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Optical photometric monitoring of γ-ray loud blazars*

II. Observations from November 1995 to June 1996

C.M. Raiteri[1], **G. Ghisellini**[2], **M. Villata**[1], **G. De Francesco**[1], **L. Lanteri**[1], **M. Chiaberge**[3], **A. Peila**[3], **and G. Antico**[1]

[1] Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025 Pino Torinese (TO), Italy
[2] Osservatorio Astronomico di Brera, Via Bianchi 46, I-22055 Merate, Italy
[3] Istituto di Fisica Generale dell'Università, Via Pietro Giuria 1, I-10125 Torino, Italy

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Abstract. New data from the optical monitoring of γ-ray loud blazars at the Torino Astronomical Observatory are presented. Observations have been taken in the Johnson's B, V, and Cousins' R bands with the 1.05 m REOSC telescope equipped with a 1242 × 1152 pixel CCD camera. Many of the 22 monitored sources presented here show noticeable magnitude variations. Periods corresponding to pointings of the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory (CGRO) satellite are indicated on the light curves. The comparison of our data with those taken by CGRO in the γ-ray band will contribute to better understand the mechanism of the γ-ray emission. We finally show intranight light curves of 3C 66A and OJ 287, where microvariability was detected.

Key words: galaxies: active — BL Lacertae objects: general — quasars: general

1. Introduction

The class of radio-loud active galactic nuclei (AGNs) called "blazars" includes BL Lacertae objects and quasars presenting a flat radio spectrum, rapid variability, high and variable polarization, high brightness temperature. Their extremely strong emission is probably due to a relativistic beaming effect, because of the small angle between the emitting jet and the line of sight (see e.g. the review paper by Urry & Padovani (1995)).

In order to shed light on the mechanisms that are responsible for the energy output, astronomers have recognized the importance of performing monitoring campaigns with a good time coverage and of collecting data simultaneously at various wavelengths, which often translates into big international collaborations. Correlations between emissions in different bands are a testing tool for theoretical models. In particular, the optical flux is expected to be correlated to the γ one, since relativistic electrons in the magnetized emitting plasma can produce optical photons by synchrotron and γ photons by inverse Compton scattering either on the same synchrotron photons (synchrotron self-Compton models) or on external soft photons.

Several blazars have now been observed at γ-ray wavelengths by the Compton Gamma Ray Observatory (CGRO), which showed how the γ emission can in many cases overcome that in the other bands. Moreover, often this emission was found to be strongly variable (von Montigny et al. 1995; Lin et al. 1996; Sreekumar et al. 1996).

With the principal aim of following the optical behaviour of the sources pointed by the Energetic Gamma Ray Experiment Telescope (EGRET) on board CGRO, a program of blazar monitoring was started at the Torino Observatory in November 1994. On some sources collaborations with other groups were set. The results of the first year observations are presented in Villata et al. (1997a), Massaro et al. (1996) about PKS 0422+00, Ghisellini et al. (1997) about S5 0716+71, Tosti et al. (1997a) about PKS 0735+17 and S2 0109+22, Tosti et al. (1997b) about ON 231, Tosti et al. (1997c) and Villata et al. (1997b) about S4 0954+65, Aller et al. (1997) about 3C 454.3; as for OJ 287, 3C 66A, and AO 0235+16, we joined the wide international collaboration named OJ-94 Project (e.g. Sillanpää et al. 1996a,b; Takalo et al. 1996, 1997; Villata et al. 1996).

Send offprint requests to: C.M. Raiteri (raiteri@to.astro.it)

* Tables 2–21 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

In this paper we present observations of 22 blazars of our monitoring list from November 1995 to June 1996. Data taken in the same period on S2 0109+22, PKS 0735+17, S4 0954+65, and ON 231 are presented in the aforecited papers, while those on S5 0716+71 and 3C 279 will be published in Wagner et al. (1997) and Pian et al. (1997), respectively. In Sect. 2 we briefly describe the instruments and data reduction and analysis procedure; light curves are presented in Sect. 3. Three cases of intranight variations are shown in Sect. 4. The main conclusions are drawn in Sect. 5.

2. Observations and data reduction

All observations were performed with the 1.05 m telescope of the Torino Astronomical Observatory. The instrument is equipped with a 1242×1152 pixel CCD camera with scale 0.47 arcsec per pixel. Data were reduced and analyzed with MIDAS and the Robin procedure locally developed. More information on the method can be found in Villata et al. (1996, 1997a). Observations were done in the Cousins' R and Johnson's V and B filters; weak sources were observed in the R band only. Exposure times ranged from 180 s in the R band for the brightest objects (Mkn 421, 3C 273) to 600 s for the faintest ones.

Magnitude calibration has been obtained through comparison with photometric sequences in the same frame of the source. In the cases where a photometric sequence is missing, the source magnitude has been normalized to the magnitude of one reference star in the same frame. In this way a comparison with data of other observers can easily be performed by measuring the same star. Finding charts are available upon request to the authors to make the identification of these stars possible.

3. Results

In the following figures only light curves in the R band (in general the best sampled ones) are shown. Pointing periods of the EGRET instrument on board CGRO are indicated by boxes. In some cases the data published in Villata et al. (1997a) relative to the first year monitoring are presented together with the new data in order to better describe the source behaviour. In other cases only the latest data are shown in the light curves to make the plot clearer. In any case, tables contain all observations made by our group in the R, V, and B bands from November 1994, together with indication of the minimum and maximum magnitudes registered and the number of frames taken in each band.

In subsets to the light curve figures an estimate of the measure accuracy is given by plotting the deviation from the mean magnitude difference between two reference stars. These deviations are also shown as error bars on the corresponding points of the light curve. However, lower limits on the error bars are set, taking also into account the brightness difference between the source and the reference stars: the nearer the brightness, the more reliable the error estimate given by the above deviation.

Table 1 contains the list of our sources, with indication of their name, right ascension, and declination. A brief outline of the observational material in the optical and γ bands available in the literature was already presented in Villata et al. (1997a), so that in this paper we quote the most recent papers only.

