15′ and 28′, respectively. A search of the NED database yields four objects as possible sources of gamma-ray emission within the 95% confidence contour. Of these, the most likely to be identified with GRO J0957+65 is the BL Lac object 0954+658 ($l = 145°.75$, $b = 43°.13$), at a distance of 1′.8. The probability of this being the correct identification is 97%, as deduced using the method of Mattox et al. (1994). The object 0954+658 has a flux of 1.4 Jy at 5 GHz and a redshift of 0.367 (Stickel, Fried, & Kühr 1993). Its two-point spectral index between 2.7 GHz and 5 GHz is 0.35 (Kühr 1977). The other three objects yielded by the search of the NED database were either weak radio sources or normal galaxies, which are unlikely to be candidates for sources of high-energy gamma-rays (Thompson et al. 1993b). The identification of the source with the BL Lac object 0954+658 is supported by the similarity of this source with other EGRET sources at high latitudes, all of which are strong, flat-spectrum radio sources, and most of which are blazars. The source was not seen during

TABLE 2

EGRET OBSERVATIONS OF GRO J0957+65

Viewing Period	Observation Dates	Flux ($\times 10^{-7}$ photons cm^{-2} s^{-1} MeV^{-1})	Inclination Angle of Source
0.6......	1991 May 07–May 10	<0.6[a]	10°.3
4.0......	1991 Jun 28–Jul 12	<1.0[a]	29.5
18.0......	1992 Jan 10–Jan 23	<0.5[a]	6.7
22.0......	1992 Mar 05–Mar 19	<1.4[a]	23.9
216.0......	1993 Apr 06–Apr 12	<2.3[a]	6.2
218.0......	1993 Apr 20–May 05	<2.2[a]	28.3
222.0......	1993 May 24–May 31	<1.6[a]	28.2
227.0......	1993 Jun 29–Jul 13	1.2 ± 0.4	2.6
228.0......	1993 Jul 13–Jul 27	1.2 ± 0.4	3.0
319.0......	1994 Mar 01–Mar 08	<1.2[a]	15.1
319.5......	1994 Mar 15–Mar 22	<1.6[a]	17.1

[a] Two sigma upper limit.

phase 1 of the EGRET observations, and a 2 σ flux upper limit of 5×10^{-8} photons cm^{-2} s^{-1} was obtained from the analysis of the summed phase 1 data (Fichtel et al. 1994).

4. FLUX AND SPECTRUM DETERMINATION

The background-subtracted energy spectra of the two sources were determined from a likelihood analysis of the combined data for VP 227 and VP 228. The energy range 30 MeV to 10 GeV was divided into 10 energy intervals for the spectral analysis, and maps of photons and exposures were made for each of the energy ranges. The shape of the spatial distribution of the diffuse emission was assumed to be energy independent for the analysis. The number of source photons in each of the 10 energy bins was estimated from the likelihood analysis. The observed spectrum of the source differs from its true spectrum due to EGRET's nonuniform detection efficiency over the energy range and its finite energy resolution. Following the general approach used in EGRET data analysis (Nolan et al. 1993b; Fichtel et al. 1993; Hughes & Nolan 1989), the data were fitted to a specified model rather than doing a deconvolution. A source model $I(E, \lambda)$ was chosen, where E is the energy and λ represents a set of free parameters. For a single power-law model as used here, λ represents two parameters: a spectral index and a normalization. Using the EGRET instrumental response function (Thompson et al. 1993a), the model source counts, $m_j(\lambda)$, were calculated for each of the 10 observed energy intervals. The parameters of the model were adjusted to minimize the function $\chi^2 = \sum_j (1/\omega_j)[n_j - m_j(\lambda)]^2$, where n_j is the number of counts from the source, and ω_j is the estimated variance of the jth energy band. The form of the model used was

$$F(E) = k(E/E_0)^{-\alpha} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} , \quad (1)$$

where the photon spectral index, α, and the coefficient, k, are the free parameters. The energy normalization factor, E_0, was chosen so that the statistical errors in the power-law index and the overall normalization were uncorrelated.

