Possible New Identifications for Southern EGRET Sources

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Introduction

The third catalog of high-energy gamma-ray sources detected by EGRET (Hartman et al. 1999; hereafter 3EG) includes 66 high-confidence identifications of active galactic nuclei (AGNs) with blazars and 27 lower-confidence potential blazar identifications. 170 sources (96 of which have $|b| > 10°$) are not yet identified firmly with known objects.

Our earlier work (e.g., Valtaoja & Teräsranta 1996; Lähteenmäki et al. 1997; Tornikoski et al. 1999; Lähteenmäki et al. 2000; Tornikoski et al. 2000) has shown that there seems to be a connection between the high radio-frequency and EGRET gamma-ray activity, and that the most probable blazar to be detected with EGRET is a source with an ongoing and still rising high-frequency radio flare.

The case of PKS 2255–282 (Tornikoski et al. 1999) and others have demonstrated that many AGNs remain undetected by EGRET until they go through an activity period which is observed both in the radio domain and at the gamma-ray energies. We believe that several of the unidentified EGRET sources in 3EG will turn out to be radio loud AGNs which probably would have shown millimeter-wavelength activity at the time of the EGRET detection.

The aim of this project was to make millimeter-domain observations of the potential EGRET counterpart AGNs.

The observations were made with the 15-meter Swedish–ESO Submillimeter Telescope (SEST) on the European Southern Observatory site of the La Silla mountain in Chile. The observing frequencies were 90 GHz (3 mm) and 230 GHz (1.3 mm).

We had two major goals in this project:

1. To make further studies of probable / potential candidates already suggested in the literature.

2. To study the new unidentified sources listed in 3EG but not included in 2EG or 2EGS: to propose possible candidates for them and to study a sample of those candidates to see if our method is feasible for making new identifications.

Sample 1:
Southern low-confidence AGN indentifications from 3EG

3EG lists twelve southern sources which are potentially identified with blazars, Table 1. The identifications are considered to be of low confidence either because the object has a low radio flux reported in the literature (historical low radio frequency data) or because it lies outside the 95% uncertainty contour. The low frequency radio data are from an observing epoch of ca. a decade ago, and because these sources are expected to be highly variable in the radio / mm domain, the historical low frequency fluxes do not necessarily correlate well with the mm-fluxes during the time of the EGRET observations.

Sample 2:
Promising candidates for new southern EGRET-identifications

Mattox et al. (1997), hereafter MSM, have presented a method to make new identifications for the unidentified sources listed in the 2nd EGRET catalog (Thompson et al. 1995; hereafter 2EG), and the Supplement to the 2nd EGRET catalog (Thompson et al. 1996; hereafter 2EGS). MSM list 17 potential identifications for which they expect further investigation to be most useful. When we exclude all Northern hemisphere sources and all sources that have been either left out from 3EG (after the improved analysis), or identified in the 3EG (including the two sources identified using our group's observations (Bloom et al. 1997)), this leaves us with the two sources listed in Table 2a.

MSM list radio sources as potential source identifications for the 2EG and the 2EGS with the probabilities of correct identification, based on the radio source position and flux density. The sources with the highest probabilities have been identified with the 2EG / 2EGS sources either in the same paper (Table 3 of MSM, ``EGRET identifications with a high probability of being correct'') or later in 3EG.

The probability listed in MSM is, however, based on low frequency radio fluxes of the Parkes-MIT-NRAO survey (Griffith & Wright 1993) obtained in 1990 at 4.8 GHz.

We have composed a list of candidates for radio identifications of EGRET sources from MSM tables 1 and 2, excluding all Northern hemisphere sources, all sources that have been identified in MSM, or in Bloom et al. (1997), or in 3EG, and all that have the identification probability $p < 0.001$. There were 20 sources left. The ones that we observed are listed in Table 2b.

Sample 3:
Possible candidates for new southern 3EG EGRET identifications

We chose potential new candidates for identifications of unidentified 3EG sources according to the following criteria:

- Only Southern hemisphere sources with $|b| > 10°$ were included.

• Only sources with no entry in 2EG or 2EGS were included, i.e., these are new sources not earlier discussed by MSM, and also these were more likely to be in an active radio state during our observations in 2000 if compared to ”old” EGRET detections from 2EG.

• We searched for the candidates within a 1 degree radius of the 3EG position, which is the size of the EGRET error box.