Table 1. List of the monitored blazars

Source	Name	RA (2000)	Dec. (2000)
0219+428	3C 66A	02 22 39.61	+43 02 07.8
0420−014	PKS 0420−01	04 23 15.80	−01 20 33.1
0422+004	PKS 0422+00	04 24 46.84	+00 36 06.3
0528+134	PKS 0528+134	05 30 56.42	+13 31 55.1
0805−077	PKS 0805−07	08 08 15.54	−07 51 09.9
0827+243	OJ 248	08 30 52.09	+24 10 59.8
0836+710	4C 71.07	08 41 24.37	+70 53 42.2
0851+202	OJ 287	08 54 48.87	+20 06 30.6
0906+430	3C 216	09 09 33.50	+42 53 46.1
1101+384	Mkn 421	11 04 27.31	+38 12 31.8
1156+295	4C 29.45	11 59 31.83	+29 14 43.8
1226+023	3C 273	12 29 06.70	+02 03 08.6
1229−021	4C −02.55	12 32 00.00	−02 24 05.8
1510−089	PKS 1510−08	15 12 50.53	−09 05 59.8
1611+343	DA 406	16 13 41.06	+34 12 47.9
1633+382	4C 38.41	16 35 15.49	+38 08 04.5
1641+399	3C 345	16 42 58.81	+39 48 37.0
1739+522	4C 51.37	17 40 36.98	+52 11 43.4
2230+114	CTA 102	22 32 36.41	+11 43 50.9
2251+158	3C 454.3	22 53 57.75	+16 08 53.6
2254+074	PKS 2254+074	22 57 17.30	+07 43 12.3
2356+196	PKS 2356+196	23 58 45.98	+19 55 18.6

3.1. PKS 0420−01

The quasar PKS 0420−01 was detected by EGRET, which revealed a variable γ-ray emission (Lin et al. 1996).

All our data on this source in the R, V, and B bands are shown in Table 2; in Fig. 1 the last-season light curve in the R band is presented. The R magnitudes are calculated by a provisional calibration; we can thus confirm the historical maximum on September 15, 1995 (Villata et al. 1997a), when the source reached $R = 14.15$. As for the V and B magnitudes, they are normalized to that of Star A of our reference stellar sequence.

This object continues to show an intense activity: after the fall of 2.63 mag in 40 days from the historical maximum, the brightness started to increase again up to

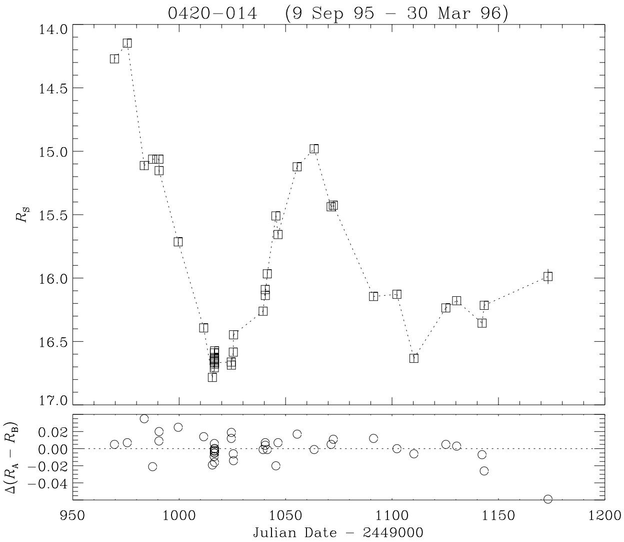

Fig. 1. Light curve of PKS 0420−01 in the R band

$R = 14.98$ on December 11, 1995 ($\overline{\mathrm{JD}} = \mathrm{JD}-2449000 = 1063$), which means a magnitude variation $\Delta R = 1.80$ in 48 days, with a steepest increase of 0.75 mag in 6 days ($\overline{\mathrm{JD}} = 1039-1045$). After a new drop, the source brightness oscillated around $R \sim 16-16.5$.

3.2. PKS 0422+00

The light curve in the R band of PKS 0422+00 is plotted in Fig. 2, showing the results of two observational seasons. The complete list of our data in the R, V, and B bands is given in Table 3. The choice of the photometric sequence for the source magnitude calibration is described in Massaro et al. (1996). Data from the first observational season have been already published in that paper as part of a national collaboration on this source. The new data confirm the pronounced oscillating behaviour of this

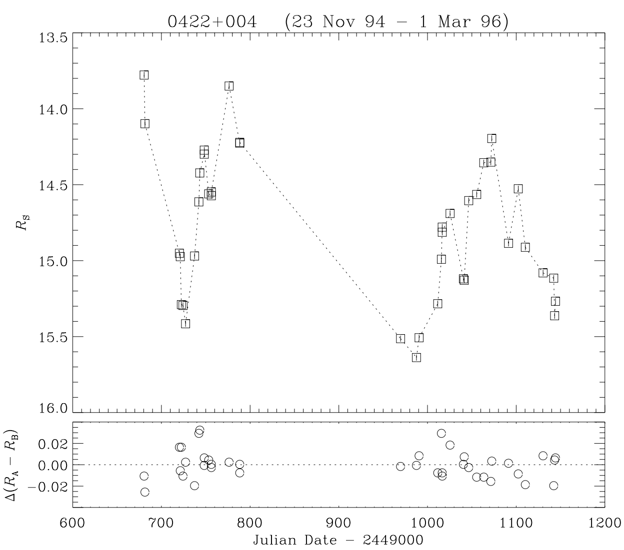

Fig. 2. Light curve of PKS 0422+00 in the R band

source, variations in the B band being wider than those in the R band. Massaro et al. (1996) have already shown that the spectral index appears to be related with the source brightness, the spectrum becoming flatter when the flux increases. In order to check this point with the new data added, colour indexes versus R magnitude are shown in Fig. 3: one can see that $B-R$ clearly decreases with increasing source brightness, even if this tendency is not so evident when looking at the $V-R$ versus R plot.

