Astron. Astrophys. 299, 680–688 (1995)

ASTRONOMY
AND
ASTROPHYSICS

Studies of some superluminal blazars and strong flat-spectrum radio quasars, that are not seen in high energy gamma-rays by EGRET

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Received 12 July 1994 / Accepted 5 January 1995

Abstract. Many of the active galactic nuclei (AGN) detected by EGRET above 100 MeV are known or suspected to be superluminal sources. We report results of observations of 35 additional blazars which have been selected from the list of known and possibly superluminal sources. In addition we included six blazars which are prominent for other reasons. For three of these sources (3C 345, 3C 216 and 0735+178) we found a signal at the 3 to 4σ significance level in high energy gamma rays. For others, the 2σ upper limits (equivalent to 95% confidence) for the gamma-ray fluxes for energies greater than 100 MeV are given here.

Key words: gamma rays: observations – radio continuum: galaxies – galaxies: active – galaxies: jets – quasars: general

1. Introduction

By the end of the COMPTON Observatory all-sky survey (November 1992), EGRET had detected 25 AGN with a high degree of confidence ($> 5\sigma$) and 12 AGN with lower confidence (4 - 5σ) in the energy range 0.03 - 10 GeV (Fichtel et al. 1994a). All of the high-confidence AGN and most of the marginal AGN are radio loud sources with a flat ($\alpha_r >$ -0.5) radio spectrum (Kühr et al. 1981). Fourteen of the EGRET high-confidence AGN are also highly polarized quasars (HPQ's) and eight have been reported to be optically violently variable (OVV). Six of them are superluminal sources (0235+164, 0836+710, 1226+023, 1253-055, 1633+382 and 2251+158) and one of them, the BL Lac object 0716+714, is a superluminal source if its redshift is larger than 0.28 (Witzel et al. 1987). A recent report (Zhang & Bååth 1990) indicates that Mkn 421 also shows evidence of superluminal flow. Thus, there is a strong correlation between the high energy gamma-ray sources detected by EGRET off the Galactic plane ($|b| > 10°$) and strong flat-spectrum radio quasars and BL Lac's, and, in spite of the relatively few AGN that have been identified as superluminal or optically violent variables (OVV's), a significant number of the high energy gamma ray emitting AGN detected with a high degree of certainty are also correlated with these sources. Therefore, it is possible that all of the EGRET sources are associated with the blazar class of AGN which is characterized by the properties mentioned above.

Nearly all theoretical models which have been developed in order to explain gamma-ray emission from these sources involve beamed emission from a jet of relativistic particles. With this assumption the problem of γ-γ attenuation implied if the enormous luminosities of the EGRET sources are isotropic can be overcome, at least to a degree. Since apparent superluminal motion is explained by relativistic bulk motion of plasma in a jet being observed at a small angle to the observer, superluminal sources in general should be considered as promising candidates for gamma-ray sources.

At present there are about 30 objects known to be superluminal sources. Ten objects are suspected to be superluminal (Impey 1987; Witzel et al. 1988; Krichbaum et al. 1990; Vermeulen & Cohen 1994). Most superluminal radio sources show properties similar to blazars: They are also strong and compact radio sources with a flat or complex spectrum, their radio and optical emission is variable as well as polarized and the polar-

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ization is also variable. They therefore seem to be a subset of the blazar class. Their individual appearance, however, can be very different (see e.g. Porcas 1987; Kellermann 1987): Some sources show one-sided inner jets (e.g. 3C 345, 3C 279, 3C 273), some are extended doubles (e.g. 3C 263, 1951+498, 3C 245). New radio components are ejected from a stationary core with time scales of a few months to a few years. In general these components are brightest as they emerge from the core and decay when moving away. The apparent superluminal velocities can be different for the various components. Some sources show superluminal components and at the same time subluminal or quasi-stationary knots (e.g. 3C 454.3, 4C 39.25 and 3C 395). Sometimes components are accelerating and changing direction while moving out (3C 345, 3C 120, 3C 279) and some show decelerating knots (BL Lac).

In this paper we examine some of the strong flat-spectrum radio sources and the superluminal quasars not seen by EGRET to see how they compare with those that are observed.

2. The EGRET telescope

The EGRET instrument has components which are commonly used in high energy gamma-ray telescopes: an anticoincidence system to discriminate against charged particles, a particle track detector consisting of spark chambers with interspersed high Z material to convert the gamma rays into electron-positron pairs, a triggering telescope that detects the presence of charged particles with the correct direction of motion, and an energy measuring calorimeter, which in the case of EGRET is NaI(Tl). A detailed description of the EGRET instrument has been given by Hughes et al. (1980) and Kanbach et al. (1988, 1989). Details of the instrument calibration, both before and after launch, are given by Thompson et al. (1993a).

EGRET covers the high energy gamma-ray range from approximately 30 MeV to 30 GeV. The effective area of the instrument is about 1.5 x 10^3cm^2 from 0.2 to 1.0 GeV, and lower outside of this range. The field of view of EGRET is about one-half steradian, with the effective area dropping to about one-half the on axis value at 20° off axis and one-sixth at 30°. The instrument is designed to be free of internal background, and the calibration tests have verified that it is at least an order of magnitude below the extragalactic gamma radiation. Hence the only significant radiation besides the sources themselves is the diffuse galactic and extragalactic radiation.

