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The radio state of extragalactic γ-ray sources detected by CGRO

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Abstract. Based on measurements by EGRET on board CGRO high energy γ-ray emission (> 50 MeV) from 14 extragalactic sources has been reported since its launch in April 1991 until July 1992. All these sources are radio loud, have a compact core, are highly variable and a large fraction of them shows superluminal expansion. We present the results of radio observations in 1991 and in 1992 for sources accessible to the Effelsberg 100-m and the IRAM 30-m telescopes and compare the present state with previous light curves. As a main result we note for most sources enhanced radio emission with a delay up to several months relative to the EGRET detection when they are most likely at a high level of activity in the γ-ray range. Exceptions from this rule are the strongest radio sources in the sample, 3C273 and 3C279, with atypical characteristics. Our results constrain current models of γ-ray emission processes in AGN.

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

1. Introduction

Observations with the Energetic Gamma Ray Experiment Telescope (EGRET, Kanbach et al. 1988) on board the Compton Gamma Ray Observatory (CGRO) have resulted in the discovery of 14 prominent extragalactic radio sources as powerful γ-ray sources (as in July 1992). Before the launch of CGRO only the quasar 3C273 has been known as an extragalactic source of > 100 MeV γ-radiation as observed by COS B. In Table 1 we list some characteristic data of the newly detected sources with the dates of CGRO detection. Details of the detected γ-ray emission have been listed by Fichtel et al. (1993). Three of the sources detected by EGRET have also been detected at energies between 1 MeV and 30 MeV by the COMPTEL instrument on CGRO: 3C273, 3C279 and 0528+134 (Collmar et al. 1993; Hermsen et al. 1993). All sources show signs of significant variability in the radio range and we have given some references of monitoring data in Table 1.

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The purpose of this paper is to describe the actual radio state of the CGRO detected sources, which is based on observations with the Effelsberg 100-m telescope and the IRAM 30-m telescope covering about two decades in frequency of the cm and mm wavelength range. We present the light curves and some spectra of the 12 sources accessible to both telescopes in 1991 and 1992 and compare our observations with their previously observed variability behaviour. Some implications of our results for current models of γ-radiation processes in these sources are discussed.

2. Observations

When it became apparent in summer 1991 that strong flat spectrum variable radio sources are counterparts of extragalactic CGRO sources, multifrequency radio observations with the Effelsberg 100-m telescope have been started in parallel to the CGRO all-sky survey. All flat spectrum, variable sources stronger than 1 Jy at 6 cm wavelength in the 50° field of view of EGRET and COMPTEL have been observed quasi-simultaneously at 2.695 GHz, 4.75 GHz and 10.55 GHz. When the sky was clear enough 32 GHz observations have been made instead of or in addition to the 4.75 GHz observations.

By our selection criterion it was possible to observe the radio emission of most of the sources at the time of CGRO detection. These sources have been subsequently monitored at short time intervals. A complete description and the results of this still running observing program of flat spectrum sources will be given elsewhere. Here we present the results for the CGRO detected sources. Some additional flux density data based on Effelsberg observations at different frequencies have been added from calibration observations in the course of VLBI programs. Flux densities at 43 GHz are from Krichbaum et al. (1993).

Observations at 90 GHz, 150 GHz and 230 GHz of CGRO detected sources have been made with the IRAM 30-m telescope. A detailed description of the observations will be given in a separate paper (Steppe et al., in prep.). A large number of extragalactic variable sources is routinely monitored with that telescope and previous results have been presented by Steppe et al. (1988, 1992).

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Table 1. AGN seen by EGRET until July 1992

Source	ID VLBI	m_v [mag]	z	CGRO Date	Ref	Radio Monitoring
0202+149 4C+15.05	Gal? AD	22.1	1.202?	92.14 - 92.18	1	9,10
0208−512	QSO	17.5	1.003	91.72 - 91.76	2	
0235+164	BL	19.5	0.94	92.14 - 92.18	1	9,10,11,12,13
0420−014	QSO CH	17.8	0.915	92.14 - 92.18	1	9,10,11,12,13
0528+134	QSO AD	19.5	2.06	91.31 - 91.46	2	9
0537−441	BL	15.5	0.894	91.57 - 91.60	3	
0716+714	BL SL?	13.2		92.03 - 92.06	3	9,11,12,13
0836+710	QSO SL	16.5	2.17	92.03 - 92.06	4	12
1101+384 Mrk 421	BL SL	13.1	0.031	91.49 - 91.53	3	9,10
1226+023 3C273	QSO SL	12.8	0.158	91.46 - 91.49 91.84 - 91.88	5	9,10,11,12,13,14
1253−055 3C279	QSO SL	17.8	0.538	91.46 - 91.49 91.84 - 91.88	2,6,7	9,10,12,13
1633+382 4C38.41	QSO AD	18.0	1.814	91.70 - 91.72	2	9,10,12
2230+114 CTA102	QSO SL	17.5	1.037	92.06 - 92.10	8	9,10,12,13
2251+158 3C454.3	QSO SL	16.1	0.86	91.60 - 91.62 92.06 - 92.10 92.31 - 92.325 92.35 - 92.37	8	9,10,11,12,13

SL = superluminal motion detected, AD = asymmetric double, CH = core halo, ? = uncertain value

References: VLBI data see section 3; optical data: Wall & Peacock 1985, MNRAS, 216, 173; Hewitt & Burbridge 1987, ApJS, 63, 1; Stickel et al. 1991, ApJ, 374, 431 and Véron-Cetty & Véron 1991, in ESO Scientific Report No. 10; CGRO data: 1) Hartman et al.: 1992c, IAU Circ. 5519; 2) Kanbach et al.: 1992, IAU Circ. 5431; 3) Michelson et al.: 1992, IAU Circ. 5470; 4) Fichtel et al.: 1992, IAU Circ. 5460; 5) von Montigny et al.: 1993, A&AS in press; 6) Bertsch et al.: 1991, IAU Circ. 5311; 7) Hartman et al.: 1992b, ApJ, 385, L1; 8) Hartman et al.: 1992a, IAU Circ. 5477; Radio monitoring data: 9) Aller et al.: 1985, ApJS, 59, 513; 10) Teräsranta et al.: 1992, A&AS, 94, 121; 11) Waltmann et al.: 1991, ApJS, 77, 379; 12) Steppe et al.: 1988, A&AS, 75, 317; 13) Steppe et al.: 1992, A&AS, 96, 441; 14) Steppe: 1992, AA, 259, 61

At both telescopes observations are made by scanning a source in orthogonal directions (cross-scans). The two subscans observed in each direction have been averaged. Peak flux densities have been obtained by fitting a Gaussian to the observed data and correcting these fit results for possible pointing errors. All receivers used at the 100-m telescope are installed in the secondary focus allowing changes of the observing frequency within a few seconds. At 2.695 GHz a single horn is available. Depending on weather conditions, either a single or double horn has been used at 4.75 GHz. At 10.55 GHz the signals from two offset-horns at 3′ and 5′ projected distance from the main horn serve to correct for atmospheric emission. At 32 GHz one offset horn at 5′ distance was used. At all frequencies circularly polarized components are recorded. The flux density calibration is based on 3C286 as the main calibrator for the Effelsberg observations assuming 10.4 Jy, 7.5 Jy and 4.5 Jy at 2.695 GHz, 4.75 GHz and 10.55 GHz, respectively. 3C48, 3C138, 3C295 and NGC 7027 served as secondary calibrators. At 32 GHz 3C286 and NGC 7027 served as calibrators assuming 2.15 Jy and 5.73 Jy, respectively (Morsi & Reich 1986). The mm data from the 30-m IRAM telescopes have been calibrated by observing planets and some galactic sources with assumed parameters as listed by Steppe et al. (1988).

