Jets in Gamma-bright AGN: Constraints on Reprocessing Mechanisms

Stefan J. Wagner

Landessternwarte, Königstuhl, Heidelberg, Germany

Abstract. Several dozen active galaxies have been detected by instruments sensitive to hard gamma-ray radiation. All of these objects are radio-loud AGN and share several other characteristics in the low-energy part of their spectra. The gamma-ray emission varies on time-scales from days to years and is characterized by a power-law spectrum. In order to determine the broad-band energy distributions of these objects, a series of simultaneous multifrequency campaigns has been arranged. Apart from providing the low-frequency properties during those states when the sources were bright enough in the gamma-ray range to be detected, such campaigns provide clues to the degree of correlation between variations in different energy regimes. Several cases were found which indicate that the optically thin part of the synchrotron radiation is closely connected to the gamma-ray range. This sets constraints on the reprocessing mechanisms responsible for the gamma-ray emission.

In addition to studies in the GeV regime, ground-based Cherenkov telescopes allow investigations of the gamma-ray properties in the TeV regime. One such source, the BL Lac object Mrk 421 has been found to emit variable TeV radiation which might be related to the variable emission seen in the optical regime.

1 Introduction

In 1991 the Compton Gamma-Ray Observatory (CGRO) was launched. It carried on board four instruments, covering the energy range from a few 10 keV up to a few 10 GeV. The highest energies are studied with the EGRET instrument, a spark chamber operating in the energy range above 30 MeV. Its wide field of view (0.6 sr) observes different regions of the sky for typically 2 weeks. Within the ~ 80 pointings during the first 2.5 years of operation it detected ~ 50 AGN, five pulsars and GRBs, as well as ~ 60 unidentified sources.

The most complete list of EGRET sources has been compiled by Thompson et al. (1996). Von Montigny et al. (1995) describe the gamma-ray characteristics and (non-simultaneous) broad-band energy distributions of the gamma-bright AGN. Models explaining the gamma-ray emission in terms of inverse-Compton (IC) scattered radiation or hadron-initiated cascades have been reviewed e.g. by Schlickeiser (1996).

All of the gamma-bright AGN are flat-spectrum radio sources, either belonging to the group of radio-selected BL Lac objects or flat-spectrum Quasars (Eckart et al., 1987). All of the sources show polarized power-law continua in the optical range. The low-energy (radio through optical) spectra are dominated by synchrotron radiation. In this energy range all of the sources vary on fairly short time-scales, most of them belong to the class of Intraday Variables (IDV sources) as described by Wagner and Witzel (1995). Most of the radio emission is compact and many of the sources show superluminal velocities in VLBI campaigns. In three sources superluminal motion was discovered as a result of following-up the detection of gamma-ray emission (PKS 0420-014 (Wagner et al., 1995a), PKS 0528+134 (Zhang et al., 1994), and PKS 1633+382 (Barthel et al., 1995)). All of the above characteristics are generally attributed to a relativistic jet pointing at small angles to the line-of-sight of the observer. It is therefore most likely that the gamma-ray emission can be attributed to the relativistic jet as well.

2 Gamma-ray Observations

Among the characteristics of the gamma-ray emission described by von Montigny et al. (1995), variability is striking. It is the most important one for the discussion below. Almost all of the sources detected so far vary in the energy range above 70 MeV. The only sources where variability could not be proven are the faint ones detected only in the deepest pointings (with other observations of the same region of sky giving only upper limits). /it Rapid variability can be studied during an individual observation only, if the average flux is large enough to yield sufficiently high statistics within individual bins of 3 to 5 days. In more than 50 % of these cases the sources were found to be variable on such short time-scales. Examples are the early discovery of strong emission from 3C 279 which showed an increase of a factor of 2 within a few days and a subsequent decay which was even faster (factor of two within 24 h) (Kniffen et al., 1993), PKS 0528+134 (Hunter et al., 1993, Mukherjee et al., 1996), PKS 2251+158 (Hartman et al., 1993), and 1633+382 (Mattox et al., 1993). One of the important conclusions which can be drawn from the rapid variations is the compactness of the gamma-ray emitting volume. If the high gamma-ray luminosities emerge from a volume less than about one light-day across, the density of gamma-ray photons is so high that they should suffer extreme losses due to photon-photon pair production (e.g. McBreen, 1979). This self-absorption can be reconciled with the observed gamma-ray luminosities if the emitting plasma moves relativistically towards the observer and the high-energy photons are Doppler-boosted, similar to the radio emission. This is a more direct evidence of the gamma-ray emission being related to the relativistic jet of these sources.