3. Observations, analysis, and results

Table 1 lists all sources which have been included in the analysis reported here. Since superluminal sources should be very promising candidates for gamma ray emission, because they exhibit evidence for relativistic beaming, a detailed study of EGRET observations of all known superluminal sources has been performed (Table 1a). The results from the suspected superluminal sources are listed in Table 1b.

A common characteristic of the AGN detected by EGRET is that they all appear to be radio-loud, flat spectrum radio sources. In addition, 20 to 24% of the known superluminal sources (depending on whether one includes 0716+714 and Mkn 421, or not) have been detected by EGRET. However, as reported here, there are a significant number of superluminal sources and radio-loud, flat spectrum radio sources not detected by EGRET. Some of the strongest sources in the latter group are particularly noteworthy: 1322-42 (CEN-A), 2134+00, 1127-14, 0438-43, 0637-75 and 2145+06. From Fig. 1, it can be seen that these six sources have all been detected at or well above 4.5 Jy and all have radio spectral indices greater than -0.4 at 5GHz. For this reason these six prominent radio sources have also been included in the analysis (Table 1c). Note also that three prominent EGRET sources – 3C 273 (von Montigny et al. 1993a), 3C 454.3 (Hartman et al. 1993) and 3C 279 (Bertsch et al. 1991; Hartman et al. 1992; Kniffen et al. 1993) – are located in the same region of this figure. The tables show the known positions of the objects, their redshift, their offsets from the instrument axis and the time of the observation and the upper limits (2σ) for the flux above 100 MeV.

The analysis used data from the EGRET all-sky survey which were obtained during April 1991 to November 1992. The typical duration of an observation was two weeks before the tape recorder failure in March 1992. Since then the observation time was increased to three weeks in order to compensate for the reduced real time telemetry coverage of approximately 60%.

The analysis (Fichtel et al. 1994b) used counts and exposure maps for photon energies greater than 100 MeV as well as the diffuse gamma-ray background predicted by the standard EGRET analysis software from HI and CO distributions (Bertsch et al. 1993a). Prominent EGRET sources in the viewing period under consideration were added to the diffuse background model. Different observation periods of the same sky region have not been added up, but have been treated separately here.

Upper limits to the gamma-ray flux have been determined with a maximum likelihood method which simultaneously gives the best fit of the diffuse background to the data. The formal significance of a source detection in units of σ is determined from the square root of the likelihood test statistic (Eadie et al. 1971) which is given by two times the ratio of the maximum likelihood values for the alternative and the null-hypothesis. Sources which have a test statistic lower than nine (corresponding to a formal significance of $< 3\sigma$) are regarded as non-detections. The 2σ upper limit for the non-detected sources is defined as the best estimate μ of the flux with its 2σ uncertainty added to it. The 2σ uncertainty of the flux is determined by that value of the flux for which the logarithm of the maximum likelihood has decreased by a factor of about 4. In the analysis the best estimate of the flux is forced to be non-negative. For the determination of the upper limits, a photon spectrum power law index of α_γ=2.0 has been assumed for the spectra of the sources which is a typical spectral index for the strong EGRET blazars.

