INTENSITY CORRELATION BETWEEN OBSERVATIONS AT DIFFERENT WAVELENGTHS FOR Mkn 501 IN 1997

Cécile RENAULT\(^1\) for the CAT collaboration, Nicolas RENAUD\(^2\) and Gilles HENRI\(^2\)

\(^{(1)}\)LPNHE Paris VI et VII  
4 place Jussieu, Tour 33 - Rez de chaussé, F-75252 Paris Cedex 05  

\(^{(2)}\)Observatoire de Grenoble  
BP 53, F-38041 GRENOBLE Cedex 9  
Email: recile@in2p3.fr, nrenaud@obs.ujf-grenoble.fr, Gilles.Henri@obs.ujf-grenoble.fr

Abstract. The CAT imaging telescope on the site of the former solar plant Thémis in southern France observed γ-rays from the BL Lac object Mkn501 above 250 GeV for more than 60 usable hours on-source from March to October 1997. This source was in a state of high activity during all this period. By studying the correlation between the photons of different energies detected by the CAT imaging telescope and by the ASM/RXTE experiment (1.3-12.0 keV) on board the Rossi X-Ray Timing Explorer, we may constrain the mechanisms which could lead to the emission of these photons.

1. Introduction

During several months in 1997, the Active Galactic Nuclei Mkn 501 (z=0.034) went into a very high state of activity. It is the second closest BL Lac object and one of the two extra-galactic sources confirmed at very high energy (the other being Mkn 421). The source was extensively observed at wavelengths ranging from radio to VHE (Very High Energy) gamma-rays. Here we use essentially X-ray and gamma-ray information respectively from ASM (All Sky Monitor) on board RXTE and CAT (Cherenkov Array at Thémis).

The spectral energy distribution of Mkn 501 exhibits two bumps. In agreement with the unified scheme of the AGN (\(^1\)), the first peak with a maximum at 10-100 keV (\(^2\)) is thought to be produced by synchrotron emission of particles in a jet pointing towards us; the second peak culminates around 1 TeV (\(^3\),\(^4\)), making Mkn 501 the hardest BL Lac object ever observed. In Section 2, the data sample is described while Section 3 provides information about theoretical models. Then, Sections 4 and 5 are respectively devoted to the search for variability and micro-variability in the VHE band. Sections 6 and 7 presents studies of correlations between emissions in X-ray and gamma-ray and correlation between different bands inside the VHE domain.
2. Data sample

The 17.8 m$^2$ CAT imaging telescope started operation on the site of the former solar plant Thémis in the French Pyrénées (southern France) in Autumn 1996. A very high definition camera of 600 phototudes (4.8° field of view) allows an analysis using the Cherenkov light distribution inside the image of the cosmic-ray shower. A complete description of the telescope and the camera can be found in [5], [6] and details about the analysis method are available in [7], [8].

After data cleaning, a total of 57.2 hours of observation of Mkn 501 and 22.5 hours on control regions is used to compute the light curve above 300 GeV.

This BL Lac object is also monitored on a regular basis by the All Sky Monitor (ASM) on board the Rossi X-Ray Timing Explorer (RXTE) ([9]), providing information about the X-ray activity in the energy region from 2 to 12 keV. The ASM count rates are determined from the “definitive” ASM data which have a dwell duration larger than 30 seconds and a flux fit with a reduced $\chi^2$-value below 1.5. The light curve is extracted using the “ftools 4.0” package.

Figure 1 presents the light curve obtained with the CAT and ASM data between March and September 1997.

![Figure 1. Light curve of Mkn 501 from March to September 1997 with a time binning of 1 day. Upper panel: X-ray data from ASM, lower panel: gamma-ray data from CAT.](image)

3. Models

In the case of leptonic model, the high energy emission of blazars can be well explained by Inverse Compton emission of relativistic particles. As BL Lacs objects are characterized by the weakness of their thermal component and of their emission lines, the principal source of photons for the Compton interaction should be the synchrotron
emission radiated by the high energy particles (SSC model). In the case of hadronic models the high energy emission is produced by pair cascades resulting from initial photopion processes. In the both cases observation of photons with an energy of $\gamma m_e c^2$ requires particles with a Lorentz factor at least $\gamma$. Particle acceleration is so an important ingredient of all model with emission at high energy. The variability and correlation between different wavelengths of this emission can give severe constraints on both models.

