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Flux density monitoring of radio sources with detected or supposed γ-ray emission

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Abstract. We present the results of a flux density monitoring program of extragalactic radio sources with the Effelsberg 100-m telescope. Data for 53 sources are listed from observations between 1991 and 1995/1996 in the frequency range from 1.4 GHz to 32 GHz[1]. The sources have either been identified by EGRET on board CGRO at a different level of confidence or at least are candidates for showing up in the γ-ray range. The data will be useful for studies of the relationship of γ-ray activity to radio activity.

Key words: γ-rays — extragalactic radio sources — quasars — BL Lacs — variability

1. Introduction

We have published multifrequency radio light curves of 12 extragalactic radio sources in the northern sky (Reich et al. 1993, Paper I), which have been detected by the Energetic Gamma Ray Experiment Telescope (EGRET, Kanbach 1988) on board the Compton Gamma Ray Observatory (CGRO). The data presented in Paper I cover the period from 1991 until the end of 1992 and represent peak flux densities measured in the cm-range and mm-range with the Effelsberg 100-m telescope and the IRAM 30-m telescope. From these data it was noted that enhanced radio emission is delayed up to several months to the γ-ray emission for the majority of the observed sources. Meanwhile more γ-ray detections of extragalactic sources have been reported and improved γ-ray flux densities have been derived (Fichtel et al. 1994; Thompson et al. 1995, 1996; Kanbach 1996; Mukherjee et al. 1997). We have continued the monitoring of extragalactic sources with the Effelsberg telescope. The relation of γ-ray activity to radio activity is of considerable interest for various reasons:

(1) First, in some γ-ray selected blazars it has been established that γ-ray flaring coincides with the launching of a new superluminal VLBI-jet component (e.g. Pohl et al. 1995; Krichbaum et al. 1995), and measuring the time delay between γ-ray flaring and radio appearance provides valuable information about the jet component formation, collimation and acceleration processes.

(2) Secondly, γ-ray loud AGN could contribute a large fraction of the diffuse extragalactic γ-ray background radiation due to the superposition of unresolved discrete sources. Most approaches (Erlykin & Wolfendale 1995; Stecker & Salamon 1996) relate the unknown γ-ray luminosity function of blazars to their radio luminosity function, and the justification of such proportionalities can only be tested by observing individual bright γ-ray loud and quiet radio AGN.

(3) Different theoretical models of the time and spectral evolution of flaring blazars make definite predictions about the onset of flares in different frequency bands, so that multifrequency broadband modelling provides an excellent test data set to discriminate quantitatively between different models.

A statistical analysis of the radio properties of EGRET sources and specifically the relation between radio and γ-ray emission has been published elsewhere (Mücke et al. 1996, 1997). It was found that those flat-spectrum radio sources which have been detected by EGRET also show more activity at cm radio wavelengths than similar sources which remain γ-ray quiet during the last years. However, there is no direct correlation between the radio and γ-ray light curves, neither in flux density nor in luminosity. Previous findings of a strict relation in luminosity can be entirely explained by the limited dynamical range of the EGRET data and selection effects inherent in the method

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[1] Table 2 is only available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

of identification. The fact that about one third of the sources listed in Thompson et al. (1995) can be identified with radio-loud AGN with catalogue flux densities of $S(5\,\mathrm{GHz}) \geq 1$ Jy indicates that there is a noisy luminosity relation which is further washed out by the strong variability both in γ-rays and at radio frequencies.

A time lag between γ-ray and radio outbursts was suggested for some sources on the basis of their light curves (e.g. Paper I) and the backextrapolation of the apparent motion of VLBI components. It should, however, be pointed out that there is no statistical evidence for this as a class property of all sources, which is mainly due to the limited sampling of the γ-ray light curve. Many of the promising candidates for a time lag in Paper I showed only one clear outburst in each wavelength regime (for example the BL Lac 0235+164, see Fig. 1). When adding more data from subsequent observations we get a less clear picture for some sources. An example is PKS 0528+134 which showed a γ-ray outburst in 1991 followed by a radio outburst, another bright γ-ray outburst in 1993 again followed by a radio outburst, and then nothing peculiar at γ-rays in 1995 while subsequently the brightest ever recorded radio outburst was noted (Pohl et al. 1996). Our findings indicate that if there is a time lag between γ-ray and radio outbursts then it has to be different from outburst to outburst, at least for the well-sampled sources 0528+134, 3C 273, 3C 279, and 3C 454.3 (Mücke et al. 1998).