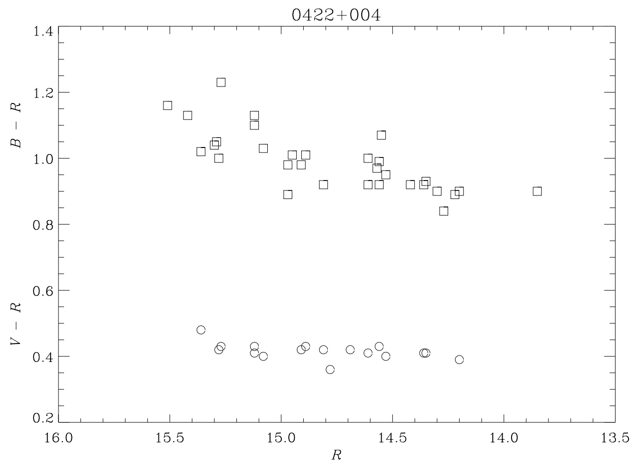

Fig. 3. Colour indexes of PKS 0422+00 versus R magnitude

3.3. PKS 0528+134

Because of its faintness, we observed PKS 0528+134 in the R band only; the corresponding last-season light curve is shown in Fig. 4, whereas the complete set of data is given in Table 4. The source magnitude is normalized to that of our reference Star A.

Small amplitude oscillations characterize the source luminosity behaviour; only at the end of the observational period we registered a brightness increase of 0.65 mag in 15 days.

3.4. PKS 0805−07

We made only four observations of PKS 0805−07, in the period around the EGRET pointing of January 2–16, 1996. The data, in the R band, are given in Table 5. Magnitudes are rescaled to that of Star B in our reference star sequence.

3.5. OJ 248 (0827+243)

The noticeable variability of OJ 248 has already been reported in Villata et al. (1997a), where calibration of the photometric sequence was also given; data from the new observational season show an even more intense activity.

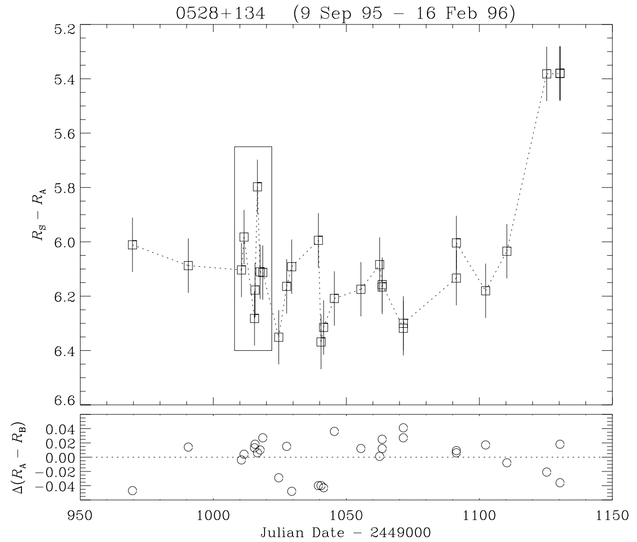

Fig. 4. Light curve of PKS 0528+134 in the R band; the box indicates the EGRET pointing period of October 17–31, 1995

As can be seen from the light curve in the R band plotted in Fig. 5 and tabulated in Table 6, the source brightness reached a maximum of $R = 15.60$ on November 18, 1995. As far as we know, this is the highest optical level ever registered for this source. A very steep brightness decrease followed the peak: a variation of 0.73 mag in about 20 hours was observed as part of a wider decrease of 1.43 mag in 16 days. Finally, another peak of $R = 16.25$ was reached, with a brightness rise of 0.85 mag in 19 days and a decrease of 0.99 mag in 15 days. Two data in the V band and three data in the B band are also given in Table 6.

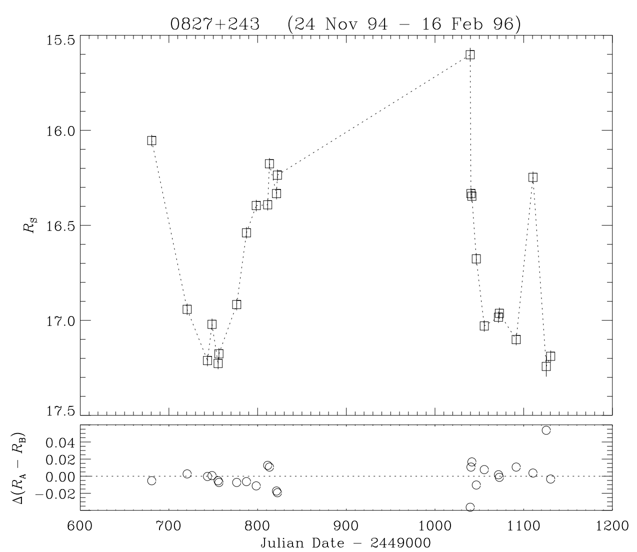

Fig. 5. Light curve of OJ 248 in the R band

3.6. 4C 71.07 (0836+710)

The complete set of our data on 0836+710 is given in Table 7. The last-season light curve in the R band is shown in Fig. 6, where the box indicates the period of EGRET pointing. Magnitude calibration has been performed according to the photometric sequence published in Villata et al. (1997a). Only small amplitude magnitude oscillations were reported in that paper, the average brightness level being $R \sim 16.7$ and the maximum overall variation $\Delta R = 0.12$. Data from the new observational season reveal a more pronounced variability, as well as the historical brightness maximum ($R = 16.09$) on November 20, 1995.

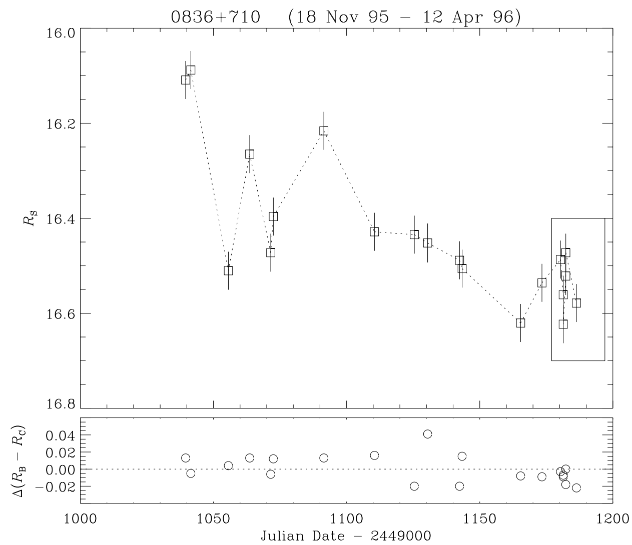

Fig. 6. Light curve of 4C 71.07 in the R band; the box shows the EGRET pointing period of April 3–23, 1996

3.7. 3C 216 (0906+430)

The results of our observations are reported in Table 8, where magnitude calibration is based on the photometric sequence published in Villata et al. (1997a). Only four data in the R band were taken in the last observational season, showing no indication of significant variability.