To make light curves and spectra clearer we show no error bars for the individual flux density measurements and have averaged a few data points observed at subsequent days. Errors

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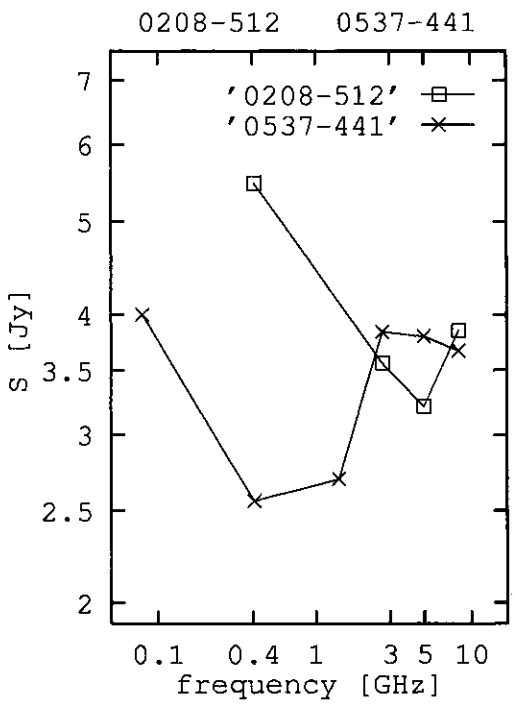

Fig. 1. Spectra based on flux densities from several epochs as listed in the PKSCAT90 database

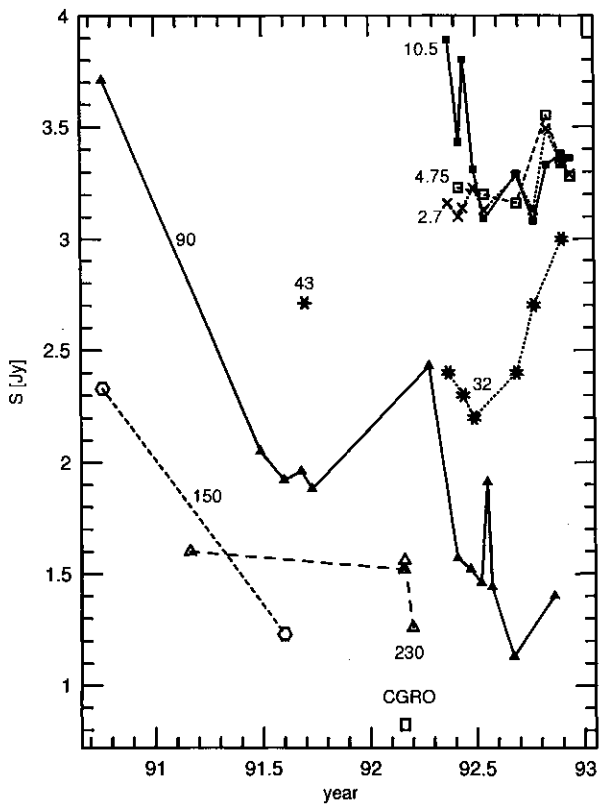

Fig. 2. Light curves of 0202+149 with indicated frequencies in GHz

for the Effelsberg flux densities in the frequency range up to 10.55 GHz and the IRAM data at 90 GHz are below 8% with very few exceptions. At 32 GHz, 150 GHz and 230 GHz flux density errors range from 10% to 20%. We used the same symbols to mark flux densities at a certain frequency for all light curves shown in the following. Spectra are plotted for some selected epochs. In cases where flux densities at a certain frequency have not been observed at the indicated epoch the data shown are obtained via interpolation. The time of CGRO detection and subsequent observations (as far as reported at the time of writing) are marked.

3. Individual sources

In the following we discuss each source in turn excluding the southern sources 0208−512 and 0537−441. We have plotted the spectra of 0208−512 and 0537−441 in Fig. 1 using the flux densities from PKSCAT90 southern sky radio source database. These data are from different observing epochs and therefore not comparable with the spectra shown in the following. Both sources show signs of variability and/or flat spectra above 2 GHz, and it is quite likely that their characteristics are rather similar to the majority of the northern 12 sources, for which more detailed observations are available. In fact Giacani & Colomb (1988) have observed a flux density increase for 0537−441 from about 3.2 Jy up to 4.6 Jy at 1410 MHz in the period May 1985 to January 1987.

3.1. 0202+149 = 4C+15.05

VLBI observations at 1.7 GHz have been reported by Padrielli et al. (1986) in the course of their study of low frequency variable sources. An asymmetric double source is seen with about 3 milli - arc second separation.

The light curves of 0202+149 at different frequencies are shown in Fig. 2. At all frequencies the emission of the source declines from the end of 1990 until mid - 1991. At the time of the CGRO detection (see Table 1) 230 GHz observations have been made. A 90 GHz observation at epoch 92.28, about 5 weeks later, shows increased emission. The highest absolute flux density is at 10.55 GHz, about 2.5 months later, and a subsequent decline in intensity is seen at 10.55 GHz, 32 GHz and 90 GHz after 92.37.

The flux density monitoring of Aller et al. (1985) shows a basically flat spectrum between 4.8 GHz and 8 GHz and an intensity decrease towards 14.5 GHz. The source varies slowly between 2.5 Jy and 3.5 Jy at 4.8 GHz and 8 GHz and between 2 Jy and 3 Jy at 14.5 GHz.

It is likely that 0202+149 exhibits a small outburst close to or just after the CGRO detection in the frequency range between 10 GHz and 90 GHz. However, our data are not sampled closely enough to fix that point.

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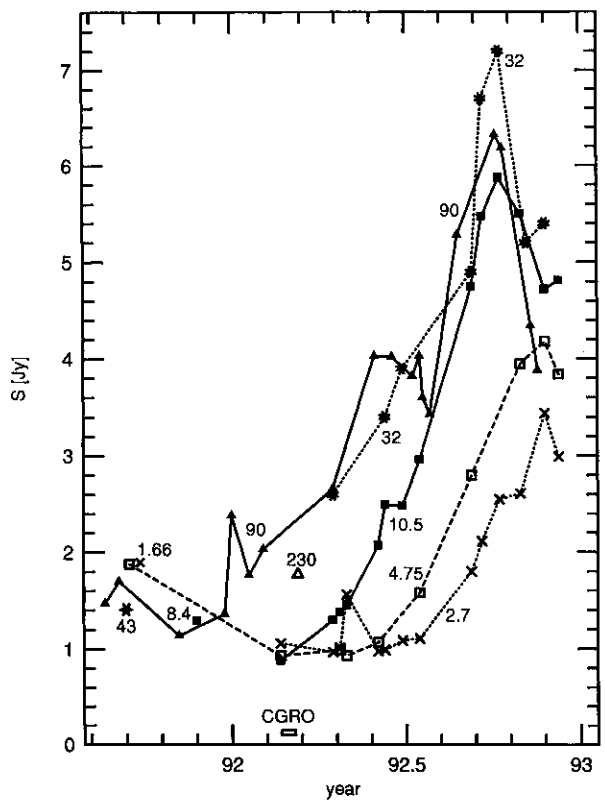