We have continued the observations presented in Paper I with the Effelsberg 100-m telescope of EGRET detected γ-ray sources and in addition we made observations of a few sources which have been expected to show up in the γ-ray range. For most of the sources observations have been made at irregular intervals starting in 1991 until mid of 1995. For a few sources flux density monitoring was continued until February 1996 when all observations stopped due to the track replacement of the telescope. The results of the observations are presented in tabulated form and for a few sources light curves are given in addition. For some sources radio light curves or data from Table 1 have already been published. We have included the references in Table 1.

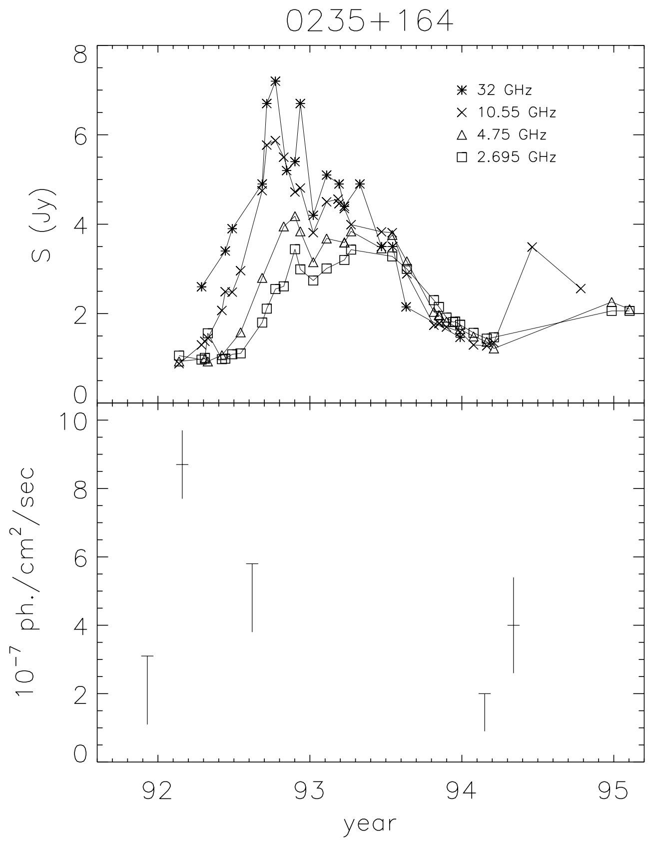

Fig. 1. Radio and γ-ray lightcurves for 0235+164

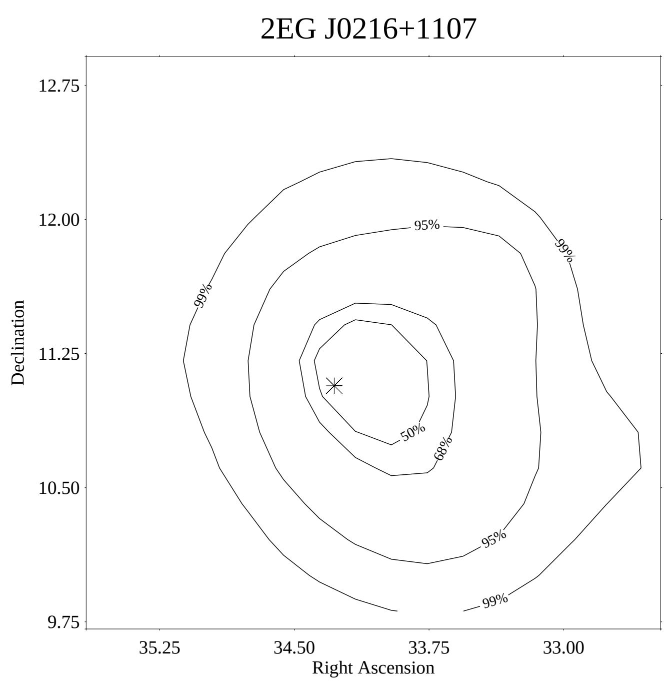

Fig. 2. Proposed identification of 0214+108 (marked by a star) with the γ-ray source 2EG J0216+1107. The contours represent the statistical probability that a single source lies within the given contour

2. The radio observations

Since autumn 1991 we have systematically monitored strong flat spectrum variable radio sources as potential counterparts of extragalactic CGRO sources at several frequencies with the Effelsberg 100-m telescope. The method of observations, the applied data reduction and the calibration have been already described in Paper I. In brief, the observations are made via orthogonal cross-scans and the peak flux densities have been obtained by fitting a Gaussian to the observed data.