3.8. Mkn 421 (1101+384)

No significant variability of the γ-ray flux from Mkn 421 was detected during phases 1 and 2 of EGRET observations (Sreekumar et al. 1996). This source is known to be very active at TeV energies. Gaidos et al. (1996) have recently reported on observations by the Whipple telescope: two dramatic outbursts were detected in May 1996, the flux reaching the highest level ever recorded in the first flare.

All our data in the R, V, and B bands are given in Table 9. Figure 7 shows the light curve of Mkn 421 in the R band; magnitudes are normalized to that of Star B of our stellar reference sequence. We have four data around middle May (the last four ones), just after the first flare observed by Whipple on May 7, but at the time of the second flare, registered on May 15. We cannot confirm a relevant brightness increase during the second TeV flare, and we can say nothing on the previous period because of lack of data. We notice however that when the second TeV flare was detected, the optical state was relatively high (see also Weekes 1996).

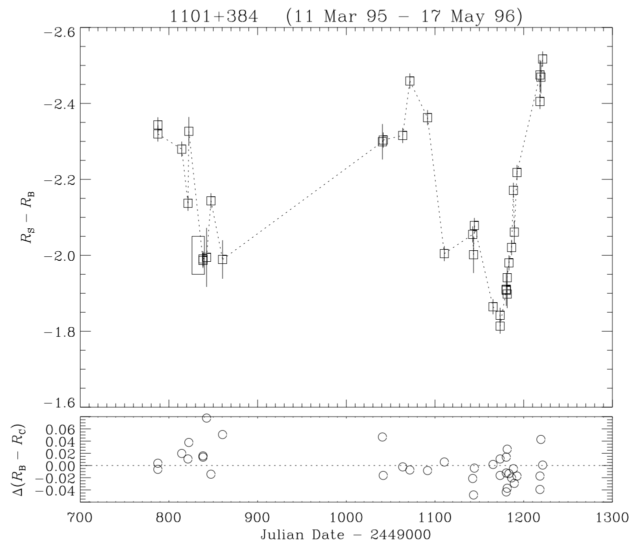

Fig. 7. Light curve of Mkn 421 in the R band; the box indicates the EGRET pointing period

3.9. 4C 29.45 (1156+295)

This quasar shows rapid variability in the γ-ray emission (Sreekumar et al. 1996). Its light curve in the R band is shown in Fig. 8, where boxes indicate periods of EGRET pointing. The complete set of our data in the R, V, and B bands is given in Table 10; source magnitude calibration was discussed in Villata et al. (1997a).

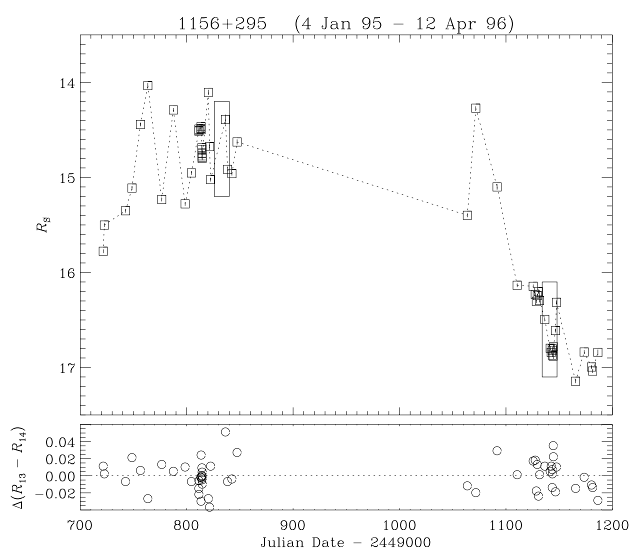

Fig. 8. Light curve of 4C 29.45 in the R band; boxes indicate EGRET pointing periods

A great activity characterizes the source luminosity behaviour: when considering the two observational seasons, the maximum magnitude variation is ΔR = 3.12 and ΔB = 3.23. By looking at the new data in Fig. 8 one can see that in December 1995 a brightening of more than a magnitude occurred in 8 days (1.13 mag, $\overline{\mathrm{JD}}$ = 1063–1071); after the peak of December 20, a brightness decrease of almost two magnitudes occurred in 39 days (1.87 mag, $\overline{\mathrm{JD}}$ = 1071–1110), within a total drop of 2.61 mag in 73 days. Data taken in the period corresponding to the EGRET pointing of February 20 – March 5, 1996 are also plotted in Fig. 9. At that time the source was in a low state and moderately active; some colour change was registered too. In particular, a rapid brightening of 0.57 mag in 3 days was observed at the end of the pointing period.

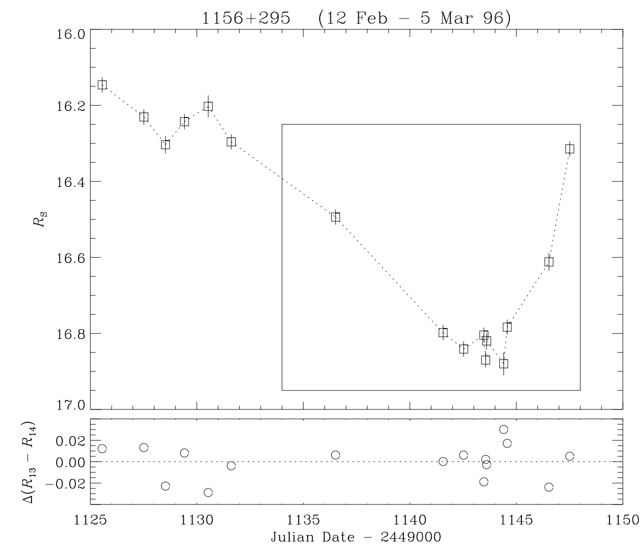

Fig. 9. An enlargement of the 4C 29.45 light curve in the R band to show data in the EGRET pointing period of February 20 – March 5, 1996

We notice that very different optical states correspond to the two EGRET pointings shown in Fig. 8; this should set serious constraints on theoretical models when optical data will be compared to the γ ones.

3.10. 3C 273 (1226+023)

This quasar was detected in a high γ-ray state during EGRET phase 3 observations (von Montigny et al. 1996).

