Extreme synchrotron blazars: the case of Mkn 501

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BeppoSAX observations of Mkn501 in April 1997 (Pian et al. 1998), have revealed an extraordinary X-ray emission from this BL Lac object, during a phase of high activity at TeV energies, as monitored with the Whipple, HEGRA and CAT Cerenkov telescopes. The 0.1–200 keV spectrum was hard, and the X-ray power output peaked at or above 100 keV, 2 or 3 orders of magnitude more than what indicated by previous observations, while the luminosity increased by at least a factor ~20. The X-ray spectrum hardens when the source is brighter, but variations seem limited to energies greater than ~0.5 keV. All these unprecedented spectral information pose severe constraints to all models, and we discuss in particular how the homogeneous, one-zone synchrotron self Compton model must be modified to account for the observed properties. Other sources, besides Mkn 501, could undergo similar flares.

1. INTRODUCTION

BL Lac objects come in at least two flavours, according to their overall spectral energy distribution (SED) viewed in a $\nu$–$\nu F_\nu$ representation: sources in the first group have the peak of their synchrotron emission in the IR–optical part of the spectrum. To this subclass belong most, but not all, BL Lacs discovered through their radio emission. In the second family the synchrotron peak is located at higher (UV and soft X-ray) frequencies. These are most, but not all, radio–selected BL Lacs. Because of this spectral difference, Padovani & Giommi (1995a) introduced the name LBL (low energy BL Lacs) and HBL (high energy BL Lacs) for the two families.

Mkn 501 is an example of HBL radio–selected BL Lacs, belonging to the complete 1 Jy BL Lac and the S4 radio samples, but also to the HEAO–1 and the Einstein Slew survey samples (see e.g. Padovani & Giommi 1995b). It is one of the closest BL Lac object ($z = 0.034$) and it was the second BL Lac object, after Mkn 421, to be detected in the TeV energy band (Quinn et al. 1996; Bradbury et al. 1997). Prior to BeppoSAX, it was observed a few times in the X-rays, showing a spectrum relatively steep (energy index $\alpha_x > 1.2$) in EXOSAT (Sambruna et al. 1994), while in two observations by Einstein the spectrum can be fitted with a power law with index flatter than 1,
Figure 2. The X–ray (ASM) and TeV light curve of Mkn 501 during 1997.

but with large errors (Urry, Mushotzky, & Holt 1986). A spectral index $\alpha_x > 1$ indicates a synchrotron peak in the far UV region.

According to the All Sky Monitor (ASM) on-board RossiXTE, its X–ray emission was relatively low during all 1996, but it entered a bright and active phase from the beginning of 1997, with an average flux roughly twice the average of the 1996 flux. This state is still continuing at the time of writing (Dec. 1997). The ASM light curve is reported in Fig. 1. During the entire 1997, the source was also extremely active at TeV energies, as demonstrated by the light curve in Fig. 2, which collects data of different observatories (Catanese et al. 1997, Aharonian et al. 1997, Protheroe et al. 1997) during the period Feb–Sept 1997. Note the recurrent rapid flares, during which the source becomes a factor 5–10 brighter than the Crab.

BeppoSAX observed Mkn 501 the 7, 11 and 16 of April 1997, during one of the TeV flares (Pian et al. 1998). Particularly interesting is the last BeppoSAX observation, coincident with a maximum of the TeV light curve. The X–ray spectrum revealed by BeppoSAX was exceptional: it shows the synchrotron peak of its emission at or above 100 keV, with a brightening of the overall power, with respect to other previous observations, by a factor $\sim 20$.

2. BEPPOSAX OBSERVATIONS OF MKN 501

In Fig. 3 we show the LECS+MECS BeppoSAX spectrum data of April 16, while in Fig. 4 we show the MECS+PDS spectrum of the same observation. In Fig. 5 we plot the ratio between the Apr 16 and the Apr 7 spectrum (Pian et al. 1998). This ratio is response matrix and calibration independent. Note how the spectrum pivots around $\sim 0.5$ keV, and the flattening of the spectrum in the high (Apr 16) state. Data analysis confirms this behaviour: in Table 1 we report the relevant information of the three observations. The Apr 16 spectrum is well fitted by a broken power law in the LECS+MECS range, and another broken power law in the MECS+PDS range.
range: comfortingly, the two separate analysis agree in the intermediate MECS range. We can therefore conclude that it is likely that the spectrum continuously steepens from 0.1 to 100 keV, but remaining always flatter than $\alpha_x = 1$. Therefore, in a $\nu - \nu F_\nu$ plot, this spectrum peaks at the highest PDS energies, i.e., above 100 keV. Note also the large flux in the [13–200] keV band of the 16 Apr observations, a factor $\sim 4$ larger than 9 days before. Smaller (30%) variations in $\sim 3$ hours are present during each pointing.