The calibration of the data is based on 3C 286 with assumed flux densities of 14.4 Jy, 10.4 Jy, 7.5 Jy, 4.5 Jy

Table 1. List of monitored radio sources

Source name(s)	Epoch 19..	EGRET designation/reference	Radio data/light curve
0130−171	91.8 – 92.1	E2m, K96	—
0202+149	92.4 – 95.5	E1, E2, Mu97, K96	R93
0214+108	92.5 – 95.0	2EG J0216+1107 ?, Fig. 2, K96	—
0219+428 3C 66A	93.9 – 94.2	E2m, Mu97, K96	—
0234+285	91.9 – 95.5	E1, E2m, K96	—
0235+164	92.1 – 95.5	E1, E2, Mu97, K96	R93, Fig. 1
0336−019 CTA26	92.1 – 92.4	Mu97	—
0420−014	92.4 – 95.1	E1, E2, Mu97, K96	R93
0440−003 NRAO190	93.4 – 95.5	E2S, Mu97, K96	MG97
0446+112	93.3 – 95.5	E1, E2, Mu97, K96	—
0454−234	92.4 – 95.1	E1m, K96	—
0458−020	92.4 – 94.8	E1m, E2m, Mu97, K96	—
0528+134	91.8 – 96.1	E1, E2, Mu97, K96	R93, P95, P96
0716+714	92.1 – 95.0	E1, E2, Mu97, K96	R93
0735+178	92.8 – 95.0	E2, Mu97	—
0738+549	93.6 – 95.1	2EG J0744+5438 ?, Fig. 3, K96	Fig. 4
0804+499	92.3 – 95.1	E1m, E2m, K96	—
0805−077	92.8 – 94.0	E2m	—
0827+243	92.8 – 95.1	E1, E2, Mu97, K96	—
0829+046	92.8 – 93.0	E1m, E2, Mu97, K96	—
0836+710	92.0 – 95.0	E1, E2, Mu97, K96	R93
0906+430 3C 216	92.7 – 95.2	K96	
0954+658	92.0 – 95.0	E2, Mu97, K96	—
1101+385 MKN 421	92.3 – 95.2	E1, E2, Mu97, K96	R93
1127−145	91.8 – 95.2	E2, Mu97, K96	—
1156+295 4C 29.45	93.3 – 95.1	E2, Mu97, K96	—
1219+285	93.0 – 95.1	E2S, Mu97, K96	—
1226+023 3C 273	91.2 – 95.2	E1, E2, Mu97, K96	R93, M97
1229−021	93.3 – 95.2	E1m, E2, Mu97, K96	—
1253−055 3C 279	91.8 – 95.6	E1, E2, Mu97, K96	R93, Fig. 5
1406−076	92.3 – 95.2	E1, E2, Mu97, K96	—
1510−089	91.9 – 95.2	E1, E2, Mu97, K96	—
1606+106	91.1 – 94.2	E1, E2, Mu97, K96	—
1611+343	91.1 – 95.1	E2, Mu97, K96	Fig. 6
1622−253	91.9 – 93.2	E1, E2, Mu97, K96	—
1622−297	91.9 – 95.6	Mu97	—
1633+382	91.8 – 95.1	E1, E2, Mu97, K96	—
1641+399 3C 345	90.9 – 95.2	—	—
1652+398 MKN 501	91.3 – 95.0	—	—
1730−130 NRAO530	91.9 – 95.6	E2, Mu97	—
1739+522	91.8 – 95.0	E2, Mu97, K96	—
1741−038	91.9 – 94.2	E1, K96	—
1823+018	91.8 – 92.1	K96	—
2200+420 BL LAC	92.3 – 93.6	Mu97	—
2230+114 CTA102	92.3 – 95.6	E1, E2, Mu97, K96	R93
2251+158 3C 454.3	92.1 – 95.8	E1, E2, Mu97, K96	R93, A98
2356+196	92.5 – 95.5	E1m, E2, Mu97, K96	—

E1 = first EGRET catalogue, Fichtel et al. (1994), E1m = marginal detections
E2 = second EGRET catalogue, Thompson et al. (1995), E2m = marginal identification
E2S = supplement to the second EGRET catalogue, Thompson et al. (1996)
Mu97 = Mukherjee et al. (1997)
A98 = Aller et al. (1998)
K96 = Kanbach (1996)
M97 = von Montigny et al. (1997)
MG97 = McGlynn et al. (1997)
P95 = Pohl et al. (1995)
P96 = Pohl et al. (1996)
R93 = Reich et al. (1993, Paper I).