• During the first round we selected candidates which are radio sources from the PMN survey (Griffith & Wright 1993) or the PKS survey (Wright & Otrupcek 1990). There were several candidates for each 3EG source.

• From the candidates we excluded all of those that had a 5 GHz flux in the PMN survey (Griffith & Wright 1993) less than 200 mJy. Even though the PMN fluxes are one-epoch fluxes obtained almost 10 years ago of sources which are expected to be highly variable, it is reasonable to assume that very few if any of the extremely faint sources would be detected in the millimeter domain with the current sensitivity of the SEST instruments.

EGRET-detected blazars have extremely flat 5 to 90 GHz spectra. The median $\alpha_{5GHz–90GHz}$ during millimeter-domain activity, for the ones that we have data for at 90 GHz, is α=+0.08. During this study our main goal was to search among a set of sources relatively faint at 5 GHz (catalog data), and thus routinely excluded from any high radio-frequency studies, for AGNs with unusually flat spectra. Our assumption was that if we find objects faint at 5 GHz being relatively bright ($\alpha_{5GHz–90GHz} \approx –0.20$ and larger) at 90 GHz, these are probably sources variable in the millimeter-domain and thus good blazar candidates.

Results: Sample 1.

Summary of our SEST data, complemented by IRAM data from the literature, is given in Table 1. For 2 out of the 12 candidates — B1716–771 and J1808–5011 — we only had one 90 GHz data point, taken after the end of EGRET operation. For both of them the S / N of the 90 GHz observation was < 4, giving us only the upper limit of the source flux density. Since both of these sources were faint at the time of the 90 GHz observation, they are neither very promising candidates of strong millimeter-wave activity nor good candidates for the EGRET-detection counterparts. For a third source, B0539–057, we have three 90 GHz data points collected between 1989.09 and 1991.16, and one 230 GHz upper limit observed in 1993.16. At least before the time of the EGRET operation the source was faint in the millimeter domain, and had a relatively steep ($\alpha_{5GHz–90GHz}$=–0.40) spectrum, which make it an unlikely blazar-counterpart for EGRET.

The remaining nine sources were bright and variable in the mm-domain. For some of the low-confidence EGRET identifications we have mm-wave monitoring data spanning a decade, giving us a very good estimate of the source behavior over a long period of time. The maximum spectral indices $\alpha_{5GHz–90GHz}$ for these sources (ν^{α}) were very flat, the largest spectral index (for B1313-333) being +0.27, and all except one being >–0.20. The steepest spectral index was that of B1145–145, $\alpha_{5GHz–90GHz}$=–0.43, but also this source is bright and variable in the mm-domain, with the maximum flux densities at 90 GHz and 230 GHz being 2.15 Jy and 1.30 Jy, respectively.

Figures 1 and 2 show examples of two sources and their millimeter-domain variability behavior that we think confirms their blazar-nature and the EGRET-identifications.

Results: Sample 2

Tables 2a and 2b list the observations made for the identification of the Sample 2 sources. The second source listed in Table 2a, J1650–5044, has a millimeter flux and spectrum which would make it a very promising candidate for the AGN counterpart of the EGRET-detection, but in 3EG Hartman et al. comment that the corresponding 3EG source, 3EG J1638–5155, lies 2° away from the 2EG position, and that the possible identification by MSM, J1648–5042, thus appears less convincing.

In Table 2b we have typeset in boldface 3 sources with a significant (S / N>4) detection at 90 GHz and very flat 5 to 90 GHz spectra, and thus likely counterparts for the EGRET detections. In addition to these, there are two sources with a marginal 90 GHz detection and flat spectra. It is worth making millimeter-wave observations of these sources at some other epochs to see whether their high radio-frequency variability corresponds to that of other flat-spectrum sources and thus makes them possible candidates for the EGRET identifications.

Figure 3 shows the radio spectra of J1058–8003 and J1703-6212.

Results: Sample 3

We observed 19 of the Sample 3 EGRET source counterpart candidates at 90 GHz in April 2000 and / or August 2000. The results are given in Table 3. Among these sources there are two significant detections (S / N>4) at 90 GHz. One of them, J1819–6345, is a known compact steep-spectrum source, and our 90 GHz data point confirms the steepness of its spectrum. It is an unlikely AGN counterpart for an EGRET-detection.