Table 1a. List of selected superluminal sources

Source	Name	l	b	z	Viewing Period	Time of Observation	Offset (deg)	Flux(E>100MeV) (10^{-7}cm^{-2}s^{-1})
0016+731		120.64	10.73	1.781	34.0	16.07.92 - 06.08.92	17.65	< 1.5
0212+735		128.93	11.96	2.367	18.0	10.01.92 - 23.01.92	29.49	< 2.9
					34.0	16.07.92 - 06.08.92	24.64	< 1.3
0333+321	NRAO 140	159.00	-18.76	1.263	15.0	28.11.91 - 12.12.91	8.11	< 1.1
					36.5	12.08.92 - 20.08.92	12.02	< 2.2
					39.0	01.09.92 - 17.09.92	12.43	< 1.9
0430+053	3C 120	190.37	-27.40	0.033	1.0	16.05.91 - 30.05.91	22.67	< 2.2
					2.1	30.05.91 - 08.06.91	20.55	< 3.0
					36.5	12.08.92 - 20.08.92	27.55	< 2.1
					39.0	01.09.92 - 17.09.92	28.47	< 3.7
0454+844		128.35	24.66	0.112	18.0	10.01.92 - 23.01.92	17.56	< 0.74
					22.0	05.03.92 - 19.03.92	23.64	< 1.2
0615+820		131.74	25.97	0.71	18.0	10.01.92 - 23.01.92	15.28	< 0.49
					22.0	05.03.92 - 19.03.92	24.16	< 1.2
0723+679	3C 179	148.01	28.42	0.846	18.0	10.01.92 - 23.01.92	14.85	< 0.70
					31.0	11.06.92 - 25.06.92	21.69	< 1.2
0735+178		201.85	18.07	>0.424	1.0	16.05.91 - 30.05.91	25.23	< 1.9
					2.1	30.05.91 - 08.06.91	26.28	< 2.4
					40.0	17.09.92 - 08.10.92	27.10	< 4.6
0850+581	4C 58.17	158.79	38.93	1.322	18.0	10.01.92 - 23.01.92	16.43	< 0.5
					31.0	11.06.92 - 25.06.92	27.28	< 1.8
					40.0	17.09.92 - 08.10.92	28.00	< 2.6
0906+430	3C 216	178.33	42.84	0.67	4.0	28.06.91 - 12.07.91	31.13	< 5.4
					40.0	17.09.92 - 08.10.92	12.80	< 1.3
0923+392	4C 39.25	183.71	46.16	0.698	4.0	28.06.91 - 12.07.91	28.92	< 1.6
					40.0	17.09.92 - 08.10.92	8.67	< 0.8
1039+811		128.74	34.73	1.26	18.0	10.01.92 - 23.01.92	8.99	< 0.52
					22.0	05.03.92 - 19.03.92	15.82	< 0.71
1040+123	3C 245	233.12	56.30	1.028	30.0	04.06.92 - 11.06.92	29.00	< 2.1
					33.0	02.07.92 - 16.07.92	29.00	< 4.2
					40.0	17.09.92 - 08.10.92	25.93	< 0.7
1137+660	3C 263	134.16	49.74	0.646	4.0	28.06.91 - 12.07.91	24.43	< 0.5
					18.0	10.01.92 - 23.01.92	9.54	< 0.5
					22.0	05.03.92 - 19.03.92	15.62	< 0.64
1150+812		125.72	35.84	1.25	18.0	10.01.92 - 23.01.92	10.33	< 0.76
					22.0	05.03.92 - 19.03.92	13.27	< 0.68
1641+399	3C 345	63.46	40.95	0.594	9.2	12.09.91 - 19.09.91	2.95	< 2.5
1642+690	4C 69.21	100.71	36.62	0.751	18.0	10.01.92 - 23.01.92	28.79	< 2.1
					22.0	05.03.92 - 19.03.92	11.87	< 0.76
1721+343	4C 34.47	58.13	32.18	0.206	9.2	12.09.91 - 19.09.91	8.19	< 0.7
1749+701		100.53	30.72	0.77	22.0	05.03.92 - 19.03.92	16.65	< 1.6
1803+784		110.04	29.07	0.68	18.0	10.01.92 - 23.01.92	25.11	< 2.3
					22.0	05.03.92 - 19.03.92	15.52	< 0.7
1901+319	3C 395	63.03	11.76	0.635	2.0	30.05.91 - 08.06.91	13.71	< 0.7
					7.1	08.08.91 - 15.08.91	21.37	< 1.4
					9.2	12.09.91 - 19.09.91	27.68	< 2.4
					20.0	06.02.92 - 20.02.92	25.63	< 1.5
1928+738	4C 73.18	105.63	23.54	0.302	22.0	05.03.92 - 19.05.92	21.66	< 1.8
					34.0	16.07.92 - 06.08.92	26.08	< 0.8
1951+498		83.66	11.43	0.466	2.0	30.05.91 - 08.06.91	13.59	< 0.5
					7.1	08.08.91 - 15.08.91	23.71	< 2.4
					34.0	16.07.92 - 06.08.92	28.51	< 2.8
2007+777		110.46	22.73	0.342	18.0	10.01.92 - 23.01.92	28.85	< 3.0
					22.0	05.03.92 - 19.05.92	21.80	< 1.0
					34.0	16.07.92 - 06.08.92	25.16	< 3.3
2200+420	BL Lac	92.59	-10.44	0.069	2.0	30.05.91 - 08.06.91	23.21	< 2.4
					7.1	08.08.91 - 15.08.91	21.95	< 2.0
					34.0	16.07.92 - 06.08.92	17.96	< 0.8

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Table 1b. List of selected suspected superluminal sources

Source	Name	l	b	z	Viewing Period	Time of Observation	Offset (deg)	Flux(E>100MeV) (10^{-7}cm^{-2}s^{-1})
0153+744		127.34	12.41	2.338	18.0	10.01.92 - 23.01.92	29.45	< 2.1
					34.0	16.07.92 - 06.08.92	23.65	< 1.1
0224+671	4C 67.05	132.12	6.23		34.0	16.07.92 - 06.08.92	24.87	< 2.5
					15.0	28.11.91 - 12.12.91	28.31	< 2.4
0355+508	NRAO 150	150.38	-1.60		15.0	28.11.91 - 12.12.91	12.04	< 1.2
					31.0	11.06.92 - 25.06.92	18.50	< 3.8
					36.5	12.08.92 - 20.08.92	19.36	< 2.5
					39.0	01.09.92 - 17.09.92	18.35	< 5.1
0415+379	3C 111	161.68	-8.82	0.0485	15.0	28.11.91 - 12.12.91	10.01	< 0.9
					31.0	11.06.92 - 25.06.92	20.79	< 5.0
					36.5	12.08.92 - 20.08.92	5.98	< 3.4
					39.0	01.09.92 - 17.09.92	5.45	< 1.2
0538+498	3C 147	161.69	10.30	0.545	15.0	28.11.91 - 12.12.91	25.38	< 2.8
					31.0	11.06.92 - 25.06.92	2.12	< 2.2
					36.5	12.08.92 - 20.08.92	20.79	< 1.6
					39.0	01.09.92 - 17.09.92	20.23	< 2.1
0605–085	OH-010	215.75	-13.52	0.870	1.0	16.05.91 - 30.05.91	26.01	< 2.9
					2.1	30.05.91 - 08.06.91	21.45	< 2.9
					29.0	14.05.92 - 04.06.92	27.45	< 4.5
1038+528	OL 564	157.52	54.97	0.678	4.0	28.06.91 - 12.07.91	17.12	< 0.8
					18.0	10.01.92 - 23.01.92	19.65	< 0.5
					40.0	17.09.92 - 08.10.92	26.38	< 1.3
1807+698	3C 371	100.13	29.17	0.051	22.0	05.03.92 - 19.05.92	18.17	< 2.5
1845+797	3C 390.3	111.43	27.07	0.0556	22.0	05.03.92 - 19.05.92	17.42	< 2.0
					18.0	10.01.92 - 23.01.92	25.31	< 2.2
2223–052	3C 446	58.96	-48.84	1.404	19.0	23.01.92 - 06.02.92	5.87	< 0.9