Table 3. Single measurements

Source name(s)	Epoch 19..	EGRET reference	S(2.695 GHz)	S(4.75 GHz)	S(10.45 GHz)
0115+027 3C 37	93.025	K96	0.89 ± 0.04	0.61 ± 0.02	0.51 ± 0.04
0430+290	93.271	K96	0.47 ± 0.03	0.50 ± 0.03	0.44 ± 0.03
0917+449	92.500	E2, Mu97, K96	1.21 ± 0.08	1.32 ± 0.07	1.74 ± 0.12
0954+556	93.331	E2, Mu97, K96	2.43 ± 0.27	1.95 ± 0.13	1.45 ± 0.13
1222+216	93.027	E2, Mu97, K96	1.36 ± 0.05	1.13 ± 0.04	1.73 ± 0.09
2022−077	93.944	E2, K96	0.95 ± 0.03	—	0.70 ± 0.10

The EGRET references are as for Table 1.

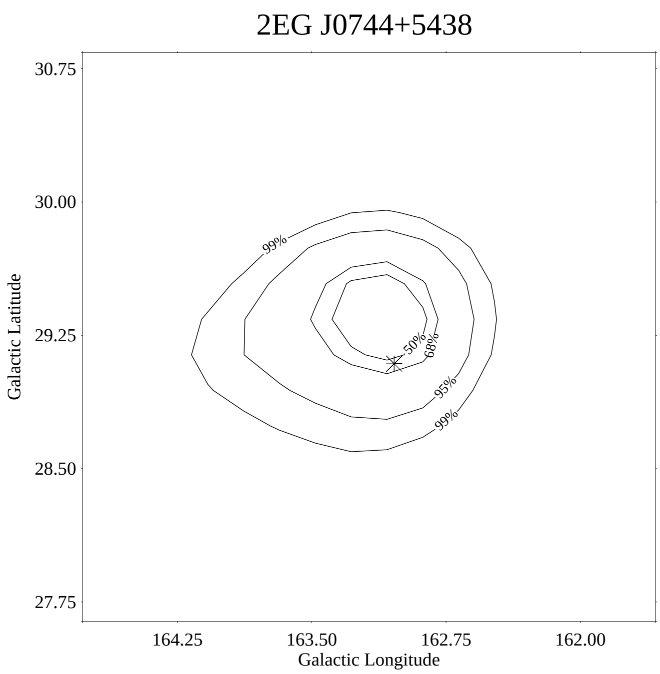

Fig. 3. Proposed identification of 0738+545 (marked by a star) with the γ-ray source 2EG J0744+5438. The contours represent the statistical probability that a single source lies within the given contour

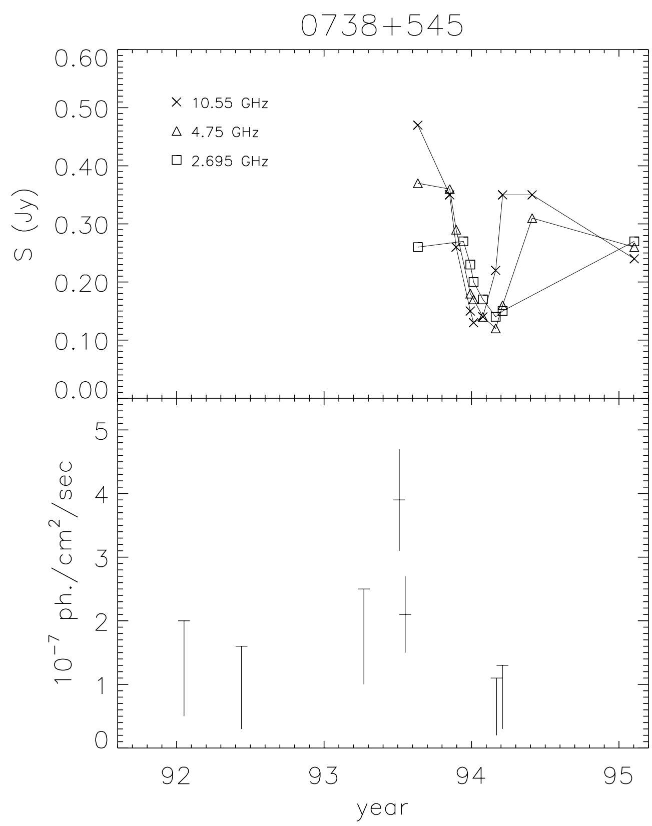

Fig. 4. Radio and γ-ray lightcurves for 0738+545. The radio source shows remarkable spectral changes on short time scales