Fig. 3a. Light curves of 0235+164

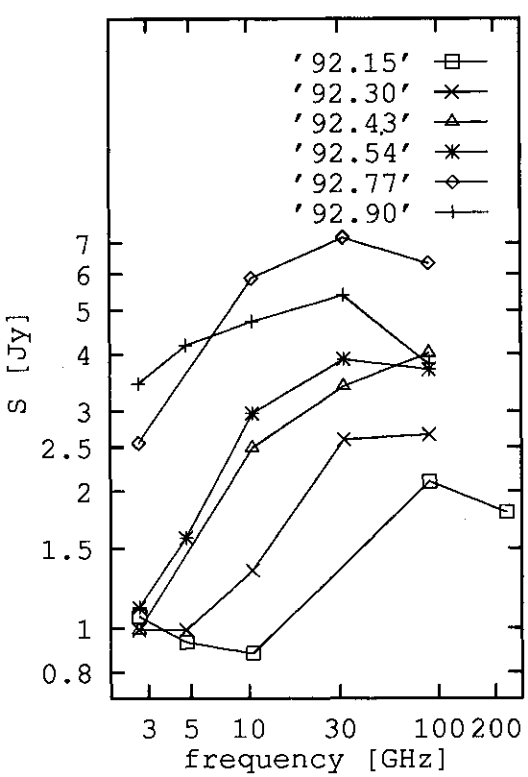

Fig. 3b. Spectra of 0235+164 at different epochs

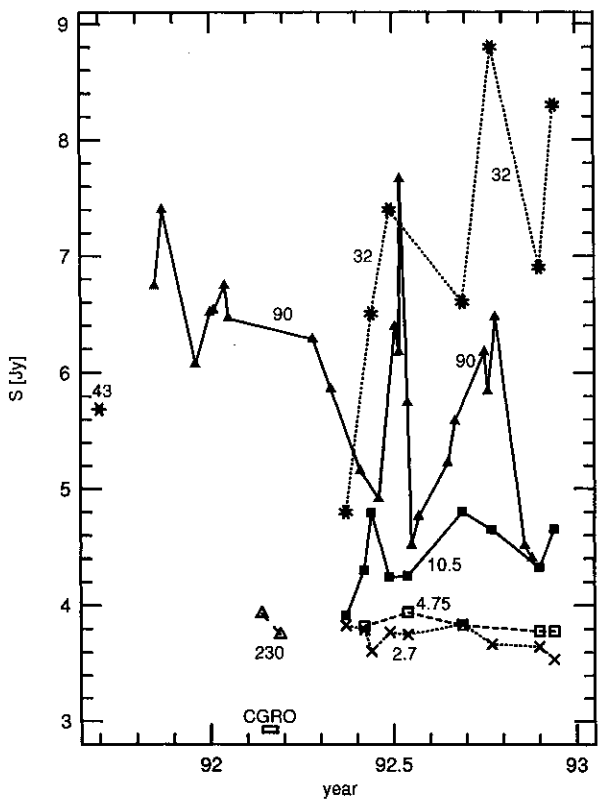

Fig. 4. Light curves of 0420-014

3.2. 0235+164

Gabuzda et al. (1989) have discussed this unusual BL Lac type object in some detail. Their own and previous VLBI observations have revealed a compact core and some evidence for faint extended extensions. Quirrenbach et al. (1992) have reported on intraday variability of 0235+164.

Light curves and spectra are shown in Fig. 3. At the end of 1991 a flare starts as visible in the 90 GHz data, which evolves with some delay at the lower frequencies. At about epoch 92.6 increased emission is noticed at all observed frequencies reaching in 92.77 an exceptionally high flux density level at 32 GHz. The evolution of the flare as a function of time is clearly seen from the spectra shown in Fig. 3b. The CGRO detection is at about three months after a radio minimum at 90 GHz.

0235+164 has been frequently monitored in the radio range before. Flares with a flux densitity increase from about 1 Jy to 4 or 5 Jy occur every two to three years. The largest one of about 8 Jy at 14.5 GHz has been noted by Aller et al. (1985) in the end of 1975, which is of the same magnitude as the present flare.

3.3. 0420−014

Wehrle et al. (1991) describe the fine structure of this QSO as seen by VLBI observations as a tight core-halo source, which might be either a "naked core" or a source where a radiating straight jet lies extremely close to the line of sight. Based on

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these properties they predict the detection of superluminal motion.

At the time of CGRO detection the source was in a phase of decreasing radio emission but still at a quite high intensity level at 90 GHz as seen from the light curve shown in Fig. 4. The spectrum of the source is inverted between 2.7 GHz and 32 GHz. A rapid intensity increase at 32 GHz of about 60% is observed between 92.37 and 92.49, while at 90 GHz a similar increase is seen reaching a maximum at 92.51. This flare peaks roughly four months after the CGRO detection.

Aller et al. (1985) observed slow variations between 2 Jy and about 6 Jy in the frequency range 4.8 GHz to 14.5 GHz. During most of the time the source spectrum is inverted except for a slight steepening between 8 GHz and 14.5 GHz in phases where the flux density decreases. Teräsranta et al. (1992) note flux density variations between 4 Jy and 7.5 Jy at 22 GHz and 37 GHz, where the highest flux density values are at the same level as we see it in 92.5. These events are rare since Teräsranta et al. have noted such high flux densities only twice during ten years of monitoring. The 90 GHz data of Steppe et al. (1988, 1992) show no flux densities above 6 Jy which supports the view of a quite high activity of the source at that frequency in the period of CGRO detection.

3.4. 0528+134

Detailed analysis of the EGRET data by Hunter et al. (1993) show variability within the few weeks of observation listed in Table 1. VLBI observations by Charlot (1990) did barely resolve this source and its structure can be described as an asymmetric double.

We show the light curves and spectra of 0528+134 in Fig. 5. The source was at a low flux density level at the time of CGRO detection. Its emission increased by a factor of 3.5 in the following months at 90 GHz. In the frequency range 22.2 GHz, 32 GHz and 43 GHz it reached a slightly lower maximum in 92.5. At 10.5 GHz an increase of about 80% is observed from 91.77 to about 92.7. The spectra show the delay of the flare at lower frequencies as a function of time.

0528+134 has been monitored by Aller et al. (1985) at 4.8 GHz, 8 GHz and 14.5 GHz. The maximum flux density is at 8 GHz and varies slowly from about 1.5 Jy to 5 Jy.

3.5. 0716+714

No redshift measurements have so far been reported for this BL Lac object. Witzel et al. (1988) list the source as a possible superluminal source if its redshift exceeds z = 0.28. The source is known to show intraday variability at cm wavelengths of the order of a few percent (Quirrenbach et al. 1992).

The light curves for 0716+714 are shown in Fig. 6. At the time of CGRO detection the radio emission from the source is at a low level or a minimum between subsequent flares. Increased emission is seen in 92.5 and 92.65 at 90 GHz and in 92.7 at 10.5 GHz and 32 GHz.

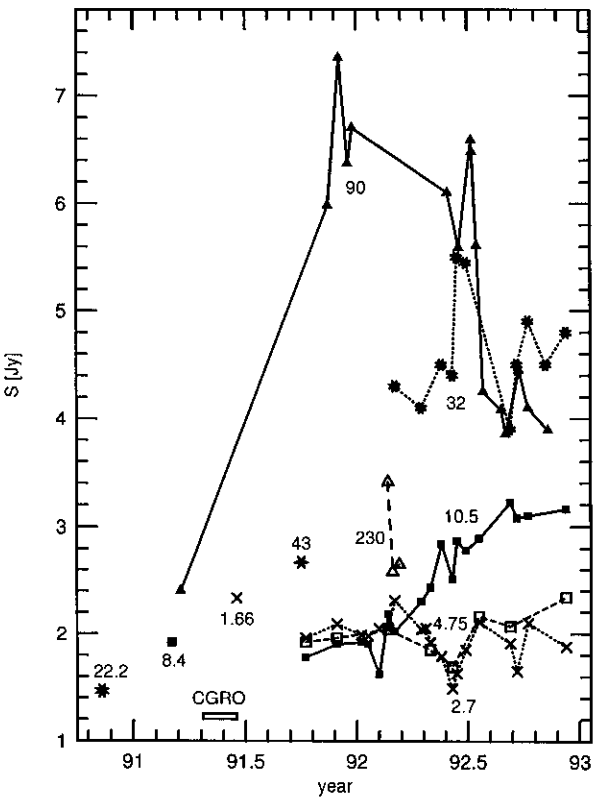

Fig. 5a. Light curves of 0528+134

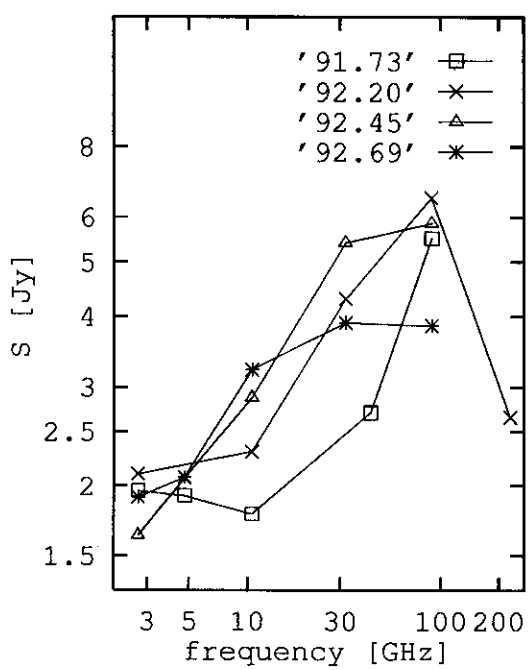

Fig. 5b. Spectra of 0528+134 at different epochs

Aller et al. (1985) have monitored the source, which always exhibits an inverted spectrum between 4.8 GHz and 14.5 GHz from 1981 to 1985. The level of emission was between 0.6 Jy at the lowest and about 1.6 Jy at the highest of their observing