Figure 1 shows the photon spectrum of the source GRO J0744+54. The superposed solid line is the best-fit to equation

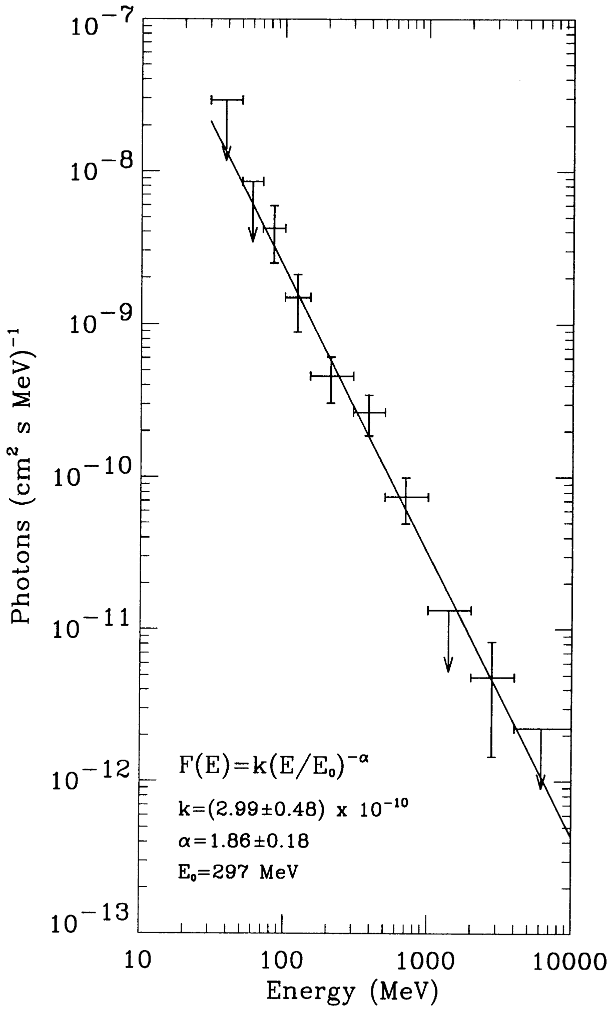

FIG. 1.—Photon spectrum of GRO J0744+54. The solid line is the best-fit to the power law shown in eq. (1). Two sigma flux upper limits have been plotted for the lowest and highest energy ranges.

TABLE 3

SOURCE AND BACKGROUND COUNTS FROM GRO J0744+54 AND GRO J0957+65

ENERGY BAND (MeV)	COUNTS FROM GRO J0744+54		COUNTS FROM GRO J0957+65	
	Source[a]	Source + Background	Source[a]	Source + Background
30–50	<39[b]	35	<36[b]	49
50–70	<33[b]	67	<41[b]	87
70–100	31 ± 13	144	<17[b]	126
100–150	15 ± 10	98	25 ± 13	117
150–300	34 ± 11	103	32 ± 13	132
300–500	9 ± 6	39	19 ± 7	46
500–1000	20 ± 6	26	9 ± 5	15
1000–2000	2 ± 1	3	6 ± 3	7
2000–4000	5 ± 2	5	3 ± 2	3
4000–10000	<2[b]	0	2 ± 2	2

[a] It is important to note that while the source counts shown above are those derived directly from the likelihood analysis, the source + background counts have been obtained by merely counting photons within an energy-dependent circle. Those values of source + background counts were not used in deriving the source counts and are shown here only for illustrative purposes. The likelihood analysis used for obtaining source counts and fluxes does not provide or depend upon counting photons within circles around a potential source. See Mattox et al. 1995 for a detailed explanation of the EGRET likelihood analysis approach.

[b] Two sigma upper limit.

(1). The best-fit parameters are $\alpha = 1.86 \pm 0.18$, $k = (2.99 \pm 0.48) \times 10^{-10}$ photons cm^{-2} s^{-1} MeV^{-1}, and $E_0 = 297$ MeV. The reduced χ^2 of the fit, 0.6, indicates an adequate fit. The errors in the above fit parameters correspond to 1 σ uncertainties and are statistical only. The systematic errors in the EGRET measurements are typically much smaller than the statistical errors (Thompson et al. 1993a) and have been neglected here. Table 3 lists the source and source + background counts for each of the 10 energy bands. The source counts were derived from the likelihood analysis. The source + background counts were obtained by counting the total number of photons within an energy-dependent circle.