4. Search for short-term variability

The search for short term variability is of special importance as it provides immediately an upper limit on the source size $R$ for a given Doppler factor $\delta$ with few assumptions needed. In order to confront a specific model or define a region in the $(R,\delta)$ plane, few hypothesis must be made.

While variability at a daily scale is directly seen Fig. 1, the search for intra-night variability must be studied in more detail. In this paper the aim is not a systematic study of all scales of variability but the identification of a rise time, i.e. the necessary time for doubling the flux with a significance of at least 3 $\sigma$. However, as the source is observed for only about one-two hours per night, we can not check sub-day variations with durations larger about 30 minutes. At the other extreme, if we are interested in a significant rise time of 1-10 minutes, the flux has to be larger than 6 gamma per minute. Only three nights satisfied this requirement: MJD 50551.08 (8.7 $\gamma$/min), 50554.13 (14.3 $\gamma$/min) and 50606.96 (7.7 $\gamma$/min).

The night of April 16, with the strongest flare (MJD 50554), appears to be flat when it is studied with time binnings of 1 to 10 minutes; this is also true for the night of April 13. Only June 7 exhibits a lightcurve with a regular increase of the flux at the beginning of the night (from 3.5 to 9 $\gamma$/min) in $\Delta t \approx 30$ minutes, as shown in Fig. 2. The $\chi^2$ of the fit by a constant on the first 6 points is 13.7.

Thus the size $R$ of the emission region must be less than $c\delta \Delta t$ which leads to $R < 5.4 \times 10^{13} \times \delta$ cm. It is possible to combine this limit with two other constraints:

- $\gamma - \gamma$ opacity $< 1$, to allow TeV photons to escape (upper limit);
- compatibility with the observed ratio $L_{\text{sync}}/L_{\text{IC}}$ from [2] (lower limit).

Fig. 3 presents the results obtained assuming an homogeneous source and a particle distribution in $\gamma^2 \exp(-\gamma/\gamma_{\text{max}})$ which leave a very restricted domain with $R < 10^{12}$ cm and $\delta > 100$. These values are quite unrealistic, the Doppler factor being too high. So the hypothesis of homogeneity should be certainly revised for further studies. Moreover, in such a homogeneous model, we would expect a very strong short-term correlation between X-ray and gamma-ray which is not observed (see Section 6).

5. Search for micro-variability

As suggested by M. Urry (private communication), a flare could result of the superimposition of many “micro-flares” with duration of a few seconds. We can study the time arrival distribution of the photons for the 1.5 hours of observation taken the April 16th. Because of the very high flux ($\approx 8 \times$ the Crab flux), we can directly use the “ON” data which contain about 90% of gammas. The result is presented in Fig. 4. No deviation from the expected exponential distribution is observed: no flares of a
Figure 2. Light curve of Mkn 501 for June 7 with a threshold of 300 GeV.

Figure 3. Permitted values in the plane ($R, \delta$). The upper line (green) shows the upper limit put by the rise time of 30 minutes. The left line (blue) indicates the upper limit induced by the requirement that $\gamma - \gamma$ opacity be lower than 1. The right line (red) indicates the lower limit dictated by the compatibility with the observed ratio $\text{Lum}_{\text{sync}}/\text{Lum}_{\text{IC}}$ from [1].
few seconds contribute significantly to the very high flux observed during this night.

Figure 4. Distribution of the time difference between two consecutive photons in seconds. The distribution is well fitted by an exponential law (full line).