J1605–1139 has a flux density of 530 mJy at 90 GHz and a 5 to 90 GHz spectral index α=+0.12, making it a good candidate for mm-domain activity. This source is located within 50.6' of the EGRET position of 3EG J1607–1101, which makes it a very promising candidate for the source identification. The 5 to 90 GHz radio spectrum of J1605–1139 is shown in Figure 4.

Table 3 also lists three other flat-spectrum (α>–0.20) sources detected at a marginal level at 90 GHz. Since our study of Sample 3 was made using 1–2 observing epochs only, the mm-variability behavior of these sources is currently unknown, but the flatness of their spectra indicates that they are active also at the high radio-frequencies. We will continue the flux density monitoring of these sources at high radio-frequencies.

Conclusions

We have made high radio-frequency observations of Southern AGNs that were considered to be possible counterparts of the unidentified EGRET sources.

Nine southern AGNs classified as "possible AGN identifications" in 3EG were found to have flat spectra and be bright and variable in the millimeter domain, thus confirming the identification. For some of the sources we have dense flux density monitoring data that show that the gamma-detection was made at the time of increased activity at high radio-frequencies.

We have also studied the millimeter flux densities and the 5 to 90 GHz spectra of sources that were considered possible candidates for the so far unidentified EGRET sources. We propose that the following four EGRET sources can possibly be identified with an AGN: 2EG 0720–4746 (id: J0726–4728), 2EGS 1050–7650 (id: J1058–8003), 2EGS 1703–6302 (id: J1703–6212), and 3EG J1607-1101 (id: J1605–1139). In addition to these, we found the 5 to 90 GHz spectra of five other AGNs, though faint, to be flatter than expected, indicating mm-activity which may be related to the gamma-ray activity.

References:

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AGN	**Candidate for**	N_{90GHz}	**90GHz data [Year]**	$S_{90GHz,max}$ **[Jy]**	$\alpha_{5GHz–90GHz}$	N_{230GHz}	$S_{230GHz,max}$ **[Jy]**
B0130–171	**3EG J0130-1758**	2	1986.86,2000.63	1.76	+0.20	0	
B0506–612	**3EG J0512-6150**	8	1994.57–1997.99	1.43	-0.13	6	0.60
B0521–365	**3EG J0530-3626**	34	1988.28–1999.77	5.43	-0.20	19	3.98
B0537–286	**3EG J0531-2940**	3	1990.16–1995.16	0.58	-0.20	4	0.17
B0539–057	3EG J0542-0655	3	1989.09–1991.16	0.50	-0.40	1	<0.25
B0805–077	**3EG J0812-0646**	19	1986.86–1997.33	2.45	+0.30	3	0.70
B1127–145	**3EG J1134-1530**	13	1988.29–1995.25	2.15	-0.43	11	1.30
B1313–333	**3EG J1314-3431**	15	1986.86–1997.99	2.94	+0.27	3	2.84
B1504-166	**3EG J1504-1537**	28	1986.92–1995.25	1.49	-0.09	14	0.23
B1514-241	**3EG J1517-2538**	65	1986.42–1999.47	3.13	+0.11	26	1.86
B1716-771	3EG J1720-7820	1	2000.63	<0.37		0	
J1808-5011	3EG J1806-5005	1	2000.63	<0.27		0	

Table 1. Sample 1.
Millimeter-wave data for the 12 Southern low-confidence AGN identifications in 3EG.
We have listed the possible AGN counterpart, the EGRET source name from the 3EG,
the number of 90 GHz observations, the epochs of the 90 GHz observations,
the maximum flux density at 90 GHz, the spectral index between 5 GHz and 90 GHz
using the maximum fluxes (i.e., the assumed flare state) at each frequency, the number of
230 GHz observations, and the maximum flux density at 230 GHz.
The 9 sources in boldface out of the 12 candidates are strong and variable
in the millimeter domain, and thus likely to be correct identifications.

AGN	Candidate for	90GHz epoch	$S_{90GHz,\,max}$ [Jy]	$a_{5GHz–90GHz}$
J1249-8303	2EG 1248-8308	2000.329	N.D.	
J1650-5044	2EG 1648-5042	2000.329	1.655 ± 0.105	–0.02

Table 2a. Sample 2.
Promising candidates for new southern EGRET-identifications from MSM.
"N.D." (no detection) indicates a signal-to-noise (S / N) ratio < 2.0.