The photon spectrum of GRO J0957+65 is shown in Figure 2. The superposed solid line is the best-fit to equation (1). The model is seen to fit the data well, yielding a reduced χ^2 of 0.8. The parameters obtained from the fit are $\alpha = 1.85 \pm 0.24$, $k = (7.78 \pm 1.73) \times 10^{-11}$ photons cm^{-2} s^{-1} MeV^{-1}, and $E_0 = 388$ MeV. The source and source + background counts from GRO J0957+65 are listed in Table 3.

The gamma-ray spectra of both GRO J0744+54 and GRO J0957+65 are hard, with photon spectral indices of 1.86 ± 0.18 and 1.85 ± 0.24, respectively. The spectral indices are, however, consistent within the errors with the spectral indices of most of the AGNs detected by EGRET (von Montigny et al. 1995).

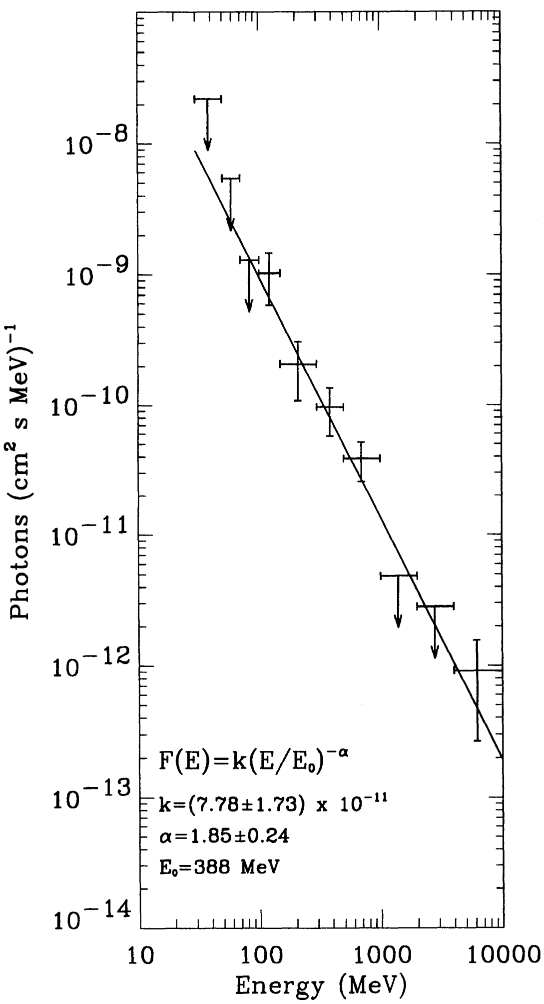

FIG. 2.—Photon spectrum of GRO J0957+65. The solid line is the best-fit to the power-law shown in eq. (1). Two sigma flux upper limits have been plotted for the three lowest energy ranges.

5. TIME VARIABILITY

Most of the blazars detected by EGRET are known to have variability in their gamma-ray emission on timescales from days to months or longer (Kniffen et al. 1993; Sreekumar et al. 1993; Nolan et al. 1993a). Figure 3*a* shows the gamma-ray flux of GRO J0744+54 over the 3 yr period covered by EGRET observations. The data points correspond to the average fluxes from the individual viewing periods listed in Table 1. Detections of the source with the highest significance were made in VP 227 and VP 228. Weaker detections, at the level of 2–2.5 σ were made in VP 18 and VP 40. The source was not evident during five of the nine observations; the 2 σ upper limits are plotted for these cases. Table 1 lists the measured flux and the flux upper limits for each of the viewing periods. The data show some evidence of time variability; the flux varies from a maximum of $(4.0 \pm 0.8) \times 10^{-7}$ photons cm^{-2} s^{-1} to a minimum of $(1.4 \pm 0.6) \times 10^{-7}$ photons cm^{-2} s^{-1}. A χ^2 test yields a probability of 3% that the observations are consistent with a constant flux.

Although the total number of photons from the source is limited, an attempt was made to study the variations of the flux from GRO J0744+54 within the 4 week interval during which it was the brightest, in VP 227 and VP 228. For the analysis, the two viewing periods were each broken into two 7 day periods, and the average flux was calculated for the four time ranges. The results are shown in Figure 3*b*. Some variability is suggested on this short timescale with the flux first increasing and then decreasing over the 4 weeks. The average flux measured in the first 7 days is about a factor of 3 smaller than that measured in the next 7 days. A χ^2 test yields a probability of 4% that the fluctuations are consistent with a constant flux.

