BEPPO-SAX OBSERVATIONS OF MKN 421: CLUES ON THE PARTICLE ACCELERATION ?

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ABSTRACT Mkn 421 was repeatedly observed with *Beppo*SAX in 1997–1998. We present highlights of the results of the thorough temporal and spectral analysis discussed by Fossati et al. (1999) and Maraschi et al. (1999), focusing on the flare of April 1998, which was simultaneously observed also at TeV energies. A theoretical picture accounting for all the observational constraints is discussed, where electrons are injected at low energies and then progressively accelerated during the development of the flare.

KEYWORDS: galaxies: active — BL Lacertae objects: individual (Mkn 421)

THE 1998 X–RAY/TEV FLARE

Mkn 421 ($z = 0.031$) is the brightest blazar at X–ray and UV wavelengths and the first extragalactic source discovered at TeV energies (Punch et al. 1992), where dramatic variability has been observed (Gaidos et al. 1996).

In 1998 *Beppo*SAX observed Mkn 421 as part of a long lasting monitoring campaign. *Beppo*SAX observations are dominated by an isolated flare (see Fig. 1), and one of the striking and important results is that in correspondence with the X–ray flare of April 21$^{\rm st}$ a sharp TeV flare was detected by the Whipple Cherenkov Telescope (Figure 1). The peaks in the 0.1–0.5 keV, 4.0–6.0 keV and 2 TeV light curves are *simultaneous within one hour* (see Maraschi et al. 1999).

Here we will focus on the X–ray characteristics of the April 21$^{\rm st}$ flare. We accumulated light curves for different energy bands. The post–flare light curves have been modeled with an exponential decay, superimposed to a steady emission. Four the main results:

<u>Decay Timescales:</u> the timescales range between 30 and 45×10^3 seconds, and *do not* show a clear (if any) relationship with the energy, rather suggesting that the post–flare spectral evolution can be *achromatic*. This result leads to reject the simplest possibility that the decay evolution is driven by the radiative cooling of emitting electrons (this simplest picture would produce a dependence of the timescale with energy, $\tau \sim {\rm E}^{-1/2}$).

<u>Flaring/Steady components:</u> exponential decay fits require the presence of an underlying less variable component.

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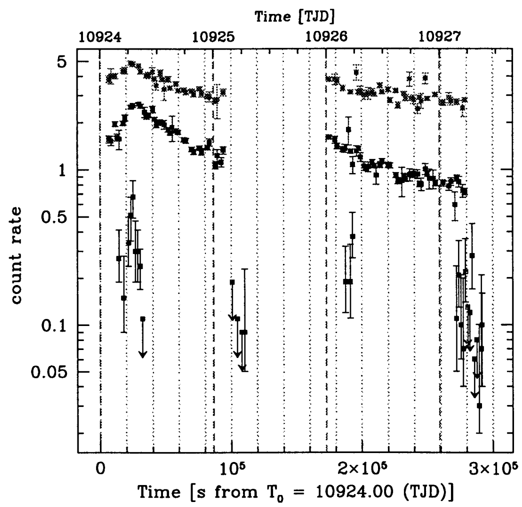

FIGURE 1. Light curves of Mkn 421 at TeV and X–ray energies, during the 1998 campaign. They are shown in order of increasing energy from bottom to top: Whipple E$\geq$ 2 TeV, MECS 4.0–6.0 keV and LECS 0.1–0.5 keV (both with 1500 s bins, multiplied by a factor 4 and 8, respectively). The count rate units are cts/s for *Beppo*SAX data, and cts/min for Whipple data.

Time Lag: the harder X–ray photons lag the soft X–ray ones. We performed a cross correlation analysis using the DCF (Edelson & Krolik 1988) and the MMD (Hufnagel & Bregman 1992) techniques and statistically determined the significance of the time lags using Monte Carlo simulations (Peterson et al. 1998). We refer to Zhang et al. (1999) for the relevant details of such analysis. The result is an average lag of $-2.7^{+1.9}_{-1.2}$ ks for DCF, and $-2.3^{+1.2}_{-0.7}$ ks for MMD (1 σ). This finding is opposite to what is normally found in the best monitored HBL X–ray spectra (e.g. Urry et al. 1993; Kohmura et al. 1994; Takahashi et al. 1996; Zhang et al. 1999) whose hard-to-soft behavior is usually interpreted in terms of cooling of the synchrotron emitting particles.

Rise vs. Fall: possible "asymmetry" of the rise/decay of the flare especially for the higher energy X–rays. The flare seems to be symmetric at the energies corresponding (roughly) to the synchrotron peak, while it might have a faster rise at higher energies. This could be connected to the observed hard–lag.

SPECTRAL VARIABILITY (1997 & 1998)

We accumulated spectra in sub-intervals, and developed an *intrinsically curved spectral model* to be able to estimate the position of the peak of the synchrotron component. In 1997 the source was in a lower brightness state, with a softer ($\Delta\alpha_{97,98} \simeq 0.4$) X–ray spectrum at all energies, and the peak energy 0.5 keV lower. There is a clear relation between the flux variability and the changes in the spectral parameters, both in 1997 and in 1998.