AGN	Candidate for	90GHz epoch	$S_{90GHz,\,max}$ [Jy]	$a_{5GHz–90GHz}$
J0156-3616	2EG 0159-3557	2000.630	N.D.	
J0159-3604	2EG 0159-3557	2000.630	N.D.	
J0719-5228	2EGS 0724-5157	2000.329, 2000.630	N.D.	
J0724-5235	2EGS 0724-5157	2000.329	N.D.	
J0718-4711	2EG 0720-4746	2000.329	N.D.	
J0726-4728	**2EG 0720-4746**	2000.630	0.340 ± 0.077	–0.19
J1057-7724	2EGS 1050-7650	2000.630	N.D.	
J1058-8003	**2EGS 1050-7650**	1997.33–2000.63	1.638 ± 0.177	–0.09
J1454-1925	2EG 1457-1916	2000.630	0.191 ± 0.080, S / N=2.4	–0.21
J1634-1440	2EG 1635-1427	2000.630	N.D.	
J1641-2728	2EGS 1641-2659	2000.630	N.D.	
J1647-6437	2EGS 1703-6302	2000.630	0.370 ± 0.082	–0.44
J1703-6212	**2EGS 1703-6302**	2000.329	1.227 ± 0.136	+0.24
J1710-0355	2EG 1709-0350	2000.630	N.D.	
J1713-0817	2EGS 1708-0927	2000.630	N.D.	
J1743-2247	2EG 1742-2250	2000.630	N.D.	
J1750-0841	2EG 1746-0935	2000.329	N.D.	
J1849-2638	2EG 1850-2638	2000.329	N.D.	
J2005-2310	2EG 2006-2253	2000.630	0.253 ± 0.125, S / N=2.1	–0.01

Table 2b. Sample 2.
Possible candidates for new southern EGRET-identifications from MSM.
"N.D." (no detection) indicates a signal-to-noise (S / N) ratio < 2.0.
The marginal detections, with 2.0 < S / N < 4.0, have an S / N entry included in the flux density column.
All the other fluxes have S / N>4, and are considered detections at a significant level.

AGN	Candidate for	90GHz epoch	$S_{90GHz,\,max}$ [Jy]	$\alpha_{5GHz-90GHz}$
B0616-329	3EG J0616-3310	2000.329	N.D.	
B0656-615	3EG J0702-6212	2000.329, 2000.630	N.D.	
J0710-3850	3EG J0706-3837	2000.329, 2000.630	0.252 ± 0.090, S / N=2.8	–0.19
J0821-5800	3EG J0821-5814	2000.329, 2000.630	N.D.	
J0825-5849	3EG J0821-5814	2000.329, 2000.630	N.D.	
B1259-435	3EG J1300-4406	2000.329	N.D.	
B1259-445	3EG J1300-4406	2000.329	N.D.	
J1302-4447	3EG J1300-4406	2000.329, 2000.630	0.243 ± 0.072, S / N=3.4	–0.25
J1254-4425	3EG J1300-4406	2000.329, 2000.630	0.379 ± 0.100, S / N=3.8	+0.03
J1502-3520	3EG J1500-3509	2000.329	N.D.	
B1454-354	3EG J1500-3509	2000.329	N.D.	
J1457-3538	3EG J1500-3509	2000.329	N.D.	
J1505-3432	3EG J1500-3509	2000.329	N.D.	
J1605-1139	**3EG J1607-1101**	2000.63	0.530 ± 0.085	+0.12
J1632-1052	3EG J1631-1018	2000.63	N.D.	
B1644-071	3EG J1646-0704	2000.63	N.D.	
J1802-0207	3EG J1800-0146	2000.63	N.D.	
J1819-6345	3EG J1813-6419	2000.63	0.537 ± 0.084	–0.73
B2247-13	3EG J2251-1341	2000.63	0.208 ± 0.095, S / N=2.2	–0.15

Table 3. Sample 3.
Possible candidates for new southern EGRET-identifications of the previously unidentified 3EG sources.
"N.D." (no detection) indicates a signal-to-noise (S / N) ratio < 2.0.
The marginal detections, with 2.0 < S / N < 4.0, have an S / N entry included in the flux density column.
All the other fluxes have S / N>4, and are considered to be detections at a significant level.