The results of our monitoring on 3C 273 in the R, V, and B bands are reported in Table 11; the light curve in the R band is plotted in Fig. 10. Periods of EGRET pointing are shown by boxes.

This source did not present relevant magnitude variations. We notice that one of the two reference stars that we chose for the source magnitude calculation (Stars E and G of the Smith et al. (1985) photometric sequence) is probably variable. This can be inferred by looking at the

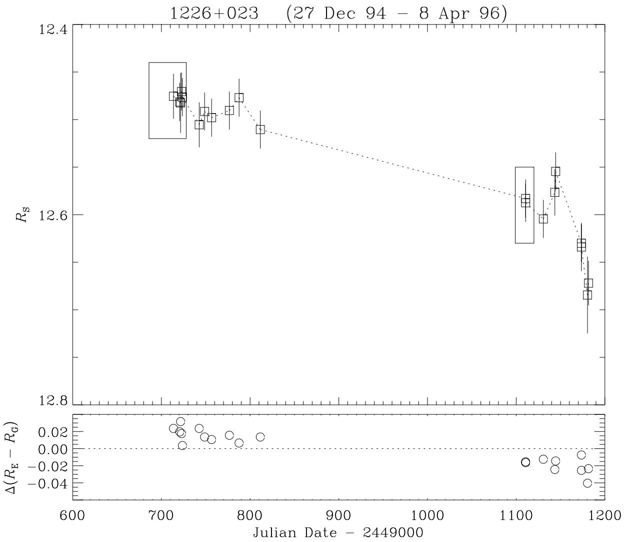

Fig. 10. Light curve of 3C 273 in the R band; boxes indicate EGRET pointing periods

subset of Fig. 10: there is a decreasing trend in the deviation from the mean magnitude difference between Star E and Star G. By comparison with the other two stars in the Smith et al. (1985) sequence, we verified that the candidate to variable star is Star E.

3.11. 4C−02.55 (1229−021)

We could collect only a few data on 4C−02.55; its light curve in the R band is plotted in Fig. 11, where boxes indicate EGRET pointing periods. Magnitude calibration was given in Villata et al. (1997a). All our data in the R, V, and B bands are presented in Table 12. No significant brightness variation was found.

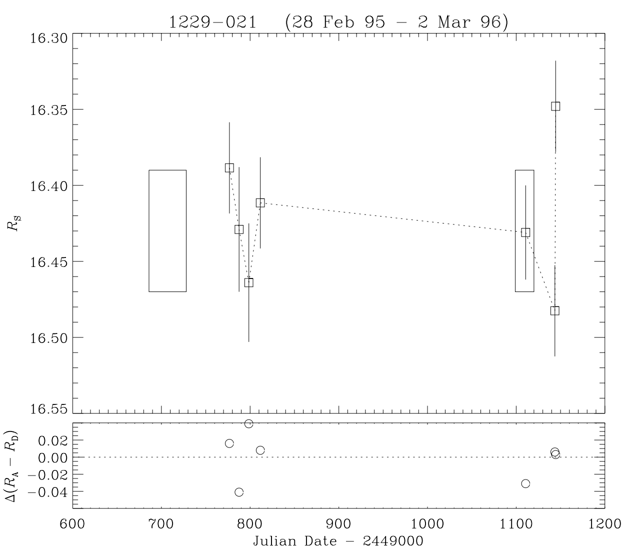

Fig. 11. Light curve of 4C−02.55 in the R band; boxes indicate EGRET pointing periods

3.12. PKS 1510−08

The results of our observations of PKS 1510−08 in the R, V, and B bands are reported in Table 13. The light curve in the R band is shown in Fig. 12, where magnitude calibration is performed according to Villata et al. (1997a).

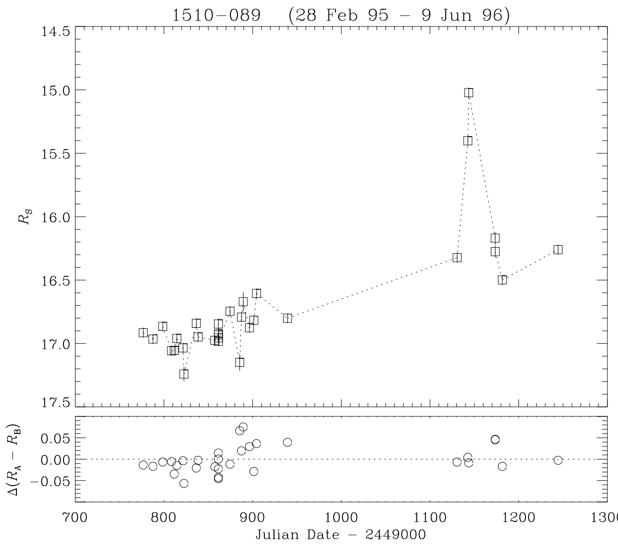

Fig. 12. Light curve of PKS 1510−08 in the R band

While in the first observational season this source did not show noticeable variations, a brightness rise of $\Delta R = 1.30$ in 13 days was detected at the end of February 1996, with a final increase $\Delta R = 0.38$ in 24 hours up to the peak of $R = 15.02$ on March 1 ($\overline{\mathrm{JD}} = 1143.7$).

3.13. DA 406 (1611+343)

Table 14 collects our observations of 1611+343 in the R, V, and B bands; the light curve in the R band is plotted in Fig. 13, where the two boxes show periods of EGRET pointing. The source magnitude calibration was done according to Villata et al. (1997a). No long time scale trend was detected for this source, but a short time scale flickering.

3.14. 4C 38.41 (1633+382)

All our observational data on 1633+382 in the R, V, and B bands are given in Table 15. Figure 14 shows the light curve in the R band; the two boxes indicate EGRET pointing periods. Magnitude calibration was performed by using the photometric sequence presented in Villata et al. (1997a).