Table 1c. List of other selected flat-spectrum radio sources

Source	Name	l	b	z	Viewing Period	Time of Observation	Offset (deg)	Flux(E>100MeV) (10^{-7}cm^{-2}s^{-1})
0438–436		248.41	-41.57	2.852	6.0	26.07.91 - 08.08.91	26.85	< 0.9
					10.0	19.09.91 - 03.10.91	28.84	< 1.1
					17.0	27.12.91 - 10.01.92	29.42	< 3.4
					29.0	14.05.92 - 04.06.92	18.48	< 1.0
0637–755		286.41	-27.16	0.656	6.0	26.07.91 - 08.08.91	7.72	< 0.6
					10.0	19.09.91 - 03.10.91	27.16	< 1.1
					14.0	14.11.91 - 28.11.91	26.46	< 1.5
					17.0	27.12.91 - 10.01.92	5.26	< 0.5
1127–145	OM-146	275.28	43.64	1.187	3.0	15.06.91 - 28.06.91	25.66	< 0.7
					11.0	03.11.91 - 17.11.91	22.77	< 2.3
					30.0	06.06.92 - 11.06.92	22.26	< 4.0
					32.0	25.06.92 - 02.07.92	22.02	< 1.7
					33.0	02.07.92 - 16.07.92	22.26	< 1.5
1322–428	CEN-A	309.52	19.42	0.0018	12.0	17.10.91 - 31.10.91	3.01	< 1.4
					23.0	19.03.92 - 02.04.92	20.52	< 5.1
					27.0	28.04.92 - 07.05.92	27.90	< 3.6
					32.0	25.06.92 - 02.07.92	23.84	< 9.1
2134+004	OX=57	55.47	-35.58	1.936	19.0	23.01.92 - 06.02.92	7.70	< 0.8
2145+067	4C+06.69	63.66	-34.07	0.99	7.1	08.08.91 - 15.08.91	26.51	< 4.0
					19.0	23.01.92 - 06.02.92	9.91	< 0.5

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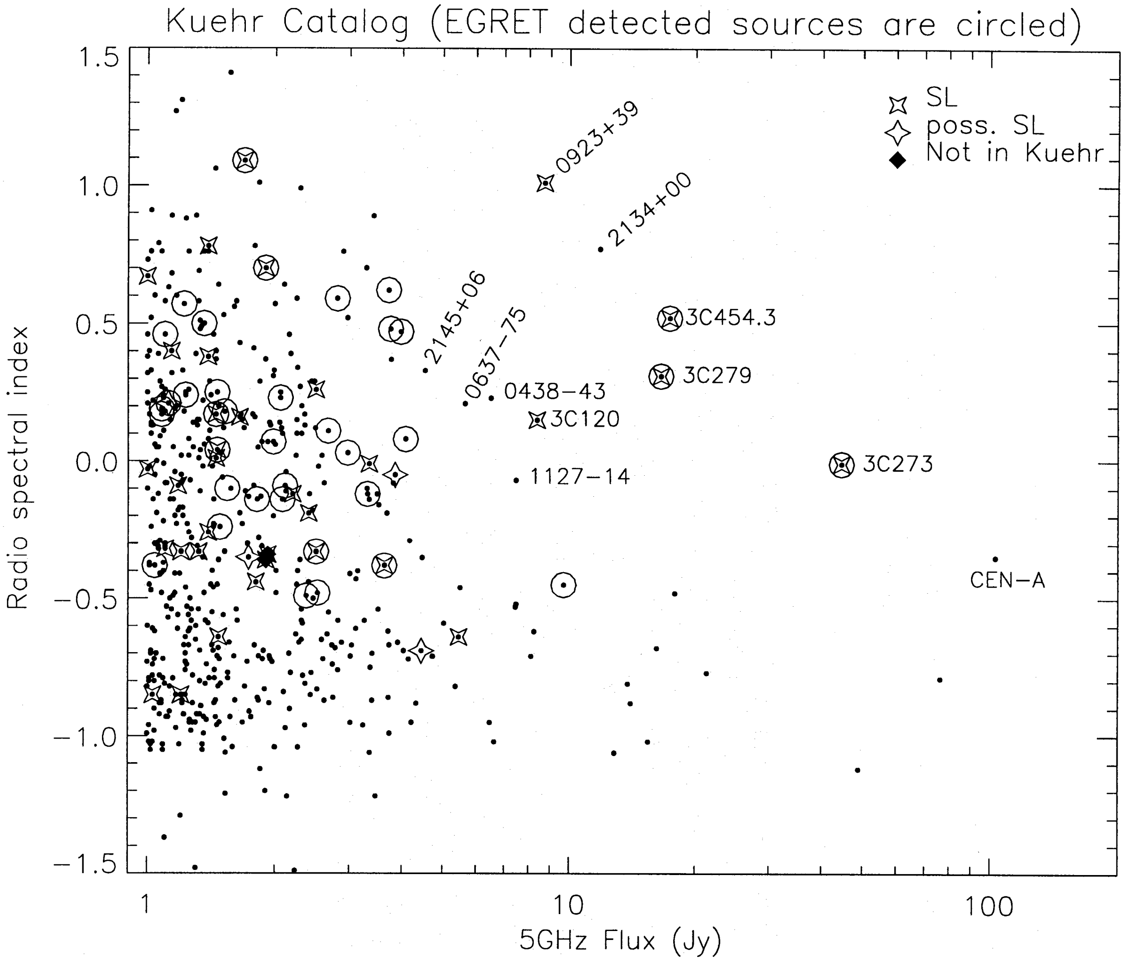