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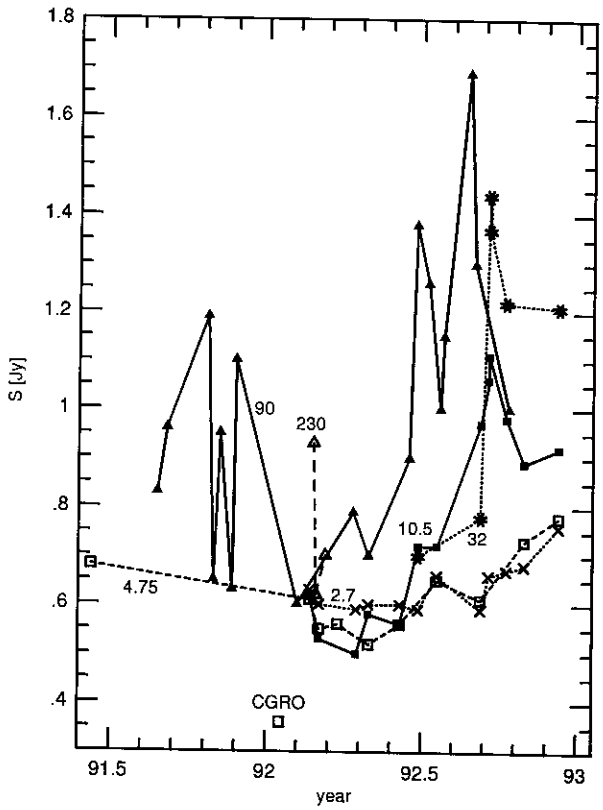

Fig. 6. Light curves of 0716+714

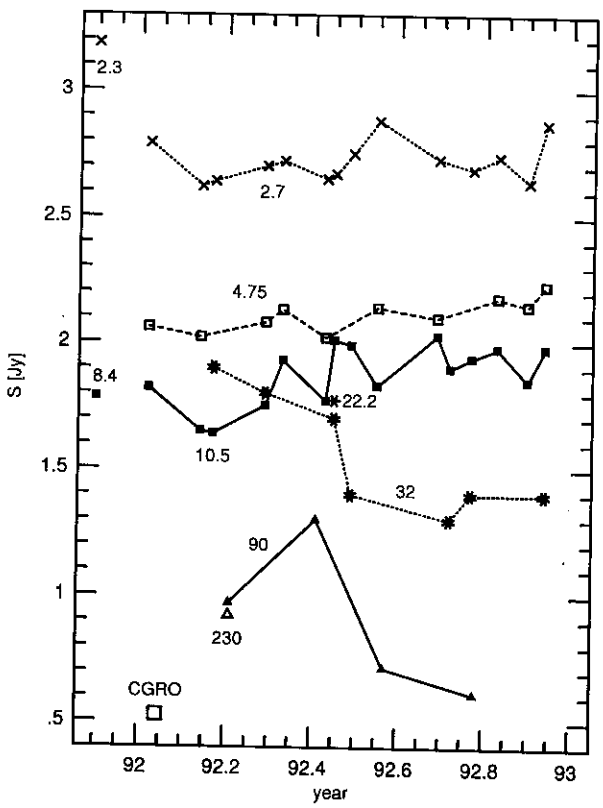

Fig. 7a. Light curves of 0836+710

frequencies. An always inverted spectrum was also observed by Waltman et al. (1991) between 2.7 GHz and 8 GHz with small variations on short time scales. Variations between 0.4 Jy and about 3 Jy at 90 GHz, 150 GHz and 230 GHz have been noted by Steppe et al. (1988, 1992) for the period 1985.9 to 1990.9. A minimum close to 0.4 Jy was seen in 1990.9. These monitoring data support the view that 0716+714 was at a rather low level of radio emission at the time of CGRO detection. The spectrum between 2.7 GHz and 10.5 GHz is flat or slightly steep till 92.4, which differs from its normal state as monitored before.

3.6. 0836+710

Witzel et al. (1988) and Krichbaum et al. (1990a) report on a superluminal motion of $v/c = 5.2 - 10.5$ for this source, which shows several components along its curved jet structure at milli - arc second angular resolution.

Figure 7 shows recent light curves and spectra of 0836+710. The overall spectrum is dominated by a steep spectrum component superposed by excess emission peaking around 30 GHz. It may be possible that a new outburst occured in early 1992 as indicated by the 90 GHz data and that the decrease at 32 GHz is attributed to an older event.

Steppe et al. (1988) observed flux densities between 0.3 Jy and 0.55 Jy in 1986 and 1987 at 230 GHz, while in 92.2 about 0.9 Jy have been observed, supporting the view of increased emission at this time. However, the number of millimeter observations is too limited to draw a firm conclusion.

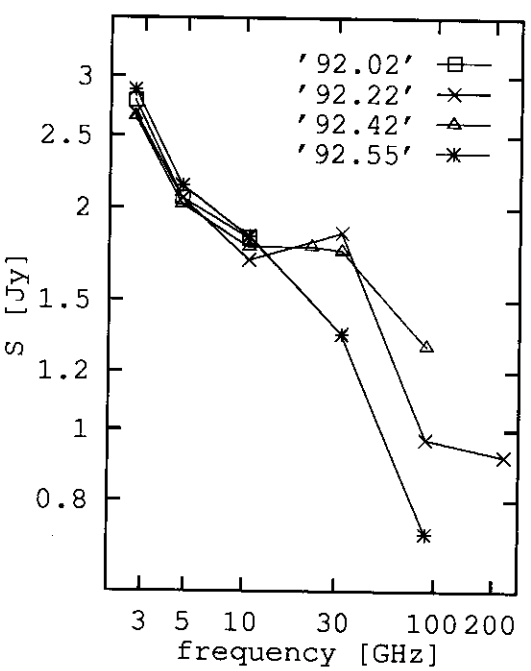

Fig. 7b. Spectra of 0836+710 at different epochs

An unusually strong outburst at optical wavelengths of 0.7 mag was observed by Schramm et al. (1992) in 92.13, which might be related to the increased mm emission in the spring of 1992.

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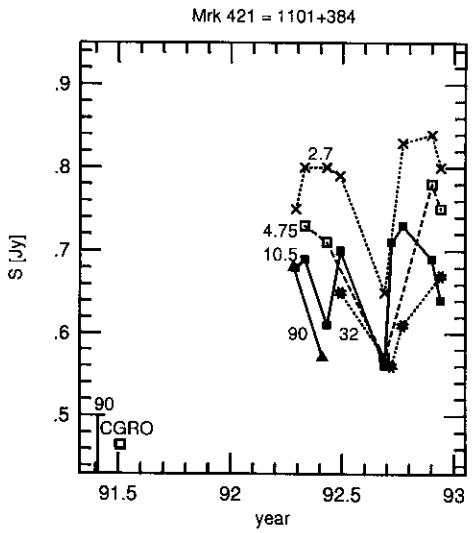

Fig. 8. Light curves of Mrk 421

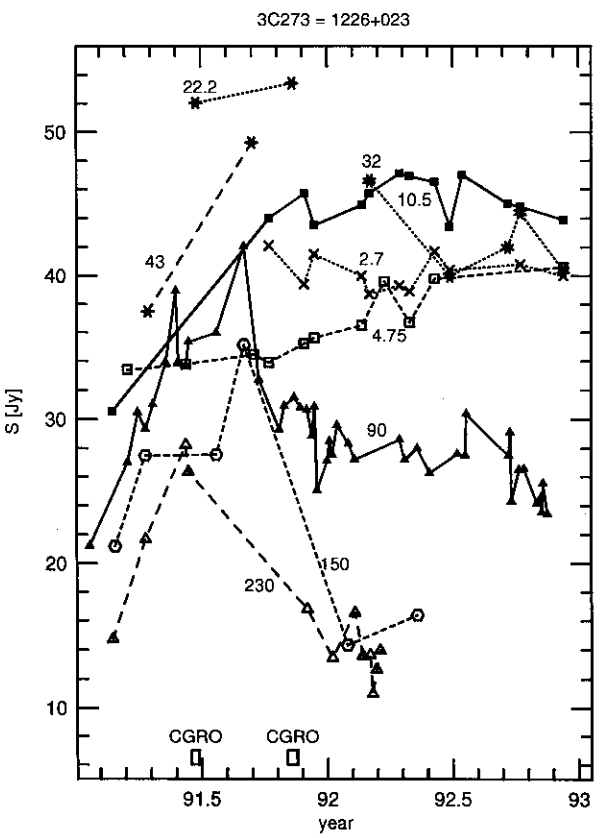

Fig. 9a. Light curves of 3C273

3.7. 1101+384 = Mrk 421

This BL Lac object is known to be highly variable at wavelengths ranging from radio to X-rays and its spectral properties have been studied in some detail (e.g. Warwick et al. 1986; Mufson et al. 1990). The source is located within an extended elliptical galaxy at a redshift of z = 0.031. Zhang and Bååth

