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Fast flares of blazars during gamma-ray observations *

Optical – gamma-ray correlations

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Abstract. A fraction of the blazars discovered by EGRET has shown rapid variations in the Gamma-ray range during an individual CGRO viewing period. Many of the EGRET blazars are known to be rapidly variable at lower photon energies as well.

We have observed ten of the gamma-bright blazars in the optical regime simultaneously during EGRET measurements. A few of these campaigns include polarimetric and spectral-index observations. Some of them were monitored during several EGRET observations. All of the objects have varied in the optical range. Variations are fast and need at least daily sampling. The changes in flux density are generally accompanied by changes of spectral indices and polarization properties. This demonstrates that the conditions leading to the synchrotron emission has changed during an individual gamma-ray observations.

We discuss evidence for comparable changes of the gamma-ray radiation, which is often plagued by the low photon statistics. We also discuss the implications of the variability for interpretations of the broad-band energy distributions and the relevance of these observations for models of gamma-ray emission. The evidence for a close link of gamma-ray emission and synchrotron radiation is discussed.

Key words: gamma-ray emission – Blazar variability – non-thermal radiation mechanisms

1. Introduction

Most of the blazars which have been seen in the gamma-ray range were found to show variations of their luminosities at photon energies above 1 MeV. Although this might have been expected due to the fact that variability is one of the defining criteria of the blazar class, the empirical confirmation strengthens the assumption that the gamma-ray emission is indeed closely connected to the emission at lower photon energies. Evidence for variation is most convincing in the EGRET data, i.e. in the energy range between 70 MeV and a few GeV (e.g. von Montigny et al., 1995). Variability has also been detected with COMPTEL and OSSE. The only confirmed blazar to be seen in TeV gamma-rays, Mkn 421, is also variable in this energy range (Kerrick et al., 1995).

The variations may help to reveal the processes leading to the enormous gamma-ray luminosities of these blazars. If the primary radiation is reprocessed and emitted over a wide energy range, variations should be correlated. The details of such correlations (e.g. the frequency dependent lag) will then constrain the reprocessing mechanism and the geometrical configuration. If the gamma-ray emission is inverse-Compton (IC) scattered synchrotron radiation, one would expect the gamma-rays to vary as a result of changes of the primary synchrotron radiation. Correlations between radio-flares and delayed gamma-emission have been suggested by various authors. Most radio studies are carried out at frequencies of a few GHz, where most of the radio cores of gamma-bright sources are optically thick. The synchrotron flare can hence be observed only with considerable delay and additional broadening of the profile of the flare. This prohibits a detailed investigation of the reprocessing mechanism which cause the gamma-ray emission. Detailed comparisons to variable synchrotron emission should hence be carried out in the optically thin regime, i.e. above 10^{13} Hz. In this wavelength range, however, blazars are known to be rapidly variable. In particular, the class of objects identified with gamma-bright AGN, the flat-spectrum radio quasars (FSRQ) and BL Lac objects are known to be variable on time scales of days or less (e.g. Wagner and Witzel, 1995). In order to study variations on such time-scales in the gamma-ray range,

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the objects have to be bright enough to permit narrow temporal binning. In at least six objects fast variations in the gamma-ray luminosity have been detected. In a few cases simultaneous optical observations have been performed. In this paper we discuss evidence for simultaneous occurrence of high gamma-ray and optical luminosity in long-term light-curves (Sect. 2) and simultaneous multi-frequency observations of fast flares (Sect. 3) using data from the EGRET instrument. In Sect. 4 we describe simultaneous monitoring in the TeV and optical range of Mkn 421. Some conclusions are given in Sect. 5.