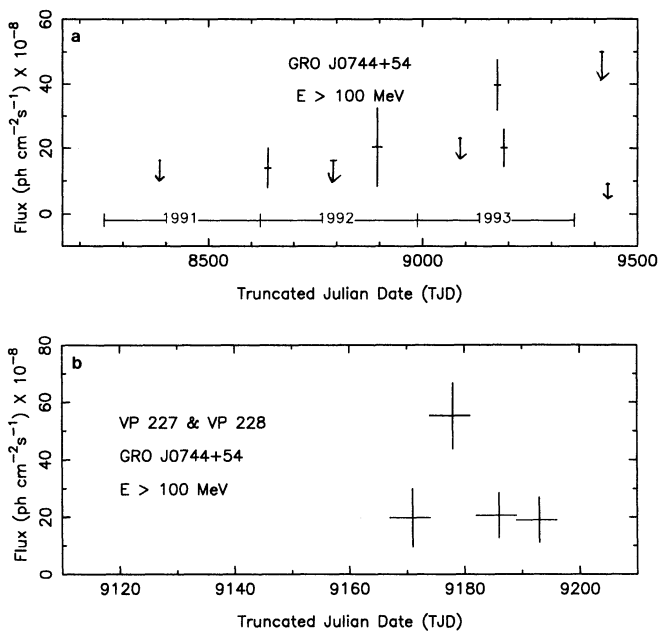

FIG. 3.—(*a*) Flux of gamma rays from GRO J0744+54 over the period 1991 May to 1994 March. Two sigma upper limits have been plotted for five of the nine observations. (*b*) Flux from GRO J0744+54 during viewing periods 227 and 228 (1993 July).

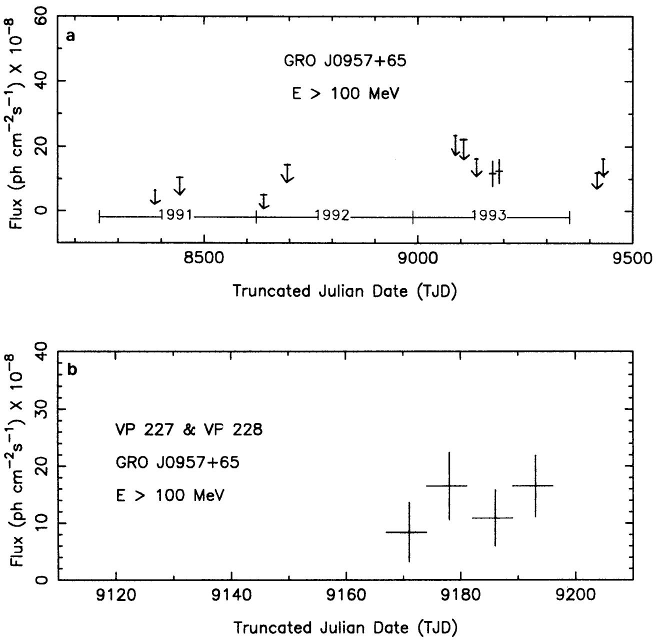

FIG. 4.—(*a*) Flux of gamma rays from GRO J0957+65 over a 2 year period. Two sigma upper limits have been plotted for all but the two observations in 1993 July. (*b*) Flux from GRO J0957+65 during viewing periods 227 and 228.

Figure 4*a* shows the flux from GRO J0957+65 for the viewing periods listed in Table 2. The source was detected only during VP 227 and VP 228. Two sigma flux upper limits are shown for the other viewing periods. The average flux does not vary significantly between the two periods when the source was evident. Table 2 lists the measured fluxes and the flux upper limits for the viewing periods that include the position of GRO J0957+65. The gamma-ray flux from GRO J0957+65 was also studied on a smaller timescale, by dividing VP 227 and VP 228 into 7 day periods. No significant evidence for variation was seen (Fig. 4*b*).

6. DISCUSSION

A candidate identification for GRO J0744+54 is the radio source 87GB 073840.5+545138, under the assumption that EGRET is more likely to detect bright, flat-spectrum radio sources than faint, steep-spectrum ones. Mattox et al. (1994) have found similar candidate identifications with flat-spectrum radio sources for about 10 previously unidentified EGRET sources. GRO J0744+54 has properties similar to the identified EGRET blazars and, at high Galactic latitude, is likely to be extragalactic. All of the blazars detected by EGRET are characterized by flat spectra and large fluxes in the radio. Further information on the candidate radio source, such as optical identification as a quasar, and measurements of polarization and redshift would be useful in verifying the identification of GRO J0744+54.

