To date, only three objects have been firmly established as very high-energy gamma-ray sources in the Northern sky: the Crab nebula, which is a plerion, and the two blazars Markarian 501 and Markarian 421. This paper reviews the most striking results obtained for these sources by the CAT atmospheric Cherenkov imaging telescope.

1 Introduction

The CAT (Cerenkov Array at Thémis) $\gamma$-ray detector operates above 250 GeV since Autumn 1996. Its observation program has been largely devoted to the study of blazars. These objects are radio-loud active galactic nuclei (AGN’s) with a relativistic jet which is pointed directly to the observer. The jet emission dominates that of the accretion disk (and of the host galaxy) over a large energy domain. Thus, blazar observations offer the possibility of investigating the physics of jets more deeply, including particle acceleration and energy extraction in the vicinity of the AGN’s central “engine”.

Until now, however, only two blazars have been clearly detected at very high-energies (VHE) from the Northern hemisphere, these are Markarian 501 (Mkn 501) and Markarian 421 (Mkn 421). Since both are variable sources, their study by an atmospheric Cherenkov experiment requires a kind of “test beam” to check that the detector response is well under control. This is further mandatory if one wishes to compare the temporal and spectral properties of these blazars between different observation epochs. In VHE $\gamma$-ray astronomy, the Crab nebula is a strong source with a steady flux which can be used as a standard candle. In the following, we review briefly the results obtained by CAT on this source over four years, before dealing with the observations of Mkn 501 and Mkn 421.

*aSee the discussion in Weekes (1999).*
2 Non-variability of the Crab nebula VHE emission

The study of the Crab nebula VHE flux, as recorded by CAT between 1996 and 2000, is detailed in Piron (2000). The time-averaged integral fluxes above 250 GeV for the four years are $14.9 \pm 0.9$, $13.3 \pm 0.6$, $14.5 \pm 0.7$, and $14.2 \pm 0.7 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$, with a mean value $\Phi_{\text{CN}} = 14.10 \pm 0.35 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$. As can be seen in Fig. 1(a), the flux residuals within each year obey a Gaussian distribution with mean value $\mu \approx 0$ and variance $\sigma \approx 1$. This shows that the dispersion of all flux measurements is here purely statistical, and confirms the stability of the source emission (and of the detector!) down to a short time-scale, i.e. that of a single data acquisition ($\sim 30$ min).

The spectral analysis of CAT data is based on a likelihood method. It assumes a given parameterization for the spectral shape, and two simple hypotheses are successively considered for the differential $\gamma$-ray spectrum: a power law, $\phi_0 E^{-\gamma}_{\text{TeV}}$, and a curved shape. When applied to the $\sim 100$ hours of data taken on the Crab nebula, this method indicates the absence of any curvature between 0.5 and 13.0 TeV, and leads to the following power-law spectrum: $\frac{d\phi}{dE} = (2.21 \pm 0.05^{\text{stat}} \pm 0.60^{\text{sys}}) \times 10^{-11} E^{-2.80^{\pm 0.03}_{\text{stat}} \pm 0.06_{\text{sys}}} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ TeV$^{-1}$. The results are very stable from one year to another, as illustrated in Fig. 1(b) which shows the confidence level contours in the plane $\{\phi_0, \gamma\}$ of spectral parameters. Finally, all measurements shown in Fig. 1 make us very confident in the analysis of variable sources like Mkn 501 and Mkn 421.

3 VHE temporal and spectral properties of Mkn 501 and Mkn 421

The observations of these two blazars by CAT are detailed in the literature. Their light curves, as sampled by CAT, are shown in Fig. 2(a) and (b), respectively. Both sources are highly variable, with long periods of intense VHE activity in which a few series of bursts can be distinguished. This is particularly the case of Mkn 501 in 1997 and of Mkn 421 in 1998 and 2000. During these flaring periods both sources underwent a large night-to-night variability on several occasions. However, Mkn 421 is the only source which can also exhibit important flux variations within a single night. For instance, Mkn 421 light curves for three nights from the 3rd to the 5th February are shown in Fig. 3. While the fluxes recorded by CAT during the first and last nights were stable, respectively $\Phi_{>250\text{GeV}} \approx 1.3 \Phi_{\text{CN}}$ and $\Phi_{>250\text{GeV}} \approx 0.7 \Phi_{\text{CN}}$, the source activity changed dramatically in a few hours during the second night. The CAT telescope
started observation after the flare maximum while the source flux was at a level of $5.5\Phi^{\text{CN}}$. This is comparable to the highest TeV flux ever recorded, i.e., that of Mkn 501 during the night of April 16th, 1997 (see Fig. 2(a)). After this first episode, Mkn 421 intensity was reduced by a factor of 2 in 1 hour and by a factor of 5.5 in 3 hours. A simple causality argument implies that the $\gamma$-ray emitting region must