Fig. 1. Radio flux at 5GHz versus the radio spectral index (data from Kühr et al. 1981). The lying stars denote superluminal sources, the upright stars suspected superluminal sources. The filled diamonds are sources from Table 1 which are not in the Kühr catalog

In an earlier paper (von Montigny et al. 1993b) preliminary upper limits for the blazars 3C 345, BL Lac and 3C 371 were reported. Revised upper limits for these sources are given here. For the sources 3C 111, 3C 390.3 (possible superluminal sources) and 3C 120, which have also been classified as Seyfert galaxies, upper limits have been determined from the combined viewing periods (Lin et al. 1993). For three of the objects listed in Table 1a (0735+178, 0906+430 and 1641+399) we found a signal at the 3 to 4σ significance level. In the following, the results of these sources are discussed in more detail.

3.1. 0735+178

This source shows an excess in the gamma-ray flux of about 3.4σ in viewing period 40.0. The corresponding flux is $(2.5\pm0.9)10^{-7}$cm^{-2}s^{-1}. The 95% confidence upper limit is F(E>100 MeV) $<4.6\cdot10^{-7}$ cm^{-2}s^{-1}.

3.2. 0906+430 (=3C 216)

For this source an excess in the gamma-ray flux of about 4.3σ was found in viewing period 4.0 as previously reported by Thompson et al. (1993b). The flux determined by the maximum-likelihood method is (3.1 ± 1.0) 10^{-7}cm^{-2}s^{-1}. The 95% confidence upper limit is F(E>100 MeV) $< 5.4\cdot10^{-7}$ cm^{-2}s^{-1}. These values have to be regarded with care. The analysis of VP4.0 showed a source at RA=138.58°; DEC=43.27° which could be identified with 3C 216 since it is just outside the 68% confidence contour. On the other hand the analysis of VP40.0 showed an excess of about 3.8σ at RA=139.29°; DEC=44.94°. The gamma-ray source from VP4.0 is outside the 99% confidence contour of this excess and 3C 216 is well outside the error box. The analysis of the all-sky data from phase I (VP4.0 and VP40.0 combined) shows a very strong (> 5σ) source at RA=139.24°; DEC=43.76°. The error box of this unidentified source (GRO J0916+43) (Fichtel et al. 1994a) clearly excludes 3C 216 but the gamma-ray source from VP4.0 is just inside the 95% confidence contour. Since the two viewing periods are about half a year apart GRO J0916+43 could be the result of two different variable sources too close together to be resolved by EGRET in the combined observations. There is obviously some confusion and only further observations can clarify the situation.

3.3. 1641+399 (=3C 345)

The analysis of 3C 345 still indicates a weak detection at the 3σ level as previously reported (von Montigny et al. 1993). The indicated flux for energies greater than 100 MeV is F(E>100 MeV) = $(1.7\pm0.6)10^{-7}$ cm^{-2}s^{-1}. Taking into account that this might be a statistical fluctuation in the counts from 1633+382 (Mattox et al. 1993) which is about 2.25° from 3C 345, a more conservative interpretation of the data is that a 95% upper limit for 3C 345 is F(E> 100 MeV)< $2.9\cdot10^{-7}$ cm^{-2}s^{-1}.

Tables 1a-c summarize the results of the detailed analysis of all the sources. It is interesting to note that the upper limits for the power in the gamma-ray band range from 0.5 to 1.5 times the power in the infrared-optical band (see e.g., Landau et al. 1986; Impey & Neugebauer 1988), except for 3C 446 where the gamma-ray upper limit is 0.22 times the power in the IR-optical regime. Since simultaneous multiwavelength data below the EGRET energy band are not available for the sources discussed here, we use the data given in Landau et al. (1986) and additional IRAS data from Impey & Neugebauer (1988) as representative for the multiwavelength spectra. The reason for choosing these data is that the radio to UV data from Landau et al. (1986) were nearly simultaneous (March - May 1983) and the additional IRAS data from Impey & Neugebauer are from the same year (duration of IRAS mission: January - November 1983). But, in fact, one can only state that the power in the gamma-ray regime does not dominate the spectra except perhaps for 3C 216 where the ratio of the γ-ray to infrared-optical power might be as large as 10.