In the first season a big flare was detected in the R band, the source reaching a historical maximum (Villata et al. 1997a; see also Bosio et al. 1995; Raiteri et al. 1996) with very steep brightness increase and decrease. A noticeable intranight variability was observed too. No particular

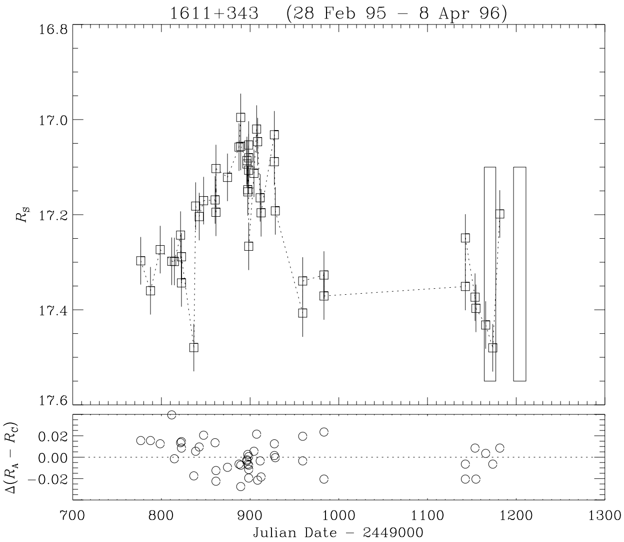

Fig. 13. Light curve of DA 406 in the R band; boxes show periods of EGRET pointing

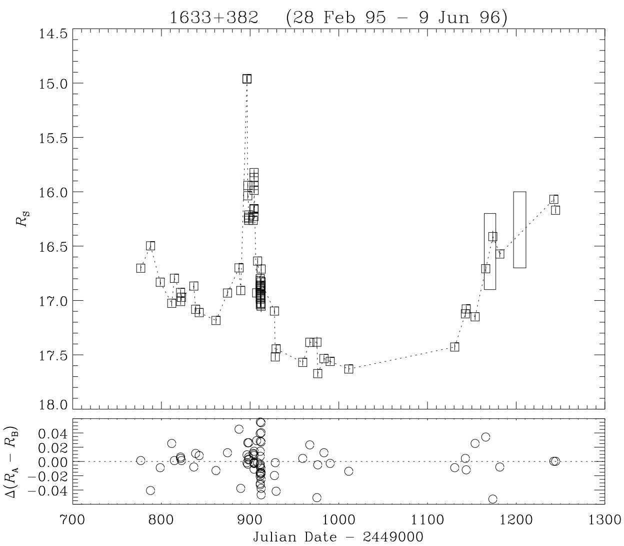

Fig. 14. Light curve of 4C 38.41 in the R band; boxes indicate EGRET pointing periods

feature was noticed during the last observational season probably because of lack of data; the range of magnitude variation was $\Delta R = 1.36$.

3.15. 3C 345 (1641+399)

The results of our optical monitoring of 3C 345 in the R, V, and B bands are reported in Table 16. Figure 15 shows the light curve in the R band; two boxes indicate EGRET pointing periods. Stars D and E from the Smith et al. (1985) photometric sequence have been used for the source magnitude calibration.

The most interesting feature in the new data is the brightness increase $\Delta R = 0.73$ in the last 54 days.

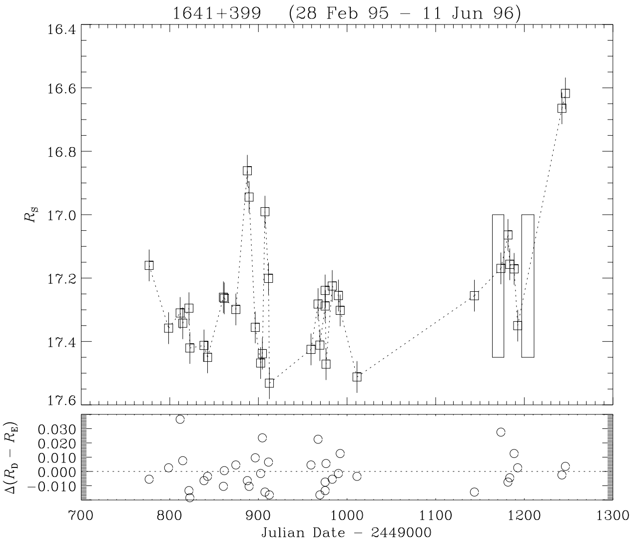

Fig. 15. Light curve of 3C 345 in the R band; boxes show periods of EGRET pointing

3.16. 4C 51.37 (1739+522)

Our data in the R, V, and B bands are given in Table 17 and the light curve in the R band is shown in Fig. 16. The source magnitude is normalized to that of Star A in our stellar reference sequence. Only three data belong to the new observational season.

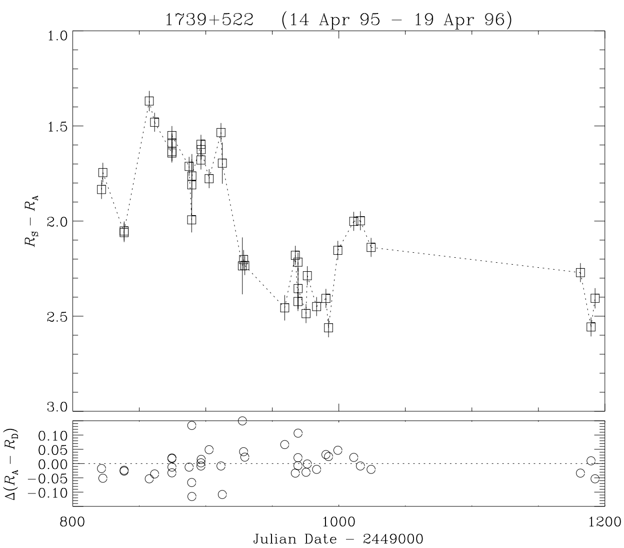

Fig. 16. Light curve of 4C 51.37 in the R band

3.17. CTA 102 (2230+114)

This quasar was detected as a strong γ-ray emitter by EGRET, with a variable photon flux (Lin et al. 1996).

The complete list of our data on CTA 102 is presented in Table 18. The light curve in the R band from June 1995 to January 1996 is plotted in Fig. 17, where the EGRET pointing period is indicated by the box. The source magnitude is normalized to that of Star B of our stellar reference sequence.

This source did not present big magnitude variations. On November 19, 1995, nine frames were taken in the R band, showing an oscillating behaviour with $\Delta R = 0.12$.