and 2.15 Jy at 1.4 GHz, 2.695 GHz, 4.75 GHz, 10.55 GHz and 32 GHz, respectively. 3C 138 served as a secondary calibrator and its flux density was measured every few months in respect to 3C 286 because of its weak variability. Occasionally also NGC 7027, 3C 48 and 3C 295 have been used as secondary calibrators in respect to 3C 286. The data obtained at other frequencies than those listed have been calibrated by interpolation of the flux densities of 3C 286. The Effelsberg 100-m telescope has an angular resolution (HPBW) of 9.′4 at 1.4 GHz, 4.′3 at 2.695 GHz, 2.′4 at 4.75 GHz, 1.′15 at 10.55 GHz and 0.′45 at 32 GHz. The 1.4 GHz receiver (tunable up to 1.7 GHz) is installed in the primary focus of the telescope, while the 2.695 GHz, 4.75 GHz, 10.55 GHz and 32 GHz receivers are located in the secondary focus.

The occasionally used receivers at 2.3 GHz and 8.6 GHz are also installed in the secondary focus, while the maser receiver operating in the 22/23 GHz band, the 3.3 GHz and 30 GHz receivers are mounted in the prime focus. More details about the different receiving systems have been compiled by Schmidt & Zinz (1994).

The 4.75 GHz receiver has been replaced by a new 4.85 GHz receiving system in August 1995. A shift of the centre frequency from 10.55 GHz to 10.45 GHz was made in early 1995 due to severe interference caused by the TV-satellite ASTRA 1D.