4. Discussion

In the EGRET detected sources, gamma-gamma absorption via photon-photon pair production, the EGRET observations of high fluxes above 1 GeV, and short time scale variability all suggests that the gamma-ray emission is beamed and that relativistic jets are involved in the emission. This is consistent with the explanation of non-thermal blazar radiation at lower energies involving emission from a jet (Blandford & Rees 1978; Blandford & Königl 1979). However, it is important to note that in most, but not all of the EGRET detected sources, time variability constraints suggest that the gamma-ray emission cannot come from radii as large as the VLBI radio cores that are themselves probably the self-absorbed bases of jets that feed extended structures.

While there is little doubt that relativistic jets are involved in both the gamma-ray and lower energy non-thermal emission, there is no consensus about detailed models of the emission. Before discussing the implications of the results reported here for specific models, we make some more general observations. This is undoubtedly the most productive approach at present, given that most attempts to constrain detailed physical models involve making a variety of assumptions that are not easily tested.

To begin with, it is clear that there is a strong empirical relationship between the radio properties (ie., radio-loud and flat spectrum) and gamma-ray emission in AGN, but it is not readily apparent what other source properties the gamma-ray emitting AGN have that distinguishes them from other similar sources not detected in high-energy gamma rays. It could be that the undetected sources (i) are persistently gamma-ray quiet because conditions conducive to high-energy gamma-ray emission do not exist in these sources, or (ii) are similar to the detected EGRET sources and may become strong gamma-ray emitters from time to time, or (iii) have gamma-ray emission that is beamed either in a different direction or more narrowly than the non-thermal radio emision.

We have found no correlation between the radio fluxes at 5GHz from the Kühr catalog and the EGRET gamma-ray fluxes. It would not be surprising if the undetected sources were members of a gamma-ray quiet class of blazars since the observed radio emission associated with superluminal ejection and non-thermal emission comes from >> 1 pc from the central engine, whereas the gamma-ray emission likely arises from a region at much smaller radius. Lacking evidence of any definitive characteristic that distinguishes these sources from the EGRET detected sources and suggests that these sources are persistently gamma-ray quiet, we focus discussion on the latter two possibilities.

The EGRET detected AGN typically exhibit strongly variable gamma-ray emission. For example 3C 279 and 0528+134 bave both shown large changes in flux on timescales of days (Kanbach et al. 1992; Kniffen et al. 1993; Hunter et al. 1993; Sreekumar et al. 1993; Nolan et al. 1993). Other sources (e.g. 3C 454.3, 1633+382, 0208-512) also exhibit variable gamma-ray fluxes, although on a longer timescale and with less dramatic changes in flux (Bertsch et al. 1993b; Hartman et al. 1993; Mattox et al. 1993; Michelson et al. 1994). Since time variability seems to be a very common feature of AGN, not only in the gamma-ray range, but also in radio and optical wavebands, the possibility cannot be excluded that the blazars discussed here might also be strong gamma-ray emitters from time to time.

Before addressing the remaining possibility, we considered the characteristics of some of the brightest and hardest sources from Tables 1a-1c (5GHz flux larger than 4.5 Jy, radio spectral index larger than -0.4, see also Fig.1) not detected by EGRET. In five of these eight sources we have evidence for bent jets or jets not directed into the line of sight, for two sources (0438-43 and 0637-75) we do not have the relevant information available while only one source (3C 120) does not show strong evidence for bending. For 1127-14 and 2145+067 jet bending is deduced from the misalignment of the VLBI and VLA jets (Wehrle et al. 1992), for 2134+004 it is deduced from a large change of the position angle of the VLBI components (Schilizzi et al. 1975; Pauliny-Toth et al. 1984, 1990). For 0923+392 detailed models (Alberdi et al. 1993a and references therein) indicate a total jet bending $\Delta\theta$=6°, with a jet-opening half-angle of only 4° while the maximum angle between jet and observer θ_{max} is about 16°. Finally based upon the energy budget of CEN-A Morganti et al. 1991 suggested that it might be a blazar *not* beamed directly to us. This interpretation is strengthened by recent observations of the mm- to submm spectral shape (Hawarden et al. 1993). All this might suggest that the reason why EGRET has not detected these sources is connected to the geometry of an object.

The degree of dominance of the flat spectrum radio core, seen in all quasars and in most radio galaxies, varies widely. This variation can be explained by relativistic beaming, with the degree of core dominance giving an indication of the angle of the source axis to the line of sight. Recall that for simple jets in which the radiation is emitted isotropically in its rest frame, the radiation pattern is $S(\nu,\theta) = S\prime(\nu)[\Gamma(1-\beta cos\theta)]^{-(2+\alpha)}$, where α is the spectral index, $c\beta$ is the speed of the jet, Γ the Lorentz factor of the jet and θ is the angle between the observer's line of sight and the direction of relative motion (Cawthorne 1991). The radiation is brightest along the direction of motion and falls by $2^{2+\alpha}$ at $\theta \sim 1/\Gamma$.

The radio core dominance of a source is often parameterized by R, the ratio of core flux to extended flux, usually at 5GHz (Preston et al. 1985). For the EGRET detected AGN, R varies from 0.0392 (3C 273) to 10 (0235+164), with values between 0.1 and 1 being typical (see Impey & Tapia 1990). For the sources discussed here that are not detected by EGRET and for which VLBI data is available (Preston et al. 1985), R ranges between 0.07 and 0.4, with the exception of CEN-A for which R$\sim$ 0.002. Accepting that R is a measure of source orientation this suggests an explanation of the lack of detectable gamma-ray emission from CEN-A. However, the other undetected sources have R values typical of the EGRET detected sources. This is consistent with the two sets of objects having a similar angular distribution of radio jets with respect to the line of sight.