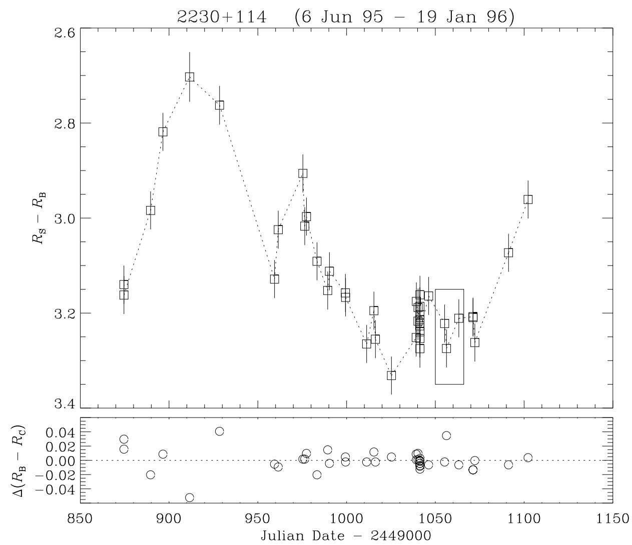

Fig. 17. Light curve of CTA 102 in the R band; the box indicates the EGRET pointing period of November 28 – December 14, 1995

3.18. 3C 454.3 (2251+158)

Blazar 3C 454.3 is another example of a strong and variable γ-ray source (Lin et al. 1996).

The data of our monitoring of 3C 454.3 in the R, V, and B bands are presented in Table 19; the last-season light curve in the R band is shown in Fig. 18, where the box indicates the EGRET pointing period.

An interesting feature is that on November 18, 1995 a peak of $R = 15.63$ was detected, immediately followed by a brightness decrease of 0.15 mag in 1.7 hours. In the same time, the source brightness in the V band varied by 0.06 mag only, which is inside the errors. Rapid variations in the R (but not in the V) band were already reported by Villata et al. (1997a).

3.19. PKS 2254+074

The BL Lac PKS 2254+074 was observed in the R band only; the light curve is given in Table 20 and Fig. 19, where magnitudes are normalized to that of Star D of our reference sequence.

The new data confirm the fast variability already noticed in Villata et al. (1997a). In particular, a brightness decrease of 0.37 mag in 21 hours is visible on November 18–19, 1995.

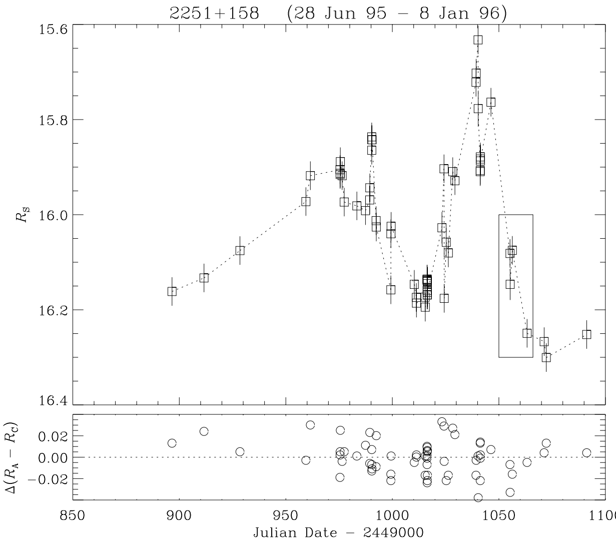

Fig. 18. Light curve of 3C 454.3 in the R band; the box indicates the EGRET pointing period of November 28 – December 14, 1995

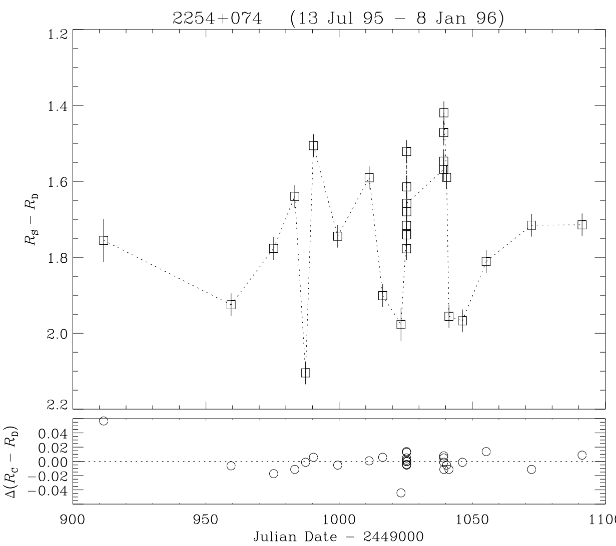

Fig. 19. Light curve of PKS 2254+074 in the R band

3.20. PKS 2356+196

The source PKS 2356+196 was observed in the R band only; data are presented in Table 21 and Fig. 20, where magnitudes are given with respect to that of Star A in our stellar sequence. The box in Fig. 20 indicates the period of EGRET pointing.

No significant brightness variation was found.

4. Intranight variability

Blazars are known to show, besides variability on long periods, flux changes on small time scales, i.e. shorter than one day. This microvariability has been observed in many bands, from radio to γ-rays (see the review paper by Wagner & Witzel (1995)), and implies emission from regions whose size is comparable to that of our Solar System. The mechanisms responsible for such rapid variations are

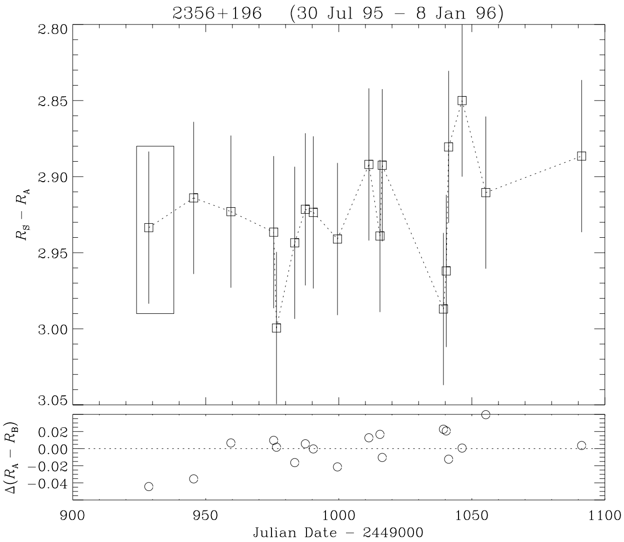

Fig. 20. Light curve of PKS 2356+196 in the R band; the box indicates the EGRET pointing period

still unclear, different interpretations being possible, and much observational effort is needed to understand this point.