In most cases the flux is too low to permit binning in sub-intervals, and light-curves can be obtained only by integrating the flux of the entire viewing periods. Structure-function analysis of such data shows that the characteristic time-scales are of the order 10 - 100 days, which is comparable to or shorter than the sampling time-scale. Apart from sources located in regions of the sky which are of particular interest, most objects are observed 1 - 3 times a year. This is illustrated in figure 1 which gives the light-curve and the structure-function of the (fairly well-sampled) source PKS 0208-512.

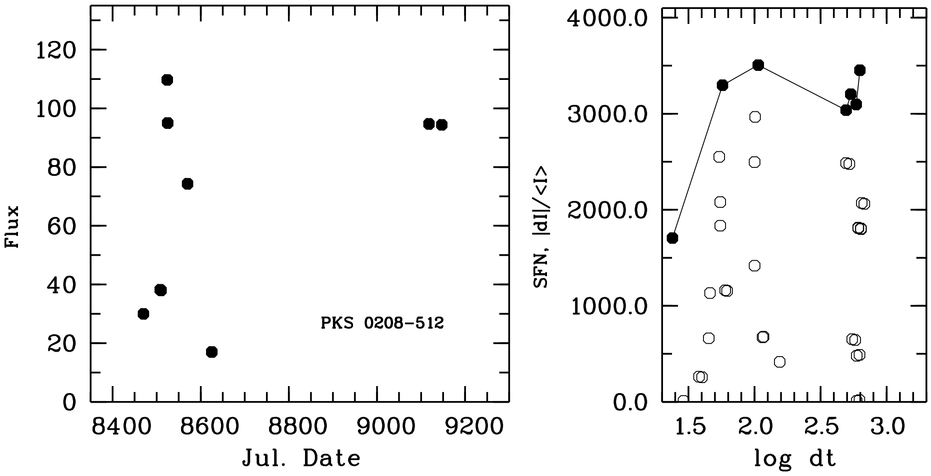


Fig. 1. Gamma-ray variations of PKS 0208-512. The left panel shows the light-curve obtained from EGRET observations (e.g. Thompson et al., 1996), the right panel illustrates the structure-function (full circles). The corresponding $\{\Delta\ I_{ij},\ \Delta\ t_{ij}\}$ pairs are shown in open circles to illustrate the sampling problem of the structure-function analysis.

Gamma-ray variability is too fast to derive the characteristics of the changes with the temporal sampling available with EGRET. This strongly limits the possibility to draw conclusions on the correlation between variations in the gamma-ray range ond other bands which occur on time-scales longer than a few weeks.

The range of variability is about an order of magnitude, almost comparable to the dynamic range between the brightest detections and the faintest levels providing secure detections. It is unclear, therefore, whether the steady, quiescent level of gamma-ray flux has been detected in any but the brightest sources. Most *detections* of AGN in the high-energy gamma-ray range seem to mark a gamma-ray *flare* of that particular source.

3 Low-frequency properties during gamma-bright states

The variability of the gamma-ray emission implies that broad-band characteristics have to be studied simultaneously in order to carry out quantitative comparisons to the gamma-ray properties. Apart from long-term monitoring campaigns which include certain fractions of the gamma-bright AGN (such as the Michigan cm monitoring program (Aller et al., 1996), or the Metsahovi mm monitoring program (Valtaoja et al., 1996)), dedicated campaigns have been set up to carry out simultaneous observations (e.g. Marscher, 1996; Reich et al., 1993; Wehrle et al., 1996). Many of these campaigns focussed on radio observations. In the following, optical observations are discussed. Optical data have the advantage of not being subject to self-absorption. Since optical synchrotron radiation is assumed to be optically thin, any direct correlation of optical and gamma-ray activity would only be subject to delays of the gamma-emission introduced by transport and reprocessing.