D

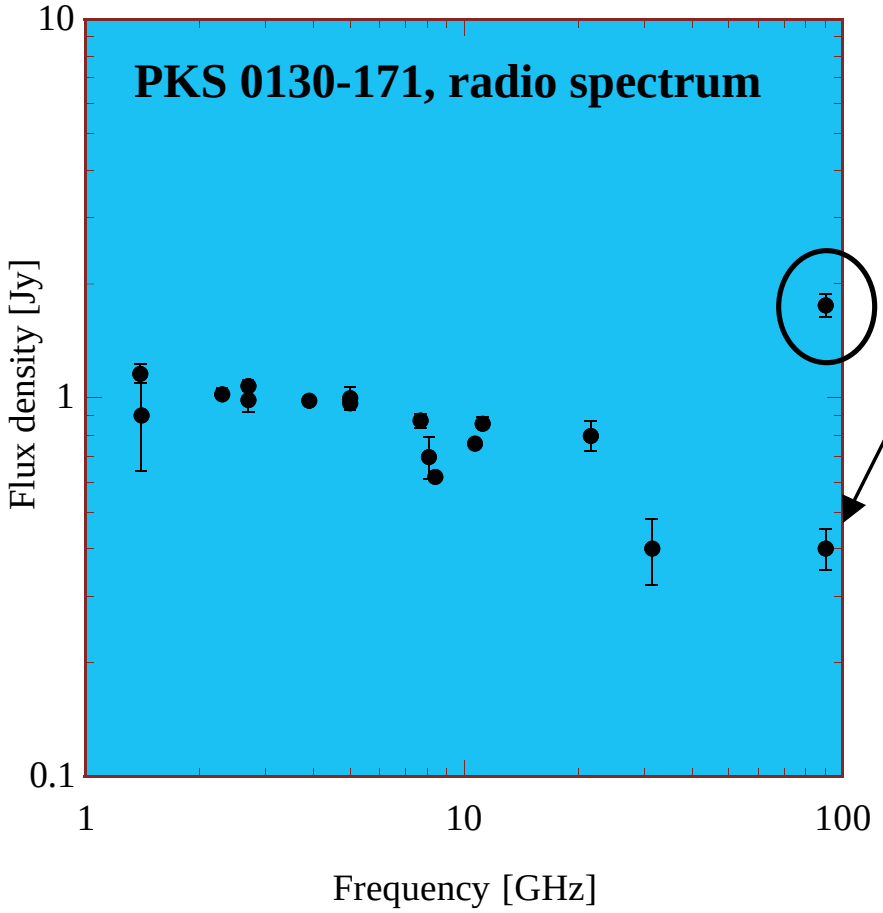


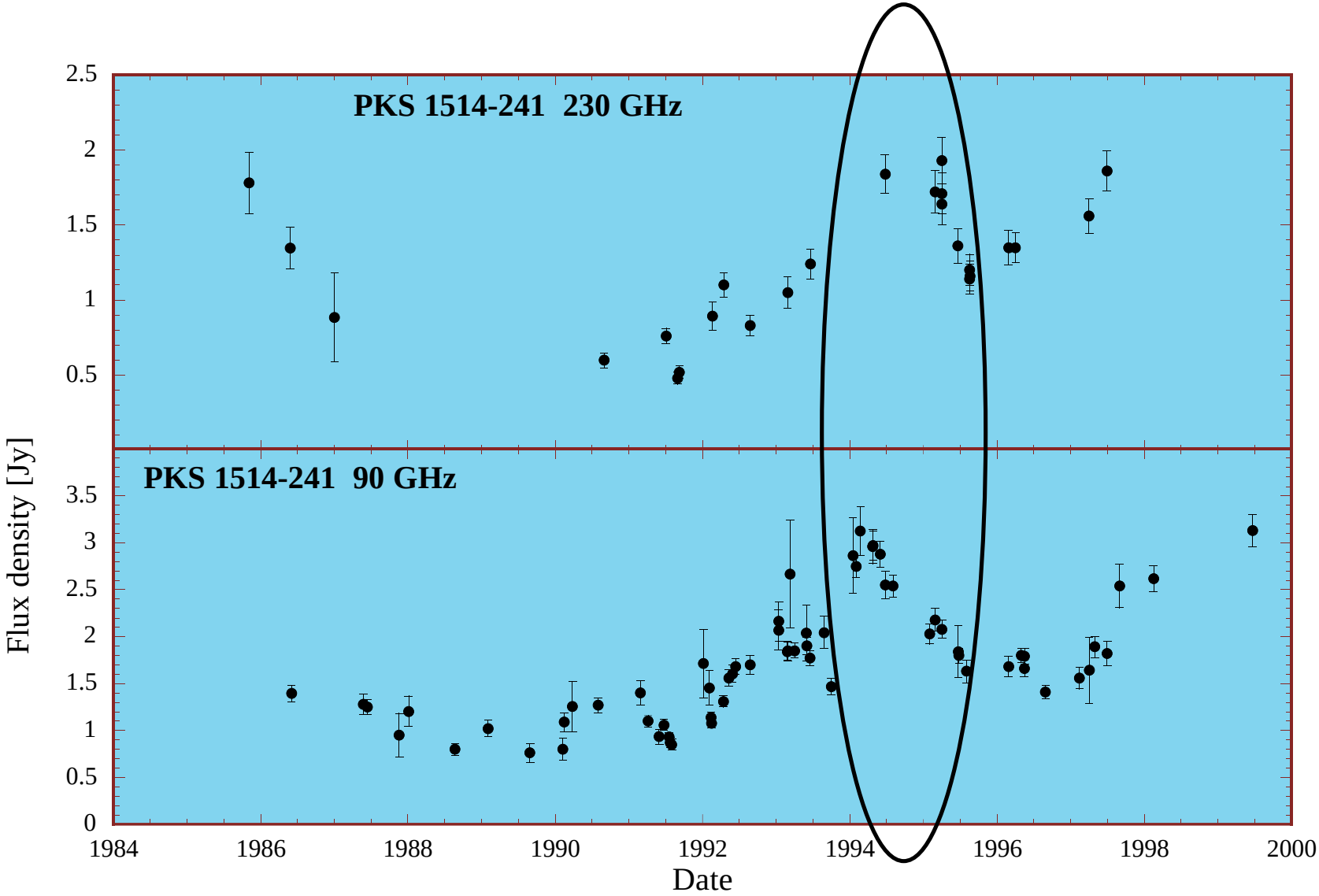
Figure 1.

There are only two 90 GHz flux density points available for this source: this one, observed in 1986 by Steppe et al.(A&AS, 1988), showing the source in a quiet millimeter-domain state with a falling spectrum...

... and the one indicated by the red circle, observed by our group last year.
This shows, even though there are only two high-frequency data points available, that the source PKS B0130-171 can be highly variable in the millimeter domain and is the likely counterpart for the EGRET source 3EG J0130-1758.

Figure 2.

PKS B1514-241, a low-confidence AGN identification for 3EG J1517-2538 in the 3rd EGRET Catalog, was detected with EGRET at a significant level only when it was in an active state in the high radio-frequency domain (red circle). The source has been within the EGRET field of view several times also in 1991–1996.