In this section we present three cases of intranight variability that we were able to detect for 3C 66A and OJ 287. Since these sources are the subjects of the OJ-94 Project, we refer to the relative papers for the general behaviour of their light curves (Sillanpää et al. 1996a,b; Takalo et al. 1996). Magnitude calibration was performed according to Villata et al. (1996).

4.1. 3C 66A (0219+428)

In Fig. 21 the light curve in the R band of 3C 66A during the night of August 29–30, 1995 is shown. A well defined trend is evident, with a total brightness increase of 0.081 mag in 6 hours and 26 minutes. The global increasing rate is 0.013 mag per hour, while the increasing rate of the final, steeper part is 0.021 mag per hour. This value is comparable to the decreasing rate of 0.024 mag per hour detected during the night of October 24–25, 1995, when the source acquired 0.144 mag in about 6 hours (see Fig. 22).

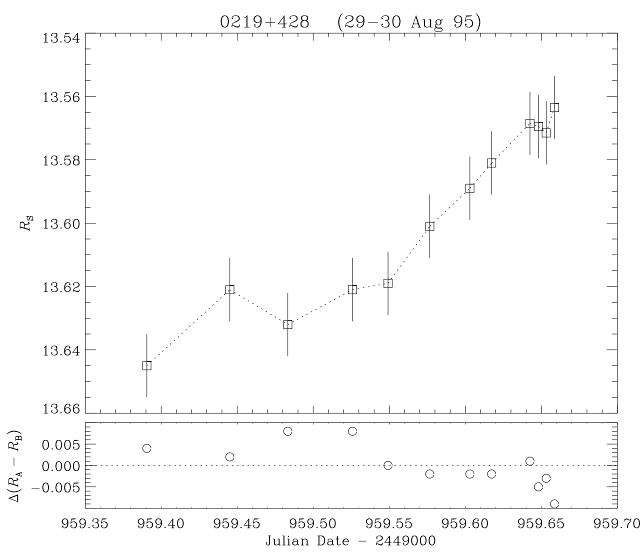

Fig. 21. Light curve of 3C 66A in the R band during the night of August 29–30, 1995

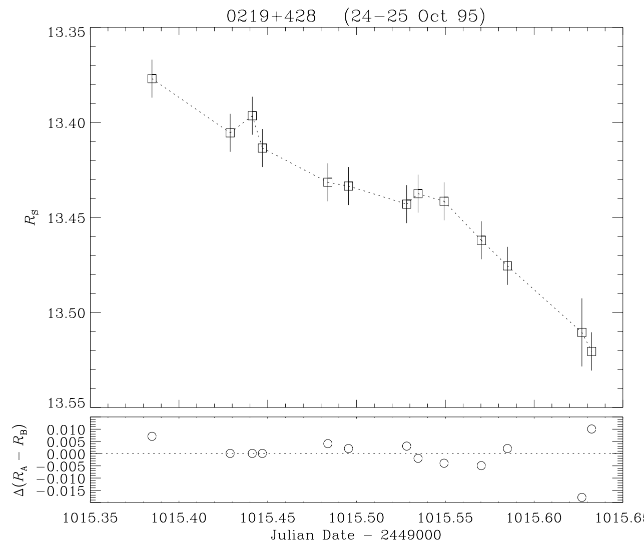

Fig. 22. Light curve of 3C 66A in the R band during the night of October 24–25, 1995

4.2. OJ 287 (0851+202)

The microvariability characteristics of OJ 287 is the subject of a recent work by González-Pérez et al. (1996), covering 26 nights from November 1993 to November 1994. They found variations in 73% of the nights. In their study

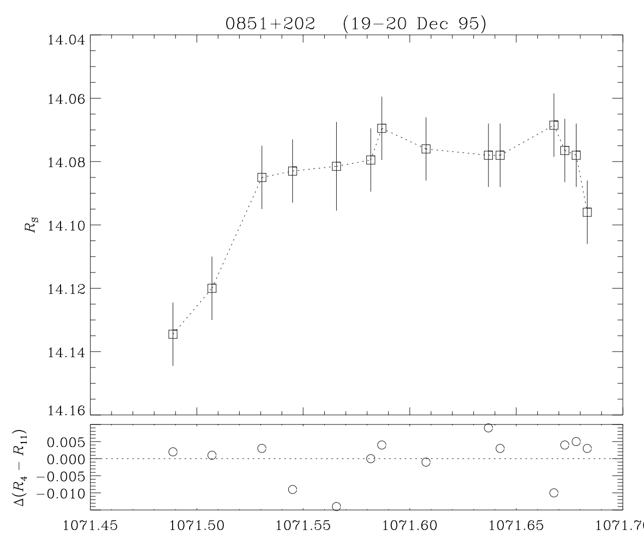

Fig. 23. Light curve of OJ 287 in the R band during the night of December 19–20, 1995

on optical intraday variability of radio selected BL Lac objects, Heidt & Wagner (1996) found a characteristic time scale of 2.8 days for OJ 287, based on a structure function analysis, and a variability amplitude of 48.5%.

The intranight behaviour of the OJ 287 R magnitude in the night of December 19–20, 1995 is plotted in Fig. 23. One can see a fast brightening of 0.05 mag in one hour, after which the source magnitude remained more or less stable. A similar rate of magnitude variation during another night can be found in Sillanpää et al. (1996c).

5. Conclusions

We have presented new data from the optical monitoring of 22 γ-ray loud blazars included in the Torino observational program. Most of the sources showed a more or less pronounced variability; some of them (PKS 0420−01, OJ 248, 4C 29.45, PKS 1510−08) revealed an intense activity. In general, the patterns of the light curves in different bands are similar; however, in a few cases (PKS 0422+00, 4C 29.45, 3C 454.3) colour changes were observed. The results of intranight observations of 3C 66A and OJ 287 have also been presented, showing microvariability.

Although the time coverage of our light curves is satisfactory for most sources, we recognize the importance of collecting data from many observatories in order to have a better understanding of the flux behaviour. This is especially needed when the observational data are used as a test for the theoretical models. In particular, a complete picture requires to know possible correlations between fluxes at different wavelengths. In this sense we expect that our data contribute to clarify the mechanism responsible for the γ-ray emission, when a comparison with the data taken by EGRET in the same period will be possible.

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