The most likely identification of GRO J0957+65, as mentioned earlier, is with the BL Lac object 0954+658. This object has been found to show intraday optical and radio variability (Wagner et al. 1993; Fiedler et al. 1987) with evidence that the radio and optical variations are correlated, as has been observed for 0716+714 (Quirrenbach et al. 1991). The object 0954+658 has been studied extensively over the period 1979–1985, using the Green Bank interferometer operating at 2.7 and 8.1 GHz by Fiedler et al. (1987).

Recent measurements of the flux from 0954+658 at 4.8 GHz, 8 GHz, 14.5 GHz, 22 GHz, and 37 GHz for the time period 1991 December to 1993 December are shown in Figure 5. The observations at 4.8 GHz, 8 GHz, and 14.5 GHz were made by Aller & Aller (1994) at the University of Michigan Radio Observatory, and the measurements at 22 GHz and 37 GHz were made by Teräsranta (1994) at the Metsahovi Radio Research Station, Finland. The variations at 4.8 GHz are slight

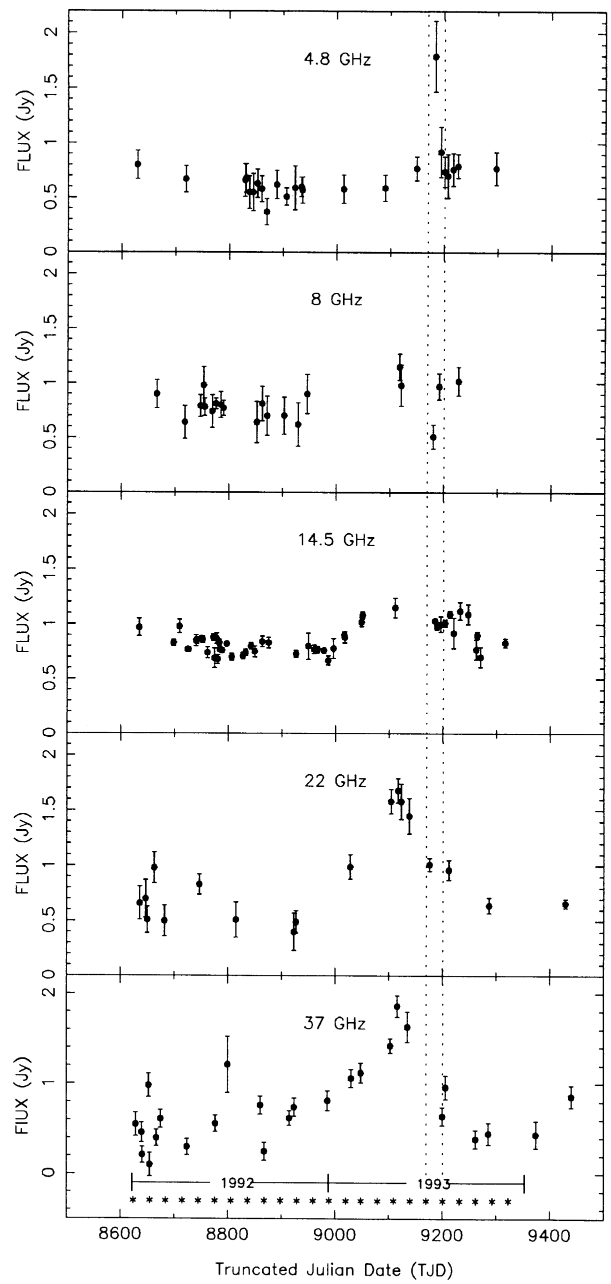

FIG. 5.—Flux from 0954+658 at radio frequencies (4.8 GHz, 8 GHz, 14 GHz, 22 GHz, and 37 GHz) for the period 1991 December to 1993 December. The beginning of each month is indicated with an asterisk near the bottom *x*-axis. The period between the two dotted lines corresponds to the EGRET observations in viewing periods 227 and 228.