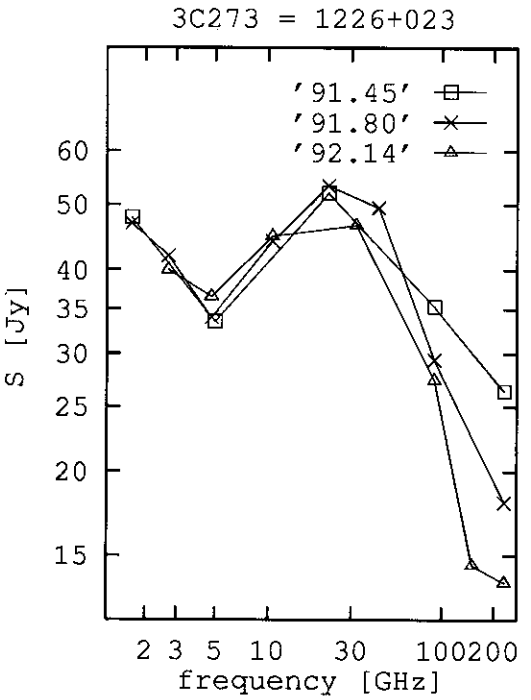

Fig. 9b. Spectra of 3C273 at different epochs

(1990) observed a superluminal motion for two components of Mrk 421 in the range $v/c = 1.36$ to 1.92.

Our observations are displayed in Fig. 8. The source is significantly weaker than most of the other CGRO detected radio sources. Unfortunately we have no radio data around the time of the CGRO detection from 91.5 until 92.25. Just before the CGRO detection a 90 GHz observation has been made yielding only an upper limit of about 0.5 Jy (3× r.m.s.-noise). The source is at 0.68 Jy at 90 GHz in 92.28, which again might indicate a delay of a radio flare with respect to the detected γ-ray emission. At that time and later the source has a slightly steep spectrum between 2.7 GHz and 10.5 GHz which considerably flattens towards 90 GHz.

Slow variations between 0.5 Jy and 0.8 Jy on time scales of one to three years have been observed by Aller et al. (1985). This is close to the level seen in our observations. Teräsranta et al. (1992) list three flux density observations at 22 GHz between 0.47 Jy and 0.8 Jy in 1989 and 1990 and 11 observations at 37 GHz (1986 to 1990) with flux densities between 0.36 Jy and 0.78 Jy. There is one exception in 1986.2 where only 0.15 Jy have been observed. Thus Mrk 421 may occasionally be at a rather low level as it is found by our 90 GHz observations close to the time of CGRO detection. It is of interest that an optical outburst of about 0.9 mag in 92.2 has been reported by Hurst (1992).

3.8. 1226+023 = 3C273

The quasar 3C273 is by far the strongest radio source in our sample. The new observations with EGRET (von Montigny et al. 1993) show that 3C273 has diminished in γ-ray intensity

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by about a factor of two since its detection by COS B (Swanenburg et al. 1978). Zensus (1990) has reviewed superluminal expansion measurements, which vary in the range $v/c = 5.1$ to 8.1.

3C273 has been exceptionally well studied at radio and other wavelengths. Light curves and some spectra are shown in Fig. 9. At the time of CGRO observations the source increased in intensity at all frequencies above 10.5 GHz. Data showing the intensity increase at 90 GHz, 150 GHz and 230 GHz until 91.3 have been published by Steppe (1992). The intensity decreases in the mm range after 91.7, while it remains nearly at the same level at longer wavelengths. The spectra show a steep spectrum component below 5 GHz and an excess emission peaking in the range of 30 GHz.

Waltman et al. (1991) found little variations (about 10%) at 2.7 GHz around 40 Jy during nine years of observations (1979 to 1988). This means that the low frequency steep spectrum component varies only slowly in time. Monitoring data by Aller et al. (1985) for nearly twenty years (1965 to 1985) show variations between 22 Jy and about 50 Jy at 14.5 GHz, while at 4.8 GHz and 8 GHz the variations are somewhat smaller. Teräsranta et al. (1992) report on variations between 22 Jy and 45 Jy at 22 GHz and 18 Jy to 50 Jy at 37 GHz with a few exceptions up to 58 Jy within ten years of monitoring (1980 to 1990). Our observed flux densities in this frequency range at or just after the CGRO detection are close to the maximum emission reported before. At 90 GHz flux densities as low as 8 Jy have been observed in 1986, since then a steady increase with considerable short time variations has been observed, as it has been summarized by Steppe (1992). These data combined with our light curve show a maximum of about 40 Jy in 91.3 and 91.7. A similar increase although at slightly lower level is noted at 150 GHz and 230 GHz.

In summary at the time of the observed low γ-ray flux density by EGRET in 1991 the radio emission in the mm range shows an exceptional maximum. Also at frequencies between 10 GHz and 43 GHz a high intensity level is reached at or after the CGRO observations.

3.9. 1253−055 = 3C279

Bertsch et al. (1991) and Hartman et al. (1992b) have reported the discovery of 3C279 by EGRET in June 1991 as a strong high-energy γ-ray source, which varied significantly in intensity during the two weeks period of observations (Kanbach et al. 1992). 3C279 must have increased in γ-ray intensity at least by a factor of 8 since 1982, because it was not seen by COS-B. This increase has also been noticed at radio and X-ray wavelengths (Makino et al. 1989, 1991). Kanbach et al. (1992) reported on repeated γ-ray observations in October 1991, where the flux density had decreased to about 20-30% of the maximum seen in June 1991.

VLBI observations have revealed superluminal expansion v/c = of 2.0 and 9.2, as listed by Zensus (1990).

Light curves and selected spectra are displayed in Fig. 10. Observations between 43 GHz and 230 GHz show an exceptionally high intensity level around epoch 91.3, if compared with previous monitoring data in this frequency range (Steppe et al.

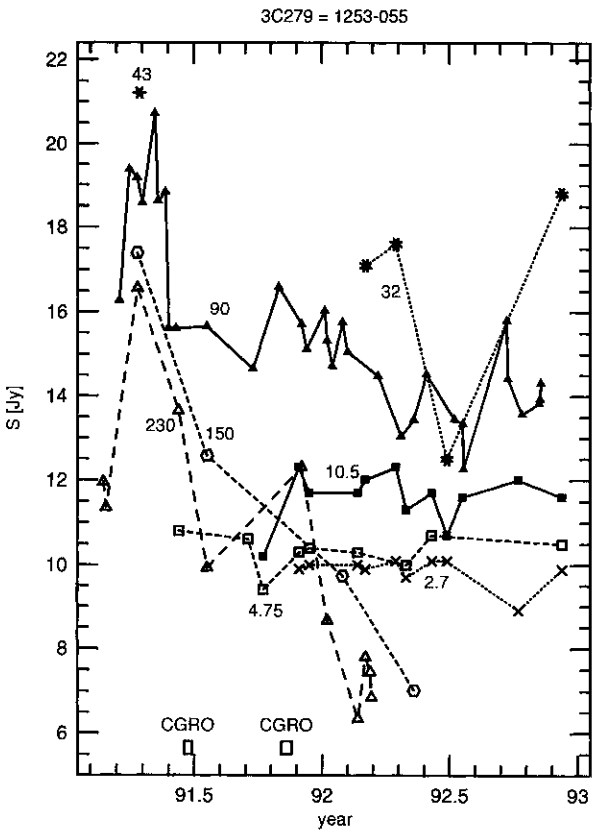

Fig. 10a. Light curves of 3C279

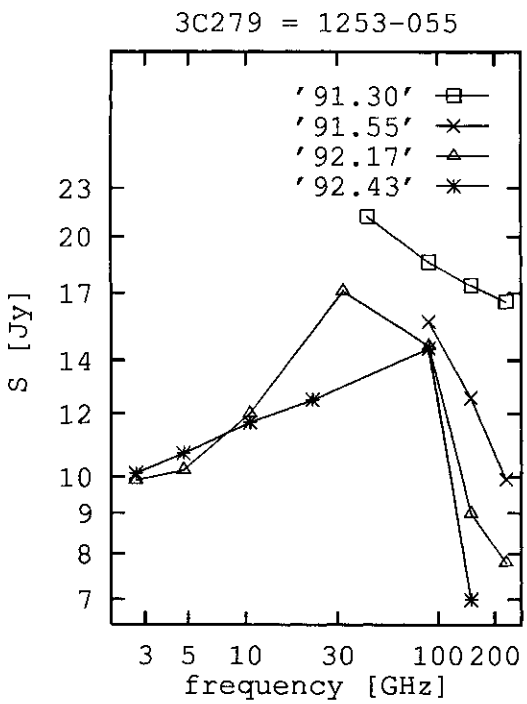

Fig. 10b. Spectra of 3C279 at different epochs

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1988, 1992; Teräsranta et al. 1992). This flare has dropped in intensity by about 20% at the time of CGRO observations in June 1991. The intensities at 90 GHz and above decline further with some fluctuation until mid - 1992. Nothing peculiar is noted at the time of the second CGRO observations in October 1991. The 32 GHz and 43 GHz data indicate that maximum emission is seen in this frequency range. Below these frequencies the spectrum is inverted with little variations during the period of observations.