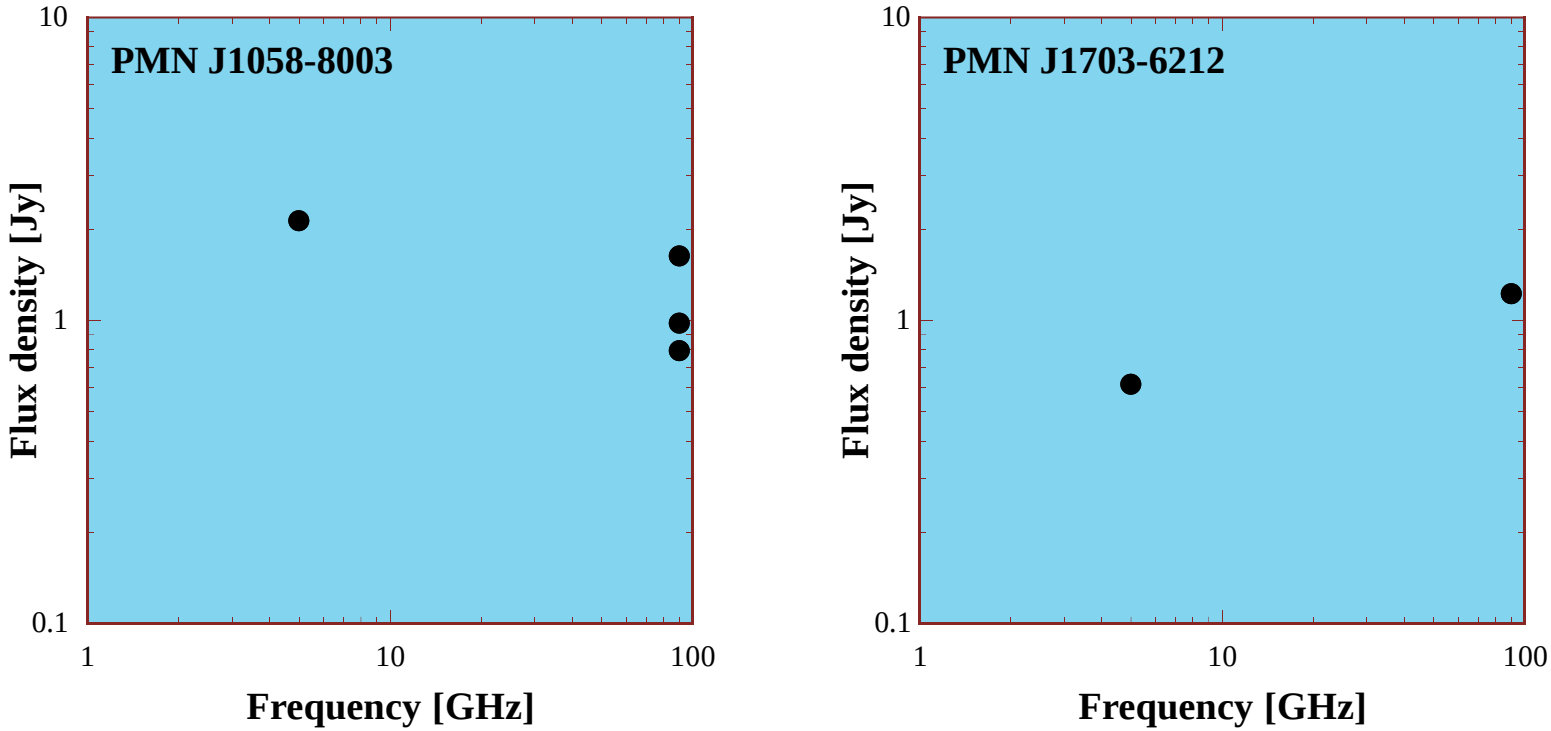


Figure 3.
The radio spectra of two AGNs from Sample 2
with flat spectra all the way to the millimeter-domain.

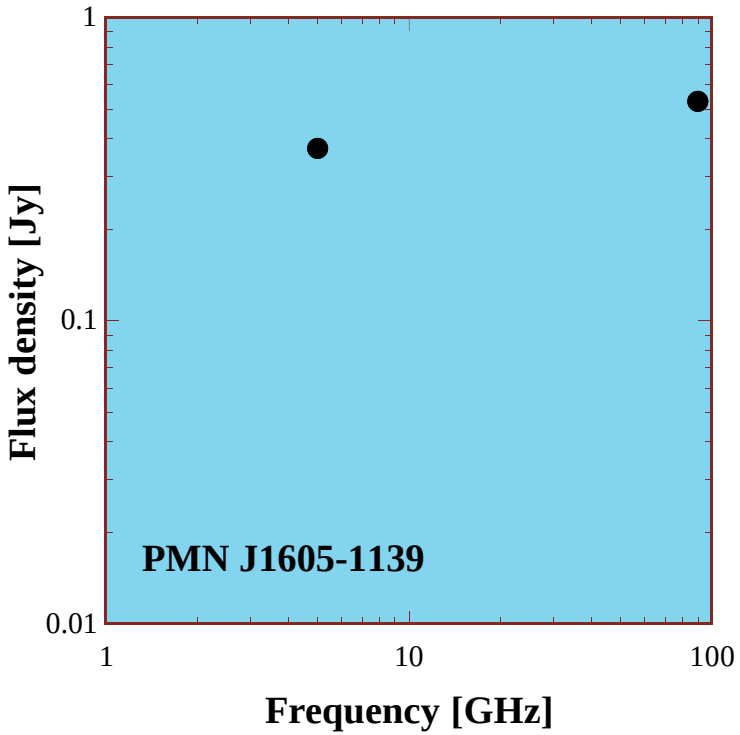


Figure 4.
The 5 to 90 GHz radio spectrum of PMN J1605-1139 is slightly inverted, possibly due to millimeter-domain variability. This source is a promising candidate for the AGN counterpart of the 3EG source 3EG J1607—1101.