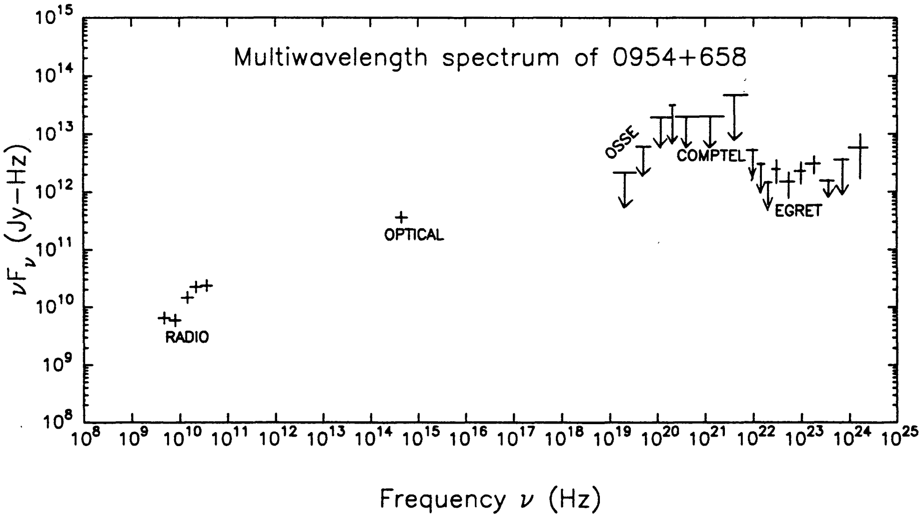

FIG. 6.—Multiwavelength spectrum of 0954 + 658. The uncertainties of the radio and optical measurements are smaller than the symbol size.

compared to those at other frequencies, and the variability increases with frequency. This is characteristic of the behavior of most of the AGNs at radio wavelengths. Opacity effects are commonly assumed to reduce the variability at 4.8 GHz relative to that at 14.5 GHz. The data at 8 GHz are not as well sampled. An outburst at 22 GHz and 37 GHz is clearly seen, substantially earlier than the EGRET detections.

The object 0954 + 658 was also monitored for a 4 week period in 1990 February in the optical (Wagner et al. 1993). The optical observations were carried out with the 0.7 m telescope of the Landessternwarte on the Königstuhl in Heidelberg, Germany. All the observations were made in the Johnson *R* band (650 nm). Several rapid outbursts were detected, and although the total duration of individual events was less than 4 days, the brightness was found to increase by more than a factor of 6 at 650 nm in these outbursts.

More recently, optical observations of 0954 + 658 at 650 nm were made during 1993 July by Wagner (1994), essentially simultaneously with the EGRET observations. All of the available simultaneous data are summarized in Figure 6, which shows the multiwavelength spectrum of 0954 + 658 from radio to gamma-ray frequencies. The source was also observed by the OSSE and COMPTEL instruments on *CGRO* at the same time as EGRET. Neither instrument detected the source, and the 2 σ flux upper limits are plotted. From Figure 6 it is apparent that the high-energy gamma radiation dominates the spectrum, but not by as large as factor as in some of the other quasars seen by EGRET, for example, 3C 279 (Hartman et al. 1992), 0528 + 134 (Hunter et al. 1993), and 2356 + 196 (Bertsch et al. 1993). It appears that the multiwavelength spectra of all of the BL Lac objects detected so far by EGRET are less dominated by high-energy gamma rays than those of the other quasars detected by EGRET (von Montigny et al. 1995).

To summarize, detections of two sources, GRO J0744 + 54 and GRO J0957 + 65, by EGRET during 1993 July have been reported. The most likely identification for GRO J0744 + 54 is with the radio source 87GB 073840.5 + 545238. GRO J0957 + 65 is identified with the BL Lac object 0954 + 658. Simultaneous multiwavelength observations of 0954 + 658 at radio, optical, and gamma-ray frequencies have been presented. No significant evidence for variation of the high-energy gamma-ray flux was seen. Because 0954 + 658 is known to show intraday variability (Wagner et al. 1993), it would be worthwhile to investigate the variability of GRO J0957 + 65 at gamma-ray energies with additional well-centered observations with EGRET. The detections in VP 227 and VP 228 suggest that the sensitivity of EGRET is sufficient to detect variability in the gamma-ray emission of GRO 0957 + 65 over timescales of 1 week or greater.

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