6. Search for correlation X-gamma

A correlation between X-ray emission, due to synchrotron radiation and gamma-ray emission, assumed to be produced by inverse-Compton scattering would reinforce the fact that the same population of particles is at the origin of both emissions. It does not presume of the nature of these particles, leptonic or hadronic. Fig 4 presents the nightly correlation of the flux of Mkn 501 as measured by ASM and CAT. We restricted the sample to the months April and June when the flux was variable and enough data were available. The night April 16 is not included in the sample because it strongly dominates the fluctuations in the TeV band and does not correspond to any flare in the 2-12 keV band. Unfortunately, it is not possible to study correlation at shorter time scales because of the differences in time sampling: CAT observe the source consecutively for 1 to 3 hours per day while ASM takes data for 90 seconds more or less every hour: the statistics in the X-ray band is not significant per bin of a few hours only.

The quite low correlation coefficient ($\approx 0.35 \pm 0.10$) could be explained by the differences in time sampling. If we can not put by this way constraints on delays between X-ray and gamma-ray fluctuations, we have evidence of simultaneous evolution in both energy ranges, comforting the hypothesis of a common origin for both emissions. The lack of ASM flare corresponding to the April 16 gamma flare, despite an increase of the flux observed by BeppoSAX in the 1-200 keV band simultaneously with the CAT flare, is understandable if the evolution of the spectral energy density follow the evolution schematized in Fig. 4.
Figure 5. Correlation coefficient in function of the time delay between X-ray radiation (ASM, 2-12 keV) and gamma-ray emission (CAT, > 300 GeV). A positive delay means that variations in the TeV range lag those in the X-ray band. It is computed from data of April and June 1997 (except 16th).

Figure 6. Schema of the evolution of spectral energy density explaining why the flare of April 16 is not observed by ASM.
7. Search for correlation gamma-gamma

One can also search for time delay between “hard” and “soft” CAT photons. In an
inhomogeneous model with pair creation (as described in [10] for an external model),
the most energetic photons should lag the softer ones because they can escape later.
In order to test this hypothesis, the lightcurves in two energy bands were computed
for two nights (see Fig. 7). Whatever the total flux is constant or increasing, no
experimental evidence for time delay is seen. This chaotic behaviour needs a detail
study of a time-dependent inhomogeneous model. Such models are in progress (for
a model only including external Compton interaction see Renaud & Henri, these
proceedings).

8. Conclusion

During its strong outburst of 1997, the BL Lac object Mkn 501 was extensively
observed at many wavelengths, in particular by All Sky Monitor in the X-ray band and
by CAT at TeV energies. The search for variability and correlations can give clues
for the understanding of the still most mysterious class of AGN. With a rise time
of 30 minutes and a nightly correlation between X-ray and gamma-ray emissions,
models with a same population of particles, leptonic or hadronic, yielding in a
compact zone synchrotron radiation and inverse-Compton emission are reinforced.
More detailed studies indicates that a simple homogeneous model can not account for
the observations and further refinements like inhomogeneity seem to be necessary.

9. References

[1] M.C Urry and P. Padovani, PASP 107, 803 (1995).
[2] E. Pian et al, ApJ 492, L17 (1998).
[3] F. Aharonian et al, A&A 342, 69 (1999).
[4] CAT Mkn501 paper A&A in preparation.
[5] A. Barrau et al, NIM A 416, 278 (1998).
[6] A. Barrau, PhD thesis Université J. Fourier (1998)
[7] S. Lebohec et al, NIM A 416, 425 (1998).
[8] S. Lebohec, PhD thesis Université paris XI (1996)
[9] R.A. Remillard, M.L. Levine, M.L., Proc. All-Sky X-ray Observations in the Next Decade, edited
by Matsuoka and Kawai astro-ph/9707338 (1997)
[10] A. Marcowith, G. Henri & G. Pelletier, MNRAS 277 (1995)
Figure 7. Lightcurve of Mkn 501 observed by CAT in 1997 in the ranges 300-800 GeV and 800-3000 GeV with time binning of 10 minutes. Upper panel: a flat night (April 16) and lower panel: the night June 7 with a rising time of 30 minutes at the beginning.