During high states of gamma-ray emission, all sources show enhanced levels of optical brightness. While this observation is limited by an incomplete sample and insufficient and inhomogeneous sampling, we have not found a single case of enhanced gamma-ray activity during 'quiescent' optical states. The optical light-curves are usually sampled sufficiently well to define a quiescent level. An example of this long-term monitoring is shown in figure 2, comparing the optical and gamma-ray light-curves of PKS 0420-014. While both light-curves are undersampled, the brightest gamma-ray state occurs exactly at the time of the brightest optical state. Likewise, slightly enhanced gamma-ray states are related to periods of lower activity (still enhanced with respect to the quiescent level).

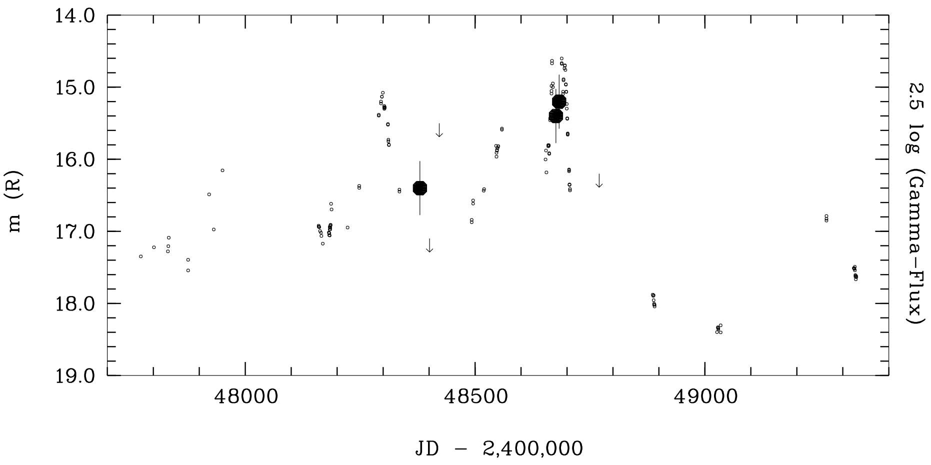


Fig. 2. Gamma-ray emission of PKS 0420-014 (full circles) and optical variations (small circles) during 1991 - 1994 (see Wagner et al., 1995a).

While there is in general no indication that very rapid optical activity in BL Lac objects and flat-spectrum quasars occur preferentially during bright states of long-term optical light-curves (Wagner and Witzel, 1995) we have found that high states of gamma-ray activity often correspond to very fast changes of the optical flux. An example is given by von Linde et al. (1993), who found rapid

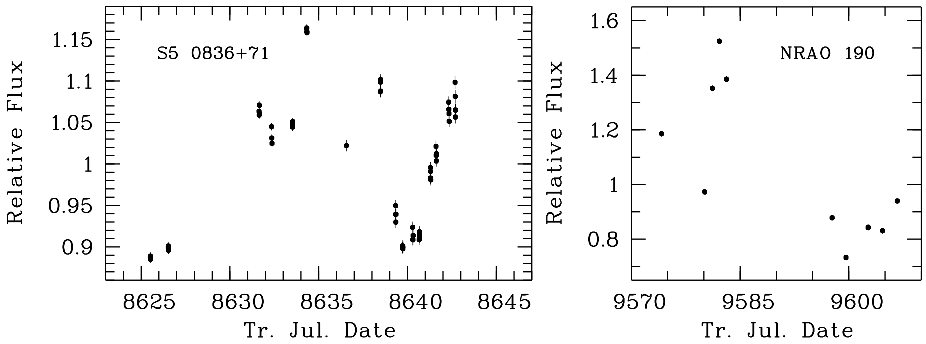


Fig. 3. Optical flares of NRAO 190 and 0836+71. The two R-band light-curves were obtained during epochs when the sources were bright in the gamma-ray range (though not bright enough to study variability on short time-scales).

changes coinciding with a high gamma-ray state of S5 0836+71, the most distant gamma-ray source known. Although this object has been studied for intraday variability in several campaigns (e.g. Wagner et al., 1990) it was hardly found to show such rapid variations as during the high gamma-ray state in January 1992. Other examples are S5 0954+65 (Mukherjee et al., 1995) and NRAO 190 (McGlynn et al., 1994, 1996). The optical light-curves of those sources, as measured by the Heidelberg monitoring group are shown in figure 3. Objects which are detected by EGRET whenever they are observed at very similar luminosities (such as the BL Lac source S5 0716+714) show these very rapid variations permanently (Heidt and Wagner, 1996) indicating a very high duty cycle of both gamma-ray activity and intraday variability.