The level of emission at frequencies of 10.5 GHz and below is relatively low if compared with the light curves of Aller et al. (1985) observed between 1965 and 1985. They record maximum flux densities of about 19 Jy at 8 GHz. Further monitoring will show if the excess emission at around 30 GHz reveals a delay at lower frequencies.

3.10. 1633+382 = 4C38.41

There have been a number of VLBI observations on 1633+382. Pearson & Readhead (1988) classified it as "asymmetric type II source": i.e. a well resolved, asymmetric object with a bright compact component at one end of an extended jet-like feature.

Light curves and spectra are shown in Fig. 11. At all frequencies the flux densities show little variation until 1992.3 or about 0.6 years after the detection by CGRO. From that time gradually increasing emission is seen at 32 GHz and 90 GHz. The spectra before 1992.3 are curved, steepening gradually with increasing frequencies.

1633+382 is known to show occasionally dramatic flares after longer periods with little activity as observed by Aller et al. (1985) and Teräsranta et al. (1992). Pauliny-Toth et al. (1973) have noted flux densities between 5 Jy and 6 Jy in the frequency interval from 8 GHz to 14.5 GHz in 1972 and 1973. Aller et al. (1985) observed maxima above 5 Jy at 8 GHz and 14.5 GHz in 1974 and above 4 Jy in 1982, while Teräsranta et al. (1992) measured maxima at about 3.5 Jy at 22 GHz and 37 GHz in the same period. In comparison to that the flare starting in 1992.3 seems weak.

3.11. 2230+114 = CTA 102

Bååth (1987) has found a superluminal motion of v/c = 18.5 for the quasar CTA 102.

Light curves and spectra are shown in Fig. 12. At the time of CGRO detection there might be a weak excess at 90 GHz, which declines until 92.5. The Effelsberg observations started with some delay after the CGRO observations, since CTA 102 was originally not selected for simultaneous observations with CGRO because of its dominating steep spectrum component of $\alpha \sim -0.4$ ($S \sim \nu^{\alpha}$). However, the spectra show some excess emission between 10.5 GHz and 90 GHz variing with time as it is characteristic for CGRO sources.

The level of the emission in the frequency range at and below 10.5 GHz is close to the minimum emission monitored by Aller et al. (1985). The source may flare up in this frequency range to a level of about 5 Jy. The 32 GHz flux densities decrease

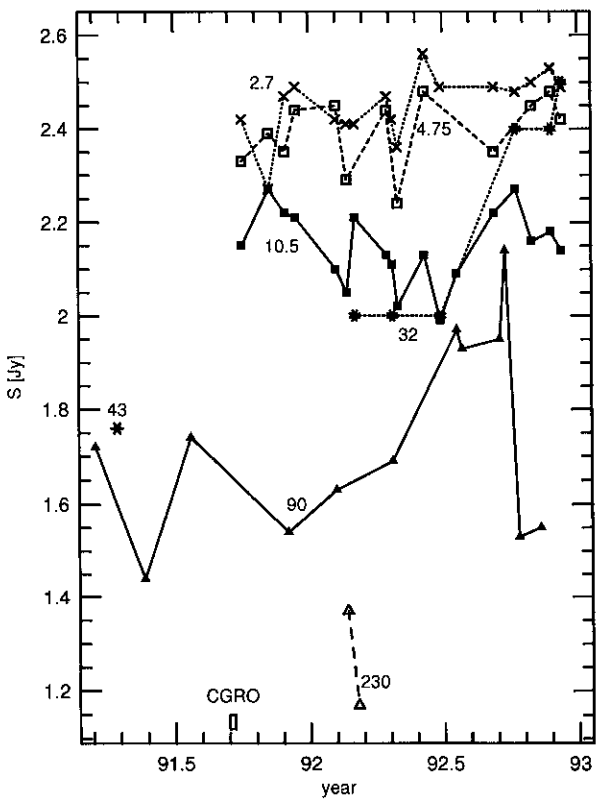

Fig. 11a. Light curves of 1633+382

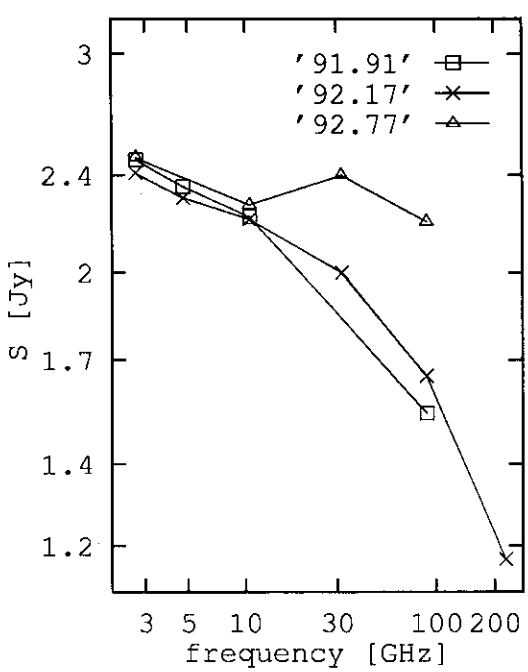

Fig. 11b. Spectra of 1633+382 at different epochs

from an enhanced level in 92.3 of about 3 Jy to the normally observed quiet level if compared with the Teräsranta et al. (1992) data. The maximum level of about 3 Jy at 90 GHz is, however, remarkable. Steppe et al. (1988, 1992) always observed flux

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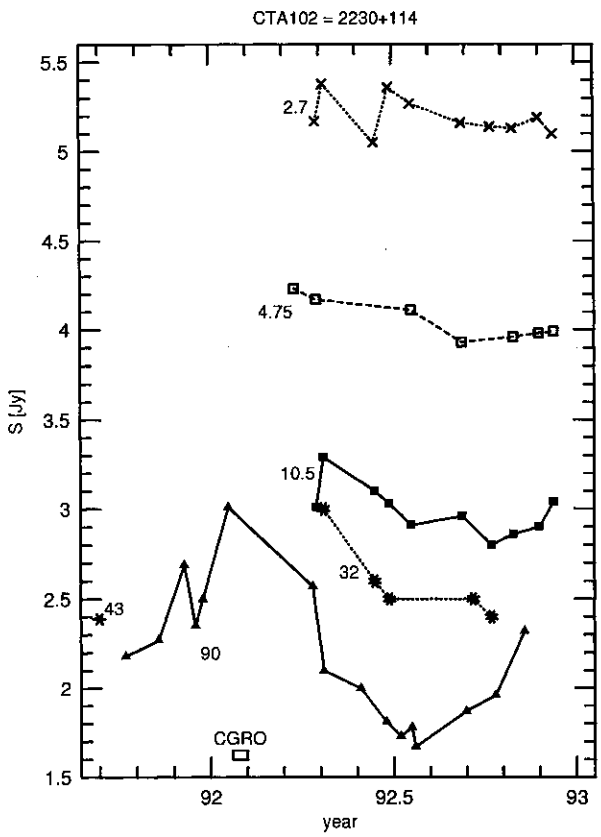

Fig. 12a. Light curves of CTA102

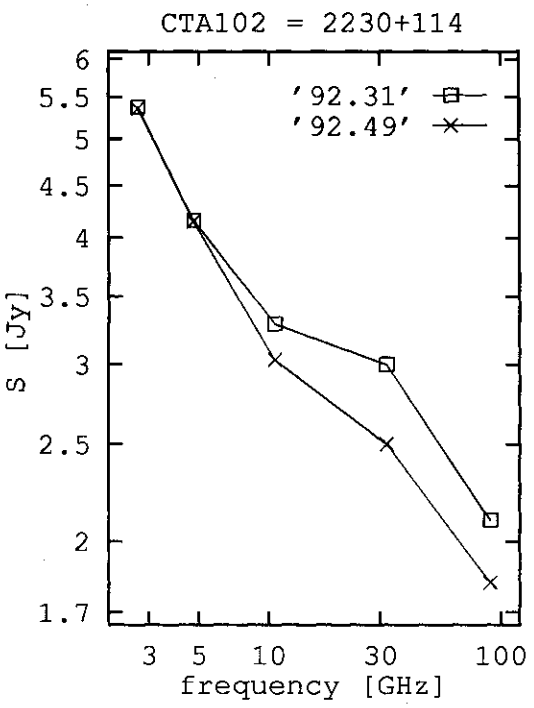

Fig. 12b. Spectra of CTA102 at different epochs

densities below that value with typical intensities between 1 Jy and 2 Jy. The only exception was in June 1990 where 3.7 Jy have been observed.