2. Longterm Variations

Light-curves of most of the EGRET-detected blazars are given in von Montigny et al., 1995. From this compilation it is obvious that almost all of the blazars which have been observed several times with adequate exposure show variations between different viewing periods. Flux densities between subsequent viewing periods show little correlation, suggesting that the characteristic time scales of variations are shorter than the typical time intervals between repeated observations. In a few objects there are optical data which indicated that such 'high states' in the gamma-ray light-curves are correlated with flares or corresponding high states at lower photon energies. Observations from the Heidelberg monitoring program have been used to trace optical flares during high states in the gamma-ray range in S5 0836+71 (v. Linde et al., 1993), S5 0954+65 (Mukherjee et al., 1995), PKS 0420-014 (Wagner et al., 1995a), NRAO 190 (McGlynn et al., 1995), PKS 1406-076 (Wagner et al., 1995b), PKS 0528+134 (Mukherjee et al., 1996), and 3C 279 (Sect. 3). Hartman et al. (1995) demonstrate that the very bright gamma-ray flare of 3C 279 during the discovery observations of EGRET in June 1991 was also accompanied by a flare of optical emission. An example of an optical outburst occurring during the detection of a high state of gamma-ray emission is shown in Fig. 1, illustrating the optical flare which occurred during the GRO viewing period 337 in August 1994. At this epoch the quasar NRAO 190 (0455-003) was detected by EGRET for the first time (McGlynn et al., 1995). Since earlier observations of the same area had good exposure, the mere detection indicates that NRAO 190 was in a high state of gamma-ray emission. Note that the optical flare faded at the end of the EGRET viewing period. An 'a posteriori' observation, based on the report of the gamma-ray detection (McGlynn et al., 1994) would have missed the optical flare.

In all of the above cases the following criteria are met:

1. The source is unusually bright in the gamma-ray range studied by EGRET (70 MeV - 5 GeV).
2. During the VP of EGRET observation the source was brighter in the optical range than before and after the gamma-ray observations. In all cases the source was brighter than the average level. In most cases it reached the highest optical luminosities reported so far.
3. In all cases observed with sufficient temporal coverage the source was rapidly variable *during* the EGRET observations. While most EGRET sources had been found to be intraday variable (IDV, see Wagner and Witzel (1995)), not all of them have high duty cycles, which indicates that the optical activity refers to high luminosities *and* fast changes. Note that the occurrence of IDV implies that it is difficult to determine the average optical luminosity during the gamma-ray observation, which would be required to determine exact simultaneous spectral indices.
4. Whenever recorded, the fast changes of optical flux are accompanied by equally fast (though not directly correlated) changes of optical polarization.

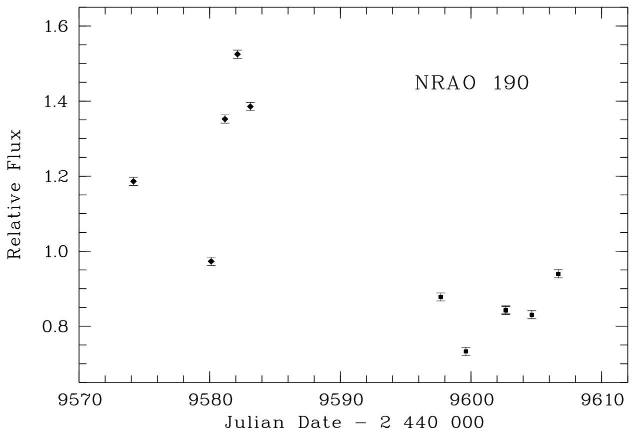

Fig. 1. Optical light-curve (650 nm) of NRAO 190 (PKS 0455-003) in August 1994. During VP 337 (JD 2 449 573-594) this source was found by EGRET to be bright (i.e. flaring) in the gamma-ray range.

The sources mentioned above have a wide range in duty cycle. In some cases the optical flare during the bright gamma-ray state was the only outburst ever reported, other sources have shown optical outbursts a few times per year. In spite of reasonably good coverage no case has been found so far of an EGRET detected source flaring in the optical band during an EGRET observation without producing an unusually high gamma-ray flux. There are other blazars however, which have never been detected by EGRET, which underwent an optical outburst while observed by EGRET without being detected at gamma-ray energies. This indicates that non-detections of blazars in the gamma-ray range is not only caused by absence of synchrotron-activity during the epoch of gamma-ray observations.

3. Fast Gamma-Ray Flares

The rapid optical variations during epochs of high gamma-ray luminosity indicate that the gamma-ray radiation may also vary on time-scales shorter than an individual viewing period. In a number of cases blazars have been bright enough in the gamma-ray range to study temporal changes on time-scales of a few days. Variations have been found e.g. in 3C 279 (Kniffen et al., 1993), PKS 0528+134 (Hunter et al., 1993), PKS 2251+158 (=3C 454.3) (Hartman et al., 1993), and 1633+382 (Mattox et al., 1993). In order to derive constraints on models of the gamma-ray emission it is important to study the correlation between the synchrotron variations and the gamma-ray variations in cases of such rapid flares.