In a few cases not only the total flux but also the polarization characteristics have been monitored. They also show rapid changes during epochs of high gamma-ray activity. These changes in polarized flux are not directly correlated to changes in total flux (Wagner et al., in preparation).

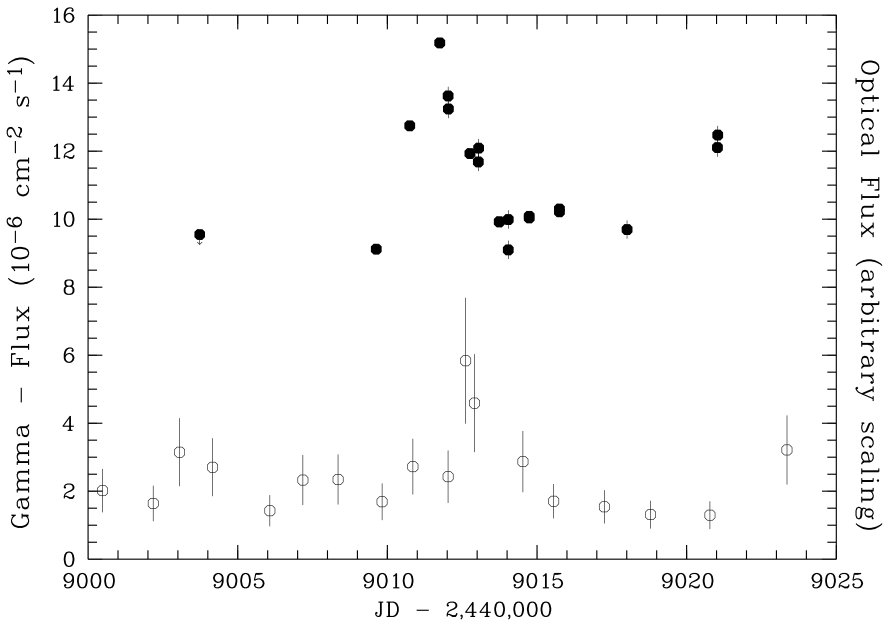
All of these characteristics illustrate that it might be misleading to directly interpret non-simultaneous broad-band energy distributions. Even a "simultaneously" derived flux density such as a single photometric measurement taken during a fortnight of gamma-ray observation might fall short in representing the *average* flux density which would correspond to the measurements above 70 MeV. The changes in Stokes parameters further illustrate that even well-sampled light-curves of total flux may not be sufficient to reveal the full information necessary for quantitative understanding of the IC scattered contribution to the gamma-ray emission.

4 Correlated flares

The gamma-bright AGN can be defined fairly well on the basis of their properties at lower frequencies. This suggests that the emission processes of gammaradiation are closely linked to the synchrotron characteristics. This can be tested quantitatively by comparing the time variability in the gamma-ray and optical ranges. Due to the sampling pattern of the gamma-ray observations this can be done best for fast flares (rapid variability). For most of the observations of fast gamma-ray flares mentioned above, there were hardly any optical observations. A more successful example are the early observation of 3C 279, where some similarity to (sparsely sampled) optical data are discussed by Hartman et al. (1996). A less significant gamma-ray flare was found in 3C 279 in December 1994 (Hartman, private communication), which is accompanied by a minor flare in optical monitoring (Wagner, 1996b).

Two additional events have been recorded with sufficient sampling both in the optical and in the gamma-ray ranges. PKS 1406-076 flared in January 1993 (figure 4) in both bands (Wagner et al., 1995b). A similar event was observed in PKS 1622-293 in June/July 1995 (Mattox et al., 1995).

Fig. 4. PKS 1406-076 exhibited a gamma-ray flare (open circles) and an outburst of optical synchrotron radiation (filled symbols) during January 1993 (see Wagner et al., 1995b).