3.12. 2251+158 = 3C454.3

Pauliny-Toth et al. (1987) report on superluminal motions for the quasar 3C454.3 of $v/c < 1.3$ and 8.9.

Light curves and spectra are shown in Fig. 13. The CGRO detection in 92.06 to 92.10 (Hartman et al. 1992a) has been made close to the minimum of the 90 GHz flux density observations. At that time the highest γ-ray flux has been observed. The radio spectrum is entirely steep in the beginning of 1992. Since then flux densities have increased in the frequency range between 10.5 GHz and 90 GHz continuously until mid of 1992. At that time also an increased 4.75 GHz flux density is observed, while at 2.695 GHz the flux density remains constant within the quoted errors. The spectra show an excess emission component peaking at around 30 GHz.

The absolute level of emission of 3C454.3 is relatively low when compared with previous light curves. Aller et al. (1985) note variations between 8 Jy and 24 Jy in the frequency range 4.8 GHz to 14.5 GHz. Teräsranta et al. (1992) observed maxima of about 18 Jy and 16 Jy at 22 GHz and 37 GHz respectively, which are significantly higher than the 11 Jy we see at 32 GHz in mid of 1992. However, the 90 GHz data from mid - 1992 exceed with observed 10 Jy previous measured flux densities at that frequency by Steppe et al. (1988, 1992) by about 2 Jy. This indicates the onset of an exceptionally strong flare close or at the time of CGRO observations.

4. Global γ-ray source statistics

Although the incoming CGRO data are not yet fully analysed, it is significant that out of the present sample of extragalactic γ-ray sources :

(1) all extragalactic γ-ray sources are radio-loud, variable and have compact radio structure. Including the two southern sources nine are identified with quasars and four with BL Lacs (see Table 1);

(2) a few repeated observations exhibit γ-ray time variability from ≥ 2 days (3C279), over a few weeks (0528+134) or several months (3C279, 3C454.3) to several years (3C273). It is very likely that all γ-ray sources will subsequently show variability, although for none of them detailed light curves exist so far to give direct evidence for the relation of a γ-ray flare to a radio flare. We should point out that the number of radio sources stronger than about 1 Jy with properties similar to those actually detected by CGRO is about 10 times larger. Therefore we may assume that CGRO detected γ-ray emission for the majority of sources is seen close to their maximum emission and that any quiet emission is below the detection limit of EGRET,

(3) six of the sources (0836+710, Mrk 421, 3C273, 3C279, CTA 102, 3C454.3) exhibit superluminal motion components. 0716+714 is superluminal in addition if its unknown redshift exceeds z = 0.28. For four more (0202+149, 0420−014, 0538+134, 1633+382), because of their VLBI classification as

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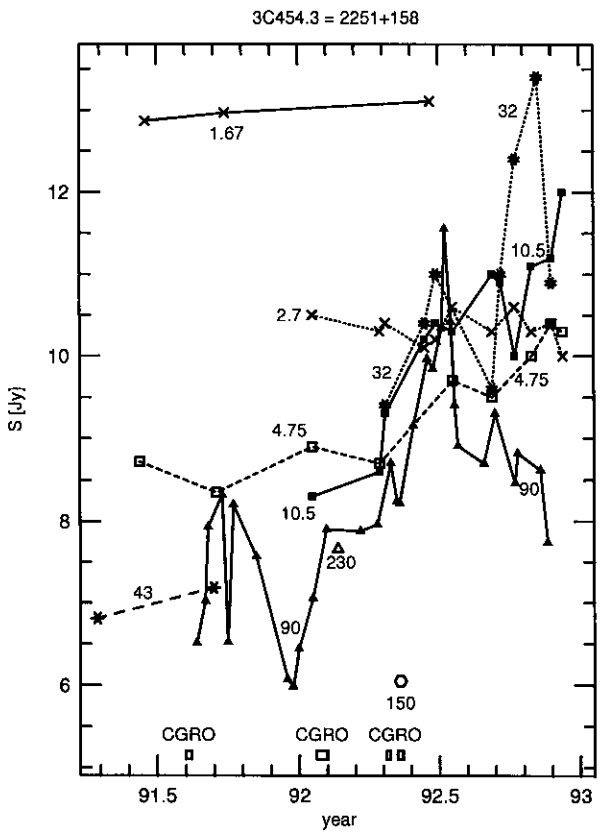

Fig. 13a. Light curves of 3C454.3

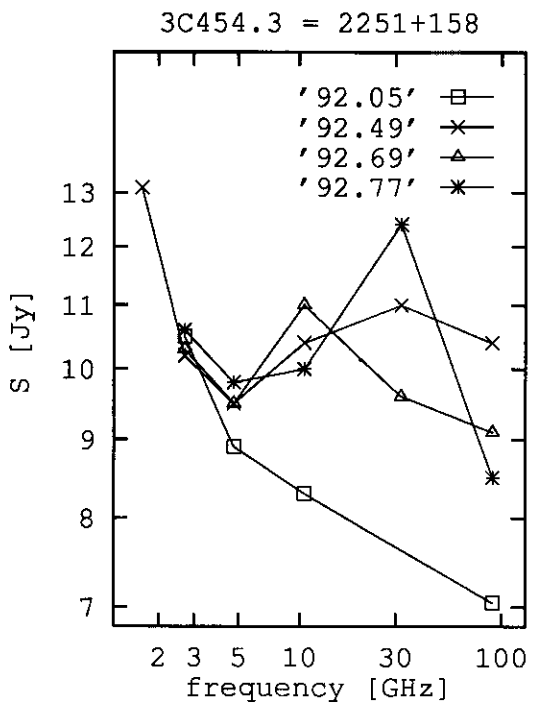

Fig. 13b. Spectra of 3C454.3 at different epochs

asymmetric or core-halo sources, superluminal motion might possibly be detected with sufficiently high angular resolution

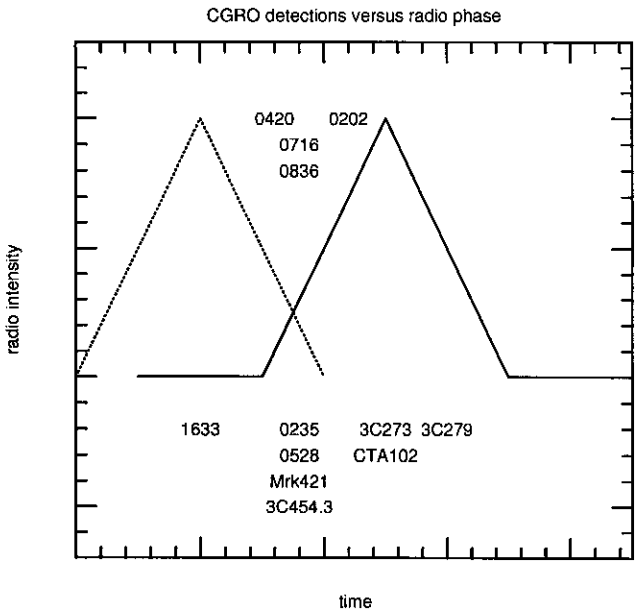

Fig. 14. Scheme of radio light curves where the abbreviated source names indicate the relative time of CGRO detection. Sources showing two subsequent radio flares (the first one shown dashed) are marked above the light curves

and dynamic range. Such a high percentage of superluminal sources in this sample is clearly remarkable;
(4) seven of the sources have been looked at for intraday variability at cm frequencies (Quirrenbach et al. 1992). Positive results have been reported for two sources (0235+164 and 0716+714) and negative results for five sources (0836+710, 3C273, 3C279, 1633+382, 3C454.3). This may indicate that intraday variability is not a typical characteristic of γ-ray sources, however, the data base for this type of observations is still very small.