3. THE OVERALL SPECTRUM OF MKN 501

In Fig. 6 we show the overall spectrum of Mkn 501, collecting data which are simultaneous or nearly simultaneous with the BeppoSAX observations. For comparison, we show also a collection of non simultaneous data taken from the literature. Note:

- The synchrotron peak shifts by almost a factor 1000
- The X–ray spectrum and flux, below 0.5 keV.

Figure 3. LECS+MECS BeppoSAX spectrum of the April 16 observation of Mkn 501, fitted with a broken power law.

Figure 4. MECS+PDS BeppoSAX spectrum of the April 16 observation of Mkn 501, fitted with a broken power law. The low energy power law index is found to perfectly agree with the high energy spectral index of Fig. 3.

Figure 5. Ratio of the Apr 16 with the Apr 7 BeppoSAX spectra of Mkn 501. Note the spectral flattening above $\sim 0.5$ keV. Below this energy the spectrum remained almost unchanged.

Figure 6. The overall spectrum of Mkn 501.
4. MODELLING

In BL Lac objects the absence of prominent emission lines and of any, albeit weak, thermal signature, such as emission from an accretion disk or reprocessing due to dust, favours emission models based on the synchrotron self–Compton (SSC) emission, where ultrarelativistic electrons scatter the synchrotron photons they themselves produce (see e.g. Maraschi, Ghisellini & Celotti

\[ \alpha_1 = 0.63 \pm 0.04, \quad 0.64 \pm 0.03, \quad 0.40 \pm 0.03 \]
\[ \alpha_2 = 0.91 \pm 0.02, \quad 0.80 \pm 0.02, \quad 0.59 \pm 0.02 \]
\[ E_b = 1.76 \pm 0.23, \quad 1.85 \pm 0.33, \quad 2.14 \pm 0.33 \]
\[ \alpha_{PDS} = 0.99 \pm 0.13, \quad 0.79 \pm 0.09, \quad 0.84 \pm 0.04 \]
\[ F_{[2-10]} = 2.20, \quad 2.45, \quad 5.35 \]
\[ F_{[13-200]} = 3.75, \quad 5.15, \quad 18.8 \]

Table 1
\( \alpha_1 \) and \( \alpha_2 \) are the indices derived by fitting the LECS+MECS data with a broken power law. Unabsorbed fluxes in units of \( 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \).

- According to ISO preliminary data analysis, the far infrared flux was at the same level of the old IRAS observations (P. Barr, private communication)
- Hard X–ray and TeV flux vary together, almost linearly
- The peak of the Compton component lies at energies below 0.5 TeV
- With respect with the ‘normal’ state (defined by the ensemble of the previous non simultaneous data), the source brightened by a factor \( \sim 20 \), and by a factor \( \sim 4 \) between the 7 and 16 of April.

Figure 6. The SED of Mkn 501, adapted from Pian et al. 1998

Figure 7. SSC spectra calculated assuming a continuous injection of relativistic electron through an homogeneous source, for different values of the injected power. Note how the self–Compton luminosity increases less than than synchrotron luminosity.
On the contrary, in more powerful emitting line blazars, the dominating process for the formation of the high energy spectrum can be the inverse Compton scattering of relativistic electrons in the jet off photons produced outside the jet, for instance by the emission line clouds or by the accretion disk (EC model, Dermer & Slikkeiser 1992, Sikora, Begelman & Rees 1994, Ghisellini & Madau 1996, Ghisellini et al. 1997).

The pure SSC model, however, fails to explain the April observations of Mkn 501. The main observational constraints are the flattening of the X-ray spectrum between April 7 and 16, and the simultaneous TeV flux variations. The radiative cooling time of the electrons producing both the X-ray and the TeV flux is short, and a continuous resupply of energy must take place. This can have the form of a continuous injection of high energy particles, which find their equilibrium distribution in a time shorter than the light travel time $R/c$. In this framework, the observed flattening at X-ray energies is caused by the flattening of the injected particle distribution. However, if the particle distribution is flatter at all energies, the pivoting at $\sim 0.5$ keV implies that less particles are emitting at IR–optical frequencies. Due to the Klein Nishina decline of the scattering cross section, these are the relevant target photons for producing the TeV emission. Even if the high energy electrons increase in number, the target photons for Compton scattering decrease, resulting in a roughly steady TeV flux. To illustrate this behaviour, Fig. 7 shows the resulting spectra of the ‘pure’ SSC model where the electron injection varies, becoming flatter when more powerful, and extending to larger electron energies $\gamma_{\text{max}}$. As can be seen the Compton luminosity is almost constant, even if, in restricted energy ranges, the change of $\gamma_{\text{max}}$ results in a possible flux change. This clearly cannot account for the observed correlated variability.