PKS 1406-076 has not been studied extensively prior to its detection by EGRET. The limited monitoring carried out after the observations shown in figure 4 suggest that the flaring rate in this object is fairly low. The January 1993 outburst is the only one recorded in about 100 days of observations spread over a two year interval. Likewise, the gamma-rays have not yet varied again in a similar way. This reduces the probability of the coincidence being by chance (physically unrelated outbursts of optical and gamma-ray radiation happening within the same three day interval) to below 10^{-6}.

Except for clues on the radiation processes, the correlated flare confirms the correct identification of the gamma-ray source. The statistical evidence of gamma-bright sources being correctly identified with flat-spectrum radio sources is very high (Mattox et al., in preparation). The large number of yet unidentified EGRET sources may indicate the presence of a second major population among gamma-bright sources which has a large scale-height or a nearly isotropic distribution on the sky. In view of the large error boxes of the gamma-ray sources any individual identification has to rely on unambiguously correlated activity.

5 Constraints on Reprocessing Mechanisms

The optical and the gamma-ray outbursts both last for about 2$\pm$ 1 days. If the radiation recorded in one of the energy bands is reprocessed from the other, this reprocessing has to occur in a volume which is not much larger than the emitting volume to avoid the flare being spread out in time. The optical flare precedes the gamma-ray flare by one day. This suggests that either the gamma-rays are reprocessed synchrotron radiation or that the increase in both frequency ranges is triggered independently by a primary process with the optical radiation responding faster.

Mannheim and Biermann (1992) suggested that the decay products of relativistic hadrons give rise to flares of electromagnetic radiation. With photon energies corresponding to the energies of the secondaries decaying in an originally highly relativistic hadronic shower, one would expect photons of higher photon energies leading those of lower energies - contrary to what is observed in PKS 1406-076. The temporal sequence cannot rule out the possibility, however, that the optical flare marks the trigger of the onset of the hadronic shower (e.g. if the optical flare were associated with the injection and acceleration of the primary particles). The (delayed) gamma-ray flare will then still be related to the decaying primary particles. Apart from energetic constraints (e.g. Schlickeiser, 1995) such a scenario would require very special tuning to explain the shapes of the flares (Wagner, 1996a). Likewise, the model of Bednarek and Kirk (1995) also suffers from the problem of producing *delayed* optical radiation.

The Synchrotron-Self-Compton (SSC) mechanism is one of the most popular models which has been put forward to predict and explain the gamma-ray emission of AGN (Marscher, 1980, Maraschi, et al., 1992). In a strict sense SSC models require the very electrons that radiate the synchrotron emission to upscatter the soft photons instantaneously and in situ and cannot explain the lag between the peaks in the two frequency ranges. IC scattering may instead occur downstream of the site of synchrotron emission. It is very likely in this case, however, that the distribution function of the radiating particles changes during the optical flare.

Several models have been suggested which involve IC scattering of external photons by the relativistic electrons within the jet. These external photons may either originate from the accretion disk (e.g. Dermer et al., 1992), the broad-line region (e.g. Sikora et al., 1994) or the dusty torus (Wagner et al., 1995a). The simplest interpretation of the tight correlation of optical variability and gamma-flares suggests that the optical flare provides the photons which are scattered up in energy. In this case the seed photons would have to emerge from a site that can produce very luminous flares of synchrotron radiation. The only site within an AGN for such a flare that has been discussed in any detail is the jet. The seed photons would then not be genuinely external but would be reflected back into the jet. The delay between the optical and the gamma-ray flare would correspond to the time required for the scattering part of the jet to reach the gamma-photosphere. If the seed photons do not originate from within the jet, such a model would be very constrained by the requirement to reproduce the IDV characteristics (Wagner and Witzel, 1995) which generally call for relativistic beaming. The studies by Begelman et al. (1994) and Sikora et al. (1994) may tie IDV and high gamma-luminosity within one model.