As already mentioned, several of the sources not detected by EGRET show evidence of bent jets on VLBI scales. Because of projection effects, a slightly bent beam can appear to be strongly curved if the jet is aligned close to the line of sight. Thus the tendency for core dominated, flat spectrum sources to have large apparent bends is additional evidence that the radio jets in these sources are aligned within a small angle to the line of sight (Muxlow & Garrington 1991; Padovani & Urry 1992).

Pearson & Readhead (1988) found that the distribution of apparent misalignment angles η (the position angle between the VLBI and VLA scale jets) within a core-dominated sample of radio sources is bimodal with one peak near 0° and a second peak around 90°. This unexpected form of the distribution was confirmed by Wehrle et al. (1992) with the variable source sample of core-dominated sources. Those sources with a misalignment angle near 0° ($\eta < 45°$) are called "aligned" sources and those sources with an angle around 90° (45°$< \eta <$135°) belong to the so called "misaligned" population (Conway & Murphy 1993). It is interesting to note that for those eight EGRET sources detected during phase I where misalignment angles are available, six of them are superluminal. The misalignment angles for these six sources are all < 35°. For four of them it is even ≤ 10°. Only one of the EGRET sources from phase I has a misalignment angle > 45°.

The undetected sources from Table 1 for which misalignment angles are available are distributed as follows: 10 sources belong to the "aligned" population and seven to the "misaligned" population. Only three of these undetected sources have an angle η ≤15°. Although the number of sources used here is very small this might indicate that EGRET preferably sees sources which have an initially very straight VLBI jet which then gradually curves into the VLA jet (Conway & Murphy 1993).

The undetected sources could have gamma-ray emission that is similar to that of the detected sources but is beamed either in a different direction or more narrowly than the non-thermal radio emission if the gamma-ray emission arises from an inner region of the jet in which the bulk Lorentz factor Γ is much larger than it is in the region of radio emission. In this case the gamma-ray emission would be beamed into a much smaller cone angle than the radio emission.

From the very detailed geometrical model for 0923+392 one can infer from the viewing angle of 16° at component *d* or 12° at component *c* (Alberdi et al. 1993) that the opening angle of the gamma-ray beam must be much less than 16° or 12°, respectively, in order to explain the non-detection of this source in gamma rays. This implies a beaming factor of less than $6.2\cdot10^{-3}$ or $3.5\cdot10^{-3}$, respectively. The model even requires a half-opening angle of 4° for the radio jet and if the gamma-ray beam is even more narrowly beamed than the radio beam this half-opening angle even implies a beaming factor of less than $1.6\cdot10^{-3}$. Although other interpretations are possible for the non-detection of this source bends in the inner jet consistent with those observed on VLBI scales could therefore beam the gamma-ray emission in a direction that makes this radiation unobservable.

Nonetheless, the correlation of high energy gamma-ray sources with superluminal sources is strong.

Many models proposed for the generation of gamma-ray emission in AGN involve a well collimated jet of relativistic electrons and magnetic fields. The gamma rays are then produced by these relativistic electrons either through synchroton self-Comptonization (SSC) of the non-thermal emission due to synchrotron radiation of the electrons (Jones et al. 1974; Königl 1981; Ghisellini & Maraschi 1989; Bloom & Marscher 1992; Marscher & Bloom 1992; Maraschi et al. 1992), inverse Compton scattering of UV and X-ray radiation from either the disk itself (Melia & Königl 1989; Dermer et al. 1992; Dermer & Schlickeiser 1993) or disk radiation reprocessed in the ambient medium, e.g. broad-line region clouds (Blandford 1993; Sikora et al. 1993) or synchroton radiation from highly relativistic $e^{\pm}$ pairs injected due to photomeson production of pions by ultra-relativistic protons (Mannheim & Biermann 1992; Mannheim 1992, 1993).

From the comparison of the EGRET upper limits with the luminosity in the infrared-optical regime (see discussion in chapter 3) it follows that the luminosity in the Compton component is less than that in the synchrotron component. Here, we make the assumption that during the EGRET observations the synchrotron emission in the optical to UV energy band was similar to that observed earlier in this energy band. In order for inverse Compton scattering to dominate over the synchrotron radiation field, the energy density of the radiation field must be greater than the energy density of the magnetic field. Since this is not the case, this means that either the magnetic field must be very strong or that there is a very weak soft photon field, minimizing inverse Compton scattering by the electrons. Another possibility to explain the lack of gamma-ray emission from the superluminal sources observed here could be that the bulk Lorentz factor Γ is not high enough in the inner jet to boost the scattered photons into the EGRET energy range (Note that the scattered photons emitted into the direction $\theta_{obs} \sim 1/\Gamma$ have energies $E \sim \Gamma^2\gamma^2 E_s$ (Sikora et al. 1994) where Γ is the bulk Lorentz factor, γ is the electron Lorentz factor and E_s is the energy of the soft photons). This would imply an upper limit on the bulk Lorentz factor of $\Gamma << 10$ for typical values of $\gamma \approx 10^3$–10^4 and $E_s \sim 5$eV.