Wagner et al. (1995b) observed a simultaneous flare in PKS 1406-076. The flare lasted for 62±14 hours at gamma-ray energies and for 70±2 hours at optical wavelengths. The gamma-ray flare *lags behind* the optical flare by 23±4 hours.

Hartman et al. (1995) compared the gamma-ray flare of 3C 279 in June 1991 to optical observations. Although the gamma-ray flare was brighter (and hence the flare-shape of the gamma-ray emission was much better constrained) it is unfortunately not possible to constrain the lag between the optical and the gamma-ray emission very well, since the the optical coverage is fairly sparse. 3C 279 produced yet another gamma-ray flare in December 1994 (Hartman, private communication) which lasted for 4±1.5 days, centered on JD 2 449 695 (±1 day). Fig. 2 gives the optical light-curve during this event. Due to the poor photon statistics in the EGRET observations, it is not possible to constrain the lag between both frequency bands to better than ±36 hours (see also Marscher, this volume).

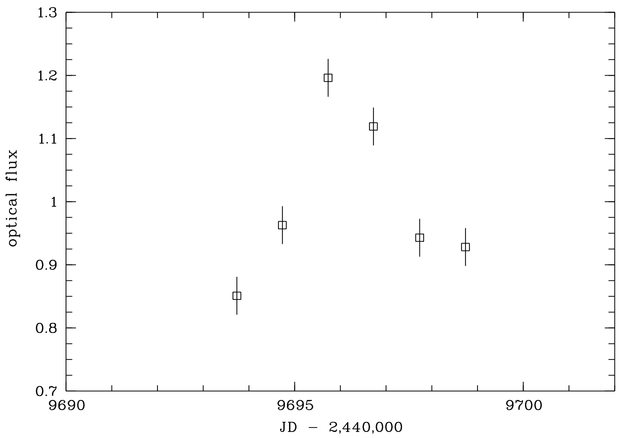

Fig. 2. Optical light-curve (650 nm) of 3C 279 in December 1994. During GRO-VP 405 EGRET detected a gamma-ray flare. The maximum occurred around JD 2 449 695.5 ± 1d. At this epoch the optical flux increased by more than 60 %.

Fast flares demonstrate that the gamma-ray radiation must be emitted from plasma flowing with relativistic speed. Mattox et al. (1993) have shown that relativistic beaming is required to avoid the absorption of the gamma-radiation due to photon-photon pair production. The same argument applies to all sources with cosmological redshifts $z > 0.3$ and variability on time-scales of days. The non-zero lag observed in the case of PKS 1406-076 rules out instantaneous synchrotron-self compton scattering with in-situ (and prompt) IC scattering. The close correspondence of the gamma-ray- and the optical flare suggests that any model which explains the gamma-emission to be scattered off ambient electrons has to avoid geometric dilution. The size s of the scattering volume must be smaller than $s < c \times |\Delta t / \Delta lnF|$. The scattering material cannot be far off axis in order to avoid geometric dilution. In the most likely interpretation the lag between the optical and the gamma-ray peak corresponds to the light-travel time required for the synchrotron flare to reach the gamma-ray photosphere. This would be the case both in models which involve a primary photon beam emerging from circumnuclear disks, scattering off the relativistic electrons in the jet (Dermer et al., 1992; Schlickeiser, this volume) as well as in models involving forward scattering of photons into the jet by the BLR- and intercloud-plasma (Sikora et al., 1994). Flares of synchrotron radiation from relativistic jets have been studied in considerable detail. It is not clear however, whether their characteristics and spectral properties can be explained by disk scenarios.

4. Correlations between optical and TeV Flares

Almost all of the EGRET detected blazars are radio-loud, i.e. they have flux-densities in the radio range which exceed 1 Jy, making them part of the sample of the 300 brightest flat-spectrum radio sources. About 20 % of the EGRET sources are BL Lac objects. All of them except Mkn 421 belong to the group of ‘radio-selected’ BL Lac objects. Only one member of the ‘X-ray selected’ BL Lac objects, which are actually much more abundant has been seen at a convincing level of significance. Mkn 421 is also one of the few EGRET sources which has been observed several times and has not shown significant variations. It is also the only AGN detected in the TeV regime[1]. Mkn 421 is long known to be rapidly variable in the X-ray and optical regime. At optical wavelengths typical amplitudes of variability are lower than for ‘radio-dominated’ BL Lac objects. This and the presence of a well-resolved host galaxy make accurate derivations of the optical variability properties difficult in spite of its high average brightness.