Synchrotron peak energy: the main new result is that we were *able to determine the energy of the peak of the synchrotron component* (with its error). We find a correlation between luminosity and shifts of the peak position (Fig. 2). The source reveals a highly coherent spectral behavior between 1997 and 1998, and through a large flux variability. The peak energies lie along a tight relation $E_{peak} \propto F^{0.55\pm0.05}$.

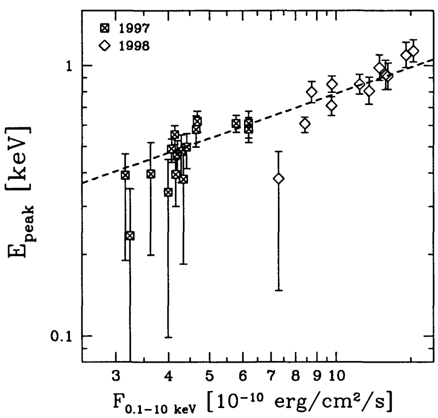

FIGURE 2. Synchrotron peak energy plotted versus "de-absorbed" 0.1–10.0 keV flux. The dashed line represents the best fitting power law, having a slope $\epsilon = 0.55$.

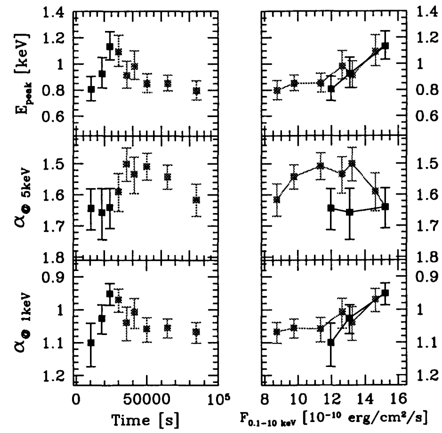

FIGURE 3. The photon spectral indices at 1 keV and at 5 keV, and energy of the peak of the synchrotron component, are plotted versus time and "de-absorbed" 0.1–10.0 keV flux.

Hard Lag in 1998 spectra: the spectral analysis confirms the signature of the hard lag. A blow up of the 1998 flare interval is shown in Figure 3. The main remarkable features are: (a) the synchrotron peak shifts toward higher energy during the rise, and then decreases as soon as the flare is over. (b) The spectral index at 1 keV reflects exactly the same behavior, as expected being computed at the energy around which the peak is moving. (c) On the contrary, the spectral shape at 5 keV does not vary until a few ks after the peak of the flare, and only then –while the flux is decaying and the peak is already receding– there is a response with a significant hardening of the spectrum.

The fact that the spectral evolution at higher energies develops during the decay phase of the flare, produces a nice counter-clockwise loop in the α vs. Flux diagram, i.e. *opposite* way with respect to all the other known cases for HBLs (e.g. Sembay et al. 1993; Kohmura et al. 1994; Takahashi et al. 1996).

PHYSICAL INTERPRETATION

Let us now focus on the possible interpretation of the two main results of this work: the *hard lag* and the *evolution of the synchrotron peak.*

The occurrence of the flare peak at different times for different energies is most likely related to the particle acceleration/heating process.

We therefore *introduced an acceleration term in the time dependent particle kinetic equation* within the model proposed by Chiaberge & Ghisellini (1999), which takes into account the cooling and escape terms and the role of delays in the received photons due to the travel time from different parts of the emitting volume.

The main constraints on the (parametric) form of the acceleration are: [A] particles have to be progressively accelerated from lower to higher energies within the flare rise timescale to produce the hard lag; [B] the emission in the LECS band from the highest energy particles (those radiating initially in the MECS band) should not exceed that from the lower energy ones, as after the peak no further increase of the (LECS) flux is observed; [C] the total decay timescale might be dominated by the achromatic crossing time effects, although the initial phase might be partly determined by the different cooling timescales.

It should be also noted that –within this scenario– the symmetry between the raise and decay of the softer energy light curve seems to suggest that at the same very energies where most of the power is released –possibly determined by the balance between the acceleration and cooling rates– the acceleration timescales are comparable to the region light crossing time.

If the timescales associated with this process are intrinsically linked to the typical size of the emitting region, we indeed expect the observed light curve to be symmetric where the bulk of power is concentrated, and an almost achromatic decay. Indeed, within a single emission region scenario, we have been able to reproduce the sign and amount of lags, postulating that particle acceleration follows a simple law, and stops at the highest particle energies. The same model can account for the spectral evolution (shift of the synchrotron peak) during the flare.

CONCLUSIONS

These results provide us with several *temporal* and *spectral constraints* on any model. In particular, they could possibly be the *first direct signature of the ongoing acceleration process*, progressively "pumping" electrons from lower to higher energies. The measure of the delay provides a tight constraint on the timescale of the acceleration mechanisms.

A last crucial point is that our results support the possibility of the presence and role of quasi–stationary emission. The short-timescale, large-amplitude variability events could be attributed to the development of new individual flaring components (possibly maintaining a quasi-rigid shape), giving rise to a spectrum outshining a more slowly varying emission. The decomposition in these two components might allow to determine the nature and modality of the dissipation in relativistic jets.

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