This is in agreement with the assumption that gamma-rays might not be able to escape the emitting region, since the optical depth for γ-γ absorption increases with decreasing bulk Lorentz factor for a given gamma-ray energy (Sikora et al. 1993; Mattox et al. 1993). In order for gamma rays with energies greater than 100 MeV to be absorbed, the bulk Lorentz factor must be of the order of 1.

Bloom & Marscher (1992) have predicted gamma-ray fluxes from the synchrotron self-Comptonization model. In this model the ratio of the X-ray flux to the radio flux is related to the expected gamma-ray flux if the gamma rays come from second order Comptonization. Taking observed values for the X-ray and radio fluxes from epoch 1980 they derived expected gamma-ray fluxes for some blazars which should lie above the sensitivity limit of EGRET ($\sim 5{\cdot}10^{-8}$cm^{-2}s^{-1}). This list contains seven blazars which also have been analyzed here. Table 2 compares the predicted gamma-ray fluxes with the observed upper limits for these seven blazars. Only for 3C 120 and 1721+343 the predicted values are higher than the observed upper limits. In order to test this model a χ^2-test has been done using the best estimate for the EGRET fluxes with their standard deviations and the predicted fluxes. The test yielded a χ^2 of 63.9 for six degrees of freedom which makes the model rather unlikely. But since the data have not been obtained simultaneously one can argue in terms of time variability. Therefore, the predictions from the SSC-model are consistent with the observations for the seven sources listed in Table 2.

Table 2. Comparison of predicted gamma-ray fluxes from the SSC-model by Bloom & Marscher (1992) with the observed upper limits for seven blazars

Name	predicted flux (10^{-7}cm^{-2}s^{-1})	observed	viewing period(s)
NRAO 140	0.9	<1.1	15.0
3C 111	0.6	<0.9	15.0
3C 120	6.0	<3.0(2.2)	2.1(1.0)
1721+343	3.1	<0.7	9.2
3C 390.3	0.5	<2.2(2.0)	18.0(22.0)
BL Lac	0.7	<2.4(0.8)	2.0(34.0)
3C 446	0.02	<0.9	19.0

The upper limits derived so far are also consistent with the overall spectra predicted by the proton initiated cascade (PIC) model (Mannheim 1992) and a proton/electron energy density ratio $\eta = u_p/u_e < 10$. For $\eta = 1$ the model predicts a gamma-ray power about a factor of 3 lower than the power in the infrared/optical while for $\eta = 10$ the power in the gamma-ray regime is already about a factor of 4 larger than in the infrared/optical range for a given set of parameters (Mannheim 1992). A quite acceptable representation of the multifrequency spectrum of 3C 279 during the "flare" state in June 1991 was obtained for $\eta = 10$. This might suggest that during the "quiet" state the energy density of the protons and the electrons is about equal and for the "active" state the energy density of the protons is enhanced by some mechanism. Another possibility to explain the "quiet" state of an AGN within this theory is that the protons could not reach their maximum energy during the acceleration process for some reason (e.g. presence of an UV-bump). This would cause the spectra in the EGRET energy range to be much steeper than it was assumed here ($\alpha_\gamma = 2.0$) for calculating the fluxes above 100 MeV. The argument that the bulk Lorentz factor is too small to boost the internal gamma-ray luminosity L_{int} ($L_{obs} \sim \Gamma^4 L_{int}$) above the EGRET sensitivity also applies here.

5. Summary

The lack of evidence for any definitive characteristic distinguishing the non-detected flat-spectrum radio sources from those detected by EGRET seems to favour two reasons why these sources have not been detected: 1) time variability and 2) the orientation and geometry of the beam.

1) The observations of active galactic nuclei with the EGRET instrument have shown that the emission of high energy gamma rays from these objects is strongly time variable. Time variability is a very common feature of AGN, not only in the gamma-ray range, but also in the radio, optical and X-ray wavebands. Therefore, it cannot be excluded that the blazars discussed here might also be strong gamma-ray emitters from time to time.

2) Although the ratios of core to extended radio flux indicate that the non-detected sources have a similar angular distribution of the radio jets with respect to the line of sight as the EGRET AGN, bends in the inner jet could beam the gamma-ray emission in a direction away from the line of sight. Several of the sources not detected by EGRET show evidence of bent jets not only on VLA but also on VLBI scales. The high gamma-ray emission could also be more narrowly beamed than the non-thermal radio emission if the gamma-ray emission originates in an inner region of the jet where the bulk Lorentz factor is much larger than it is in the region of the radio emission.

Of course, there is always the possibility that many of the undetected sources in Table 1 may be members of a gamma-quiet class of blazars that are otherwise difficult to distinguish from the time-variable, strong gamma-ray emitting class of blazars. It would not be surprising if this were the case since the observed radio emission associated with superluminal ejection comes from >> 1pc from the central engine, whereas the gamma-ray emission likely arises from a region at much smaller radius.

Acknowledgements. We wish to thank Ann Wehrle for access to data prior to publication. We also thank the referee for very useful suggestions. The EGRET team gratefully acknowledges support from the following: Bundesministerium für Forschung und Technologie, Grant 50 QV 9095 (MPE); NASA Grant NAG5-1742 (HSC); NASA Grant NAG5-1605 (SU) and NASA Contract NAS5-31210 (GAC). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the JET Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

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