A variant of the above suggestions would be two-fluid models (see e.g. Kundt and Gopal-Krishna, 1980, Sol et al., 1989). Even in a simple jet model the particle distribution varies along and across the jet. Treated as a multiple set of fluids, synchrotron-flares which originate in localized sections of the jet will be IC scattered by other parts of the jet where electron densities, local magnetic field structures and particle distribution functions are different, invalidating attempts to model the scattering within straightforward SSC scenarios. Electron-Proton beams may also give rise to the gamma-ray emission through annihilation (Henri et al., 1993). As mentioned by Herni et al., optical synchrotron radiation may accompany the gamma-ray flare. The delay between the optical and gamma-ray burst would be caused by the high gamma-ray opacity at the onset of the flare.

Many of the models discussed above have illustrated one specific reprocessing scenario. More detailed studies are needed which take all of these scenarios into account since all of them contribute to the gamma-ray emission to some extend (i.e. a certain degree of SSC, scattering of external photons, etc. is unavoidable). The occurrence of correlated variations suggests that most of the reprocessing is dominated by a single mechanism (otherwise the response in the gamma-ray range would be diluted very much). On the other hand, the characteristics described in sections 2-4 illustrate that the full set of observables must be monitored with high precision and dense sampling to be modeled quantitatively.

6 TeV flares in Mrk 421

As shown above, the rapid flares seen in several gamma-bright AGN show up also at lower photon energies, indicating that the IDV variations are correlated throughout the entire spectrum up to the GeV range. At even higher energies the photon fluxes get extremely low and sufficiently high photon statistics can be

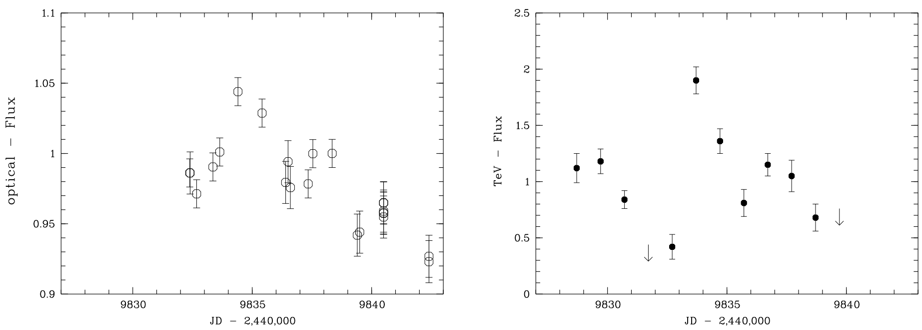


Fig. 5. The optical flares of Mrk 421 and simultaneously recorded TeV emission (compiled from Buckley et al., 1995).

achieved only by the atmospheric Cherenkov technique. The Whipple telescope which has a maximum efficiency at energies of a few TeV had reported significant detections of the nearby BL Lac object Mrk 421 during several observing runs (e.g. Kerrick et al., 1994). During some of these observations the source was flaring in a manner similar to the variations seen among the brighter EGRET detected sources. While being an EGRET-detected source as well, the GeV fluxes of Mrk 421 have always been too low to permit investigations of variability on short time-scales. On longer time-scales the source has been fairly steady and showed little variability in the GeV range.

Mrk 421 is different from other EGRET-detected sources also in being a low-luminosity source at all frequencies. The synchrotron spectrum extends up into the X-ray regime where high (flux and spectral) variability has been detected with several X-ray instruments (see e.g. Wagner and Witzel, 1995). The amplitude of variations is largest close to the high energy cutoff of the synchrotron spectrum and significantly lower in the optical range. Within the context of IC models for the GeV emission, which identify the GeV emission as scattered optical radiation, one expects that the variation within the gamma-range follow the trend of increasing amplitude with photon energy. This explains the high degree of variation of Mrk 421 at TeV energies and its low degree of variations in the GeV regime. Likewise, this assumption predict correlated variations in the TeV regime and at lower frequencies.

We carried out optical monitoring in parallel to the TeV observations by the Whipple group in April 1995. The Whipple team reported variations in Buckley et al. (1995), reproduced in the right hand panel of figure 5. As shown in the left hand panel of fig. 5, optical variations with a similar pattern but much reduced amplitude have been recorded. The sampling pattern is not perfect and the campaign lasted only for 15 days but the degree of correlation is very high, indicating that the non-thermal radiation in this source is indeed correlated over at least 13 decades of photon energy (Takahashi et al., 1996, Wagner et al., 1996).

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