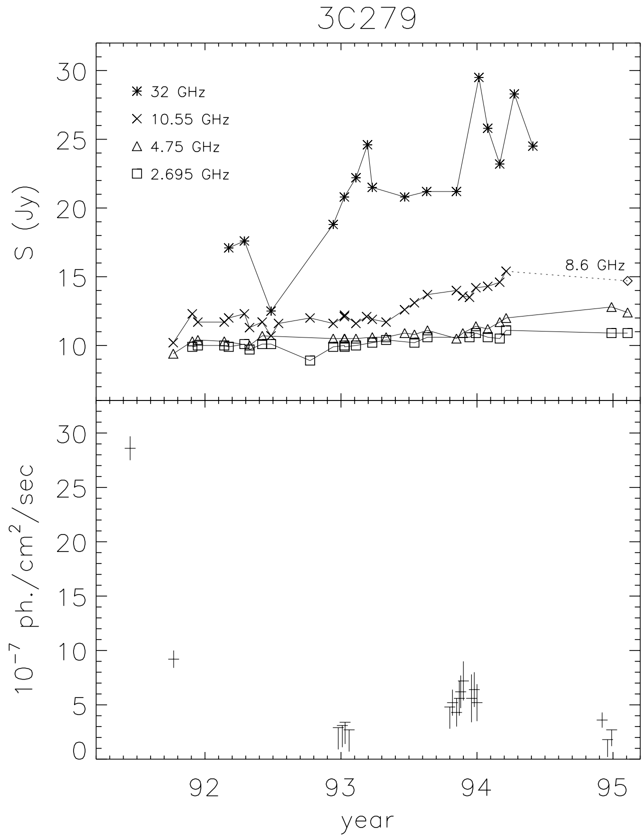

Fig. 5. Radio and γ-ray lightcurves for 3C 279

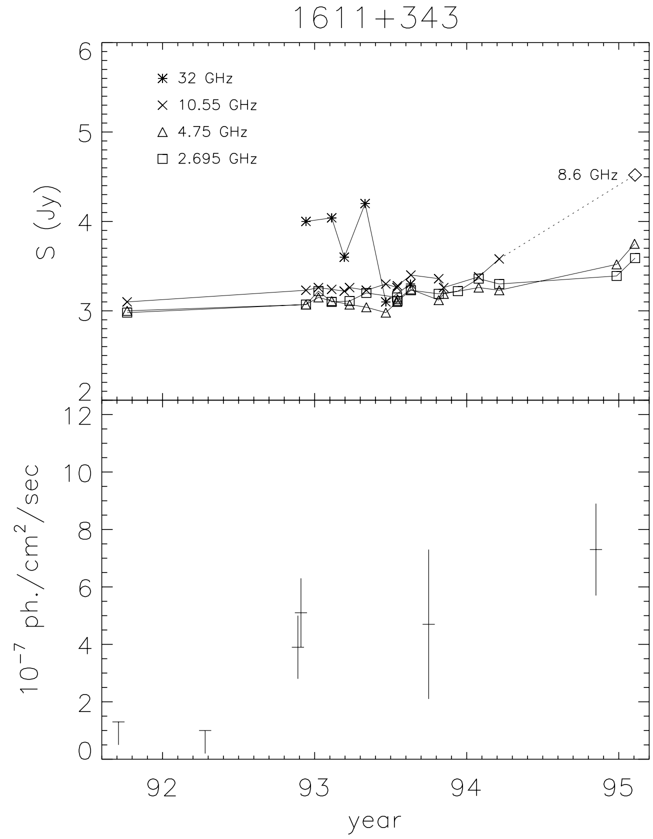

Fig. 6. Radio and γ-ray lightcurves for 1611+343

3. Results

3.1. Tabulated data

In Table 1 we have listed the sources monitored and the epoch of observations. Table 2 contains the peak flux densities and the calculated errors. Table 2 is available only in electronic form at the CDS, Strasbourg via anonymous ftp 130.79.128.5 or via http://cdsweb.u-strasbg.fr/Abstract.html.

In Table 2 we list the day of the observation, the frequency, peak flux density and error. The peak flux has been calculated from the Gaussian fit of the two orthogonal scans observed and is corrected for residual pointing errors of the telescope. The pointing corrected amplitudes are derived for each scanning direction independently and are averaged. The error includes uncertainties from the Gaussian fit parameters and the pointing results. The maximum error from both results is taken for the averaged amplitude. We convert the data into flux densities by using the mean of scaling factors found from all the observed calibrators during an observing session. We used the maximum and minimum of all these scaling factors and add the resulting flux density changes to the error. By this approach the resulting error includes a number of time dependent effects like changes in opacity, focal changes or gain variations of the antenna during an observing run. To take these effects into account is of particular importance when variability is under investigation. We note, however, that the errors resulting by our approach are systematically higher than those quoted from other flux density monitoring programs.

3.2. Comments on individual sources

Our sample includes two radio sources which have not been taken as identification for the respective γ-ray sources in the EGRET catalogues, but included in the list of Kanbach (1996). The association of 0738+549 with 2EG J0744+5438 has already been pointed out by Mukherjee et al. (1995). We also regard 0214+108 as a likely identification for 2EG J0216+1107. In Figs. 2 and 3 we show likelihood finemaps of both γ-ray sources (taken from Thompson et al. 1995) with the position of the radio source indicated. Both radio sources have also been listed as potential EGRET sources by Mattox et al. (1997) who used Bayesian statistics to evaluate the probability for a correct cross-identification of γ-ray and radio sources.

A few examples of radio and γ-ray light curves are shown for 0235+164 (Fig. 1), 0738+545 (Fig. 4), 3C 279 (Fig. 5) and 1611+343 (Fig. 6) in order to illustrate the rather different variability behaviour of sources in the sample. In general, the sampling of the γ-ray light curve is rather coarse if compared to the radio light curves and much short-term variability remains undetected. This needs to be taken into account when comparing the variability behaviour in both wavelength ranges.

We have added observations of MKN 501 in Table 1 which has not been identified as an EGRET source but has recently been seen at TeV γ-ray energies with the Whipple Cherenkov telescope (Quinn et al. 1996) or the HEGRA Cherenkov telescope (Bradbury et al. 1997). Also data for 3C 345 are included, since its strength in flux density and its high variability make it a potential γ-ray source candidate.

3.3. Single radio measurements

In Table 3 we list flux densities for six sources which have been observed once. Most of the data are from a program to observe quasi simultaneously the spectra of radio sources with soft X-rays counterparts as revealed by ROSAT (Reich et al., in preparation). We note that most of the sources listed in Table 1 are visible in the ROSAT all-sky survey.

4. Conclusion

We have observed flux densities of 53 extragalactic radio sources with the Effelsberg 100-m telescope in the frequency range from 1.4 GHz to 32 GHz around the time of detection by EGRET on board CGRO and afterwards until the end of 1995 or the beginning of 1996. Nearly 2500 individual measurements have been made. The results are available in electronic form.

The radio database will be helpful to clarify the relation of the γ-ray variability to the radio variability. First studies by Mücke et al. (1996, 1997) indicate that the correlation of the light curves is rather complex and a statistical analysis needs to take into account the coarse sampling and limited dynamic range of the EGRET data.

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