Mkn 421 has been flaring in the TeV regime in 1994 (Kerrick et al., 1995), which led to more intense monitoring during 1995. In April the Whipple team reported another flare in the TeV range (Buckley et al., 1995). We had carried out simultaneous observations in the optical range. Fig. 3 shows the optical light curve (650 nm) and the variations of flux density in the TeV regime, as reported by Buckley et al., 1995.

[1] Quinn et al. (1996) have now also reported the detection of Mkn 501 in the TeV regime. This source has not been detected by EGRET but also belongs to the ‘X-ray dominated’ BL Lac objects.

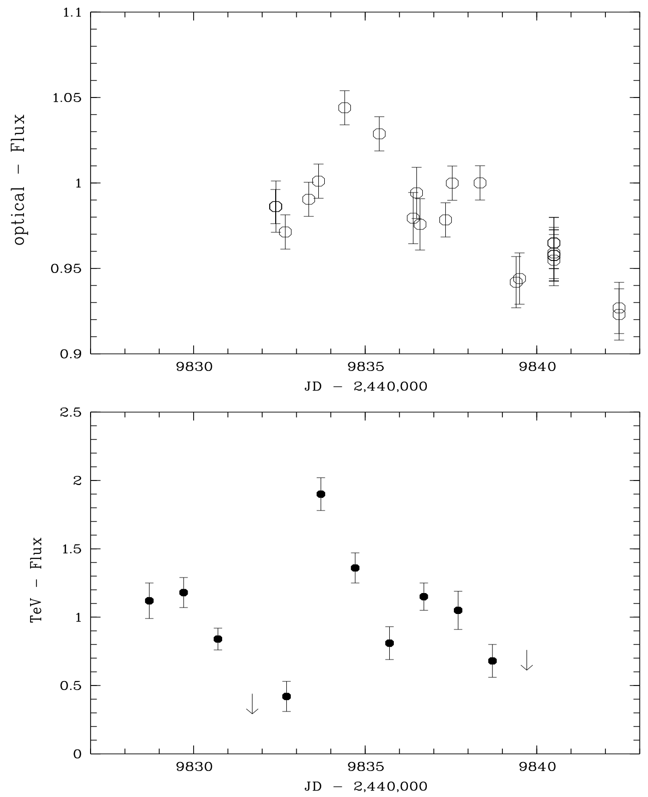

Fig. 3. Optical light-curve (650 nm) (top) and gamma-ray variations (bottom) of Mkn 421 in April 1995. The optical data come from two different telescopes and show low amplitude variability. The TeV data are taken from Buckley et al. (1995). The TeV-peak on April 6 occurs at the epoch of the optical maximum.

The small amplitude of the optical variations, and the similarity of (high amplitude) variations at X-ray- and TeV energies (Takahashi, this volume) suggest that Mkn 421 differs from other EGRET detected AGN not only in distance (which is short enough for TeV photons not to be absorbed by the intergalactic IR background). We speculate that the synchrotron branch in Mkn 421 extends above 10 keV. The variable component has a hard spectrum, i.e. variability amplitudes increase towards X-ray energies. This is in contrast to the radio-loud blazars which exhibit a break between synchrotron cut-off and rising IC branch in the soft (few keV) X-ray regime. The IC branch of Mkn 421 thus also extends to higher energies and variability amplitudes in the gamma-ray range increase from 10^{23} Hz to 10^{27} Hz in the same way as amplitudes in the synchrotron branch increase from 10^{14} Hz to 10^{18} Hz.

5. Conclusions

High states of gamma-ray emission always coincide with flares of optical emission. The optical synchrotron radiation always varies on very short time scales during the gamma-ray outbursts (intraday variability). In most cases the small number of gamma-ray photons and insufficient sampling of the optical light curves prohibit a comparison on time scales shorter than a few days. In these cases the gamma-ray flares and optical outbursts appear to occur simultaneously. This proves an intimate correlation of the gamma ray emission and synchrotron radiation at much lower photon energies and strongly suggests that the gamma-ray emission is reprocessed. In the source PKS 1406-076 a gamma-ray flare was observed which was delayed with respect to an optical outburst seen in simultaneous observations. This poses strong constraints on the relative orientation and spatial extent of the emitting/reprocessing regions in any model which involves inverse Compton scattering.

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