5. Variability behaviour

From the light curves of the 12 sources studied we get the following:
(1) the two CGRO observations of 3C279 are made after a strong flare at mm wavelengths at declining or constant radio intensity;
(2) 0202+149, 3C273 and CTA 102 are observed by CGRO close to a maximum of high frequency radio emission, which subsequently declines;
(3) 0235+164, 0528+134 and 3C454.3 are at a low level when observed by CGRO and subsequently show a strong intensity increase. The same behaviour although more complex in detail describes the light curves of 0420−014, 0716+714, 0836+710 and Mrk 421 as discussed above. 1633+382 is at a normal level of emission until about 0.6 years after its CGRO detection and shows increasing emission afterwards.

We have summarized our results in a simplified form in Fig. 14 showing the time of γ-ray detection relative to one or two subsequent radio flares. For most sources a low or normal level of radio emission is observed at the time of γ-ray detection.

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We have argued above that the detected γ-ray emission is likely close to the maximum of a γ-ray flare. From the radio light curves of most of our sources we might then conclude that the possibly related radio flare develops in general with some time delay after the γ-ray flare. It is first visible at the highest frequencies and then moves towards lower frequencies possibly as a result of decreasing optical thickness. Some flare spectra (e.g. 0235+164, 0528+134) resemble at least qualitatively the evolution predicted by the shock model of Marscher & Gear (1985). A detailed comparison with that and similar models has to be worked out. Its seems remarkable in that context that the 150 GHz and 230 GHz intensities are always – with a possible exception for 0716+710 – below those at 90 GHz. This behaviour has also been noted by Chini et al. (1988) and Steppe & Salter (in prep.) when studying the spectra of a larger sample of sources.

3C273 and 3C279, which are the strongest sources in the sample, obviously do not fit within this scenario. Both sources show large variations in the γ-ray emission and it seems possible that the sensitivity of EGRET is high enough to detect them at nearly all stages of activity.

6. Implications for the γ-ray radiation processes

As noted above the majority of our sources display compact radio cores with a small fraction of extended emission. Although detailed VLBI studies have not yet been made for all of the CGRO detected sources, it seems very likely that out of the multitude of AGN, only those showing strong radio emission associated with radio jets directed towards us are strong γ-ray sources. This strongly suggests that the relativistic electrons which produce the radio emission in the jets are also responsible in some way for the γ-ray emission. The established delay and variability of the high frequency radio emission provides corroborative evidence for this suggestion, and argues against emission from the core.

According to the unified scenario (Blandford & Rees 1978; Scheuer & Readhead 1979; Barthel 1989) the appearance of galaxies and AGN strongly depends on the source orientation with respect to the observer. Only some 5% to 10% of optically-selected quasars are radio-loud. The properties of flat spectrum radio quasars (FSRQs; $\alpha \geq -0.5$ ($S \sim \nu^{\alpha}$)) and steep spectrum radio quasars (SSRQs; $\alpha < -0.5$) are markedly different (Kellerman & Pauliny-Toth 1981). FSRQs have higher optical polarization and more compact cores, whereas the SSRQs generally display more extended emission. FSRQs are more likely Optically Violent Variables (OVVs), showing dramatic optical variability within a few days and a highly polarized continuum. Moreover, unlike SSRQs, FSRQs often show superluminal motion (Pearson et al. 1987) which is also commonly seen from BL Lac objects (Mutel 1990).

The Blazar category unites compact radio sources having continuum characteristics common to the OVVs and BL Lac Objects, including superluminal motion. Blazars must therefore be those extragalactic radio sources which have jets closely aligned along the observing direction. Sources whose jet axes are inclined at larger angles to us appear as SSRQs or radio galaxies. The relativistic beaming of the emission, which amplifies the radiation intensity by orders of magnitude, complicates the relationships among the different types of sources. It is remarkable that AGN reported as sources of > 50 MeV energies are associated overwhelmingly with Blazar-type radio sources. For instance, EGRET has failed so far to detect the prominent Seyfert galaxies NGC 4151 and NGC 1275 (3C84), though both were pointing targets. Krichbaum et al. (1992) noted subluminal motion for the components of NGC 1275, so that there is no evidence for any beaming effect.

The 14 extragalactic sources detected by EGRET are clearly associated with the class of compact core, flat-spectrum radio sources, in particular, those showing evidence for superluminal motion. The delay between flaring in both frequency regimes place restrictions on models of γ-ray emission in radio jets. This implies that the high energy γ-rays originate from strongly beamed sources also alleviating the energetics problem (Dermer & Schlickeiser 1992). Thus it appears that quasi-isotropic models involving, for example, two-temperature accretion disks (Eilek & Kafatos 1983) or quasi-spherical neutron outflow (Giovanoni & Kazanas 1990), will have a difficult task in accounting for the EGRET observations. Models with γ-ray production in the jets seem required.

One of the earliest models proposed for the 100 MeV emission from 3C 273 involved pion production from collisions of protons with matter in the intergalactic gas near the outer lobes of the radio jet (Morrison et al. 1984). The reported rapid variability of the γ-ray emission requires an emission site less than about a light-week away from the central black hole, although there could be more slowly varying emission produced at greater distances in the jets of the γ-ray AGN. Secondary pion production could occur near the base of the jet if there is an ambient plasma outflow with which the high energy protons and ions can interact. But such a spectrum would be expected to exhibit a feature near 70 MeV being blueshifted to higher energies by the relativistic motion of the jet. No such feature is observed in the spectra published so far.

Synchrotron - self Compton models for the γ – radiation from extragalactic radio sources have also been proposed (Marscher 1980; Königl 1981; Maraschi et al. 1992). Here the same electrons that produce the radio emission rescatter these low energy photons to higher energies through the inverse Compton process. Such emission is inevitable, however the observed power-law γ-ray spectra are difficult to model with this process, since rather curved comptonized synchrotron spectra are obtained unless the electron spectrum is a power law over a large energy range. The simplest version of this model also predicts that radio flares should accompany γ-ray flares, which is generally not in accord with the observations presented here.

In the model of Dermer et al. (1992) electrons are accelerated to high energies near the base of the radio jet in the vicinity of the supermassive black hole, in accord with the variability on scales of a few days of some γ-ray flares. Low-energy photons radiated by the accretion disk surrounding the supermassive black hole

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enter the jet almost directly from behind and will be upscattered to high energies with the remarkable property that most of the γ-ray intensity is emitted in a hollow cone around the jet axis, a characteristic that favors detection of superluminal sources and may explain the prevalence of this class of sources among the γ-ray AGN. At larger distances from the accretion disk the number density of accretion disk photons becomes too small for this process, and the synchrotron - self Compton mechanism takes over. Since the nonthermal electrons significantly cool in both interactions, the time evolution of the flaring from high to low radio frequencies can easily be accounted for. VLBI studies will be of interest to identify outburst - related new components emitted from the core already found for 3C273 (Krichbaum et al. 1990b).

7. Conclusion

(1) We have observed the radio light curves of twelve γ-ray emitting extragalactic radio sources for a wide frequency range around the time of detection by EGRET on board CGRO.
(2) Excluding the strongest radio sources in our sample, 3C273 and 3C279, which are possibly detectable by EGRET at most stages of activity, we find for most sources a delay of the radio flare to the γ-ray detection by up to a few months. γ-ray detections likely correspond statistically to a temporal peak in the γ-ray emission of the source. At radio wavelengths the excess emission is strongest between 10 GHz and 90 GHz and evolution effects at lower frequencies are visible.
(3) The prevalence of superluminal sources with a compact core in the sample of CGRO detected extragalactic γ-ray sources agrees well with emission models which explain the γ-ray emission as the result of inverse Compton scattering of UV photons from the accretion disk by energetic electrons in the relativistic jet of the AGN. The beaming effects in such a scenario are most operative for viewing angles which are also favourable for superluminal motion, and thus provide a natural selection effect favouring superluminal sources. They also alleviate the energy requirements.

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