However the emission, here modelled to come from a single homogeneous zone, is likely to be produced at a range of radii along a relativistic jet. Especially so for the radio – far IR flux. In addition, even in a simple homogeneous model, it is possible that one zone of the region undergoes a violent acceleration event producing a flat electron distribution. At birth, these electrons are already embedded in a ‘quiescent’ radiation field, and scatter these ambient photons together with the ones produced by themselves. The word ‘ambient’ has been chosen to distinguish this model from the ones where the target photons for Compton scattering are produced outside the jet.

We have then modelled the spectrum of Mkn 501 along these lines, assuming that the region producing the X-ray/TeV flare is embedded in a steady radiation field (extending in frequency from the mm to the optical), corresponding to the observed flux.

Results of these models are shown in Fig. 6, along with the fit to the ‘quiescent’ spectrum (i.e. to the collection of non simultaneous data prior to the BeppoSAX observations). Note that in this case we can well reproduced all the main spectral characteristics of the source. For all models we assumed a source size $R = 5 \times 10^{15}$ cm, a beaming factor $\delta = 15$, and a magnetic field $B \sim 0.8$ Gauss. For the quiescent state, we assumed to continuously inject relativistic electrons with a power law distribution $\propto \gamma^{-2}$ between $\gamma_{\text{min}} = 3 \times 10^3$ and $\gamma_{\text{max}} = 6 \times 10^5$, at a rate corresponding to an intrinsic injected power of $L' = 4.6 \times 10^{40}$ erg s$^{-1}$. For the Apr 7 spectrum the injected distribution is $\propto \gamma^{-1.5}$ between $\gamma_{\text{min}} = 10^4$ and $\gamma_{\text{max}} = 3 \times 10^6$, with $L' = 1.9 \times 10^{41}$ erg s$^{-1}$. Finally, for the Apr 16 spectrum, the injection is $\propto \gamma^{-1}$ between $\gamma_{\text{min}} = 4 \times 10^5$ and $\gamma_{\text{max}} = 3 \times 10^6$, with $L' = 5.5 \times 10^{41}$ erg s$^{-1}$. According to these parameters, the magnetic field energy density is greater than the particle energy density, but smaller than the overall radiation energy density. On the other hand, if we integrate the radiation energy density up to the energy $h\nu = 1/(\gamma_{\text{max}} m_e c^2)$, accounting then for only those photons available for scattering in the Thomson regime, we have that the magnetic field is dominant. Interestingly, the radiative cooling time is equal to the light crossing time for particles emitting at $\sim 1$ keV, where there is the pivot in the X-ray spectrum.
5. CONCLUSIONS

From the BeppoSAX observations of Mkn 501 we have learned that BL Lacs can undergo major flaring events, in which their overall, bolometric power increases by a huge factor, while at the same time increasing the typical energy of their radiating electrons. Such events must correspond to a dramatic increase of the power of the particle acceleration mechanism and of its efficiency in accelerating electrons up to TeV energies. The huge shift of the synchrotron peak frequency excludes in fact other possibilities, as a change of the beaming factor or of the magnetic field, since unreasonably large variations would be necessary in this case ($\nu_{\text{syn}} \propto B^3 \delta^2$).

We have also learned that it is likely that a pure, simple, one–zone SSC model cannot account for what we observe, but that there is the need to invoke another, steadier, source of IR photons as targets for the inverse Compton process. The coincidence of the amount of needed radiation density with what we derive from the observed flux is an indication that these photons are produced in the vicinity of the hard X–ray and TeV emitting region, probably by another, steadier, electron population.

Finally we can wonder if Mkn 501 is really exceptional, or if other sources exist with the same characteristics, namely a synchrotron peak located in the hard X–rays. These would guarantee the presence of TeV energy electron, and therefore these sources are the best candidates to be strong TeV emitters. From what we have observed of Mkn 501, it might be not easy to find these sources, since: i) Mkn 501 was observed with a steep X–ray spectrum prior to BeppoSAX; ii) even during the April 1997 flare, the low energy X–ray flux of Mkn 501 was not varying dramatically.

To find these ‘extreme synchrotron BL Lacs’ one should select sources with flat ($\alpha_X < 1$) X–ray spectra, checking, by constructing the SED, if the X–ray spectrum is produced by the synchrotron process (in this case the X–rays smoothly connect with the optical-UV data). For sources without a measured X–ray spectrum, overall spectral indices joining the radio, optical and the X–ray band can give some hints, since these broad band indices roughly measure the location of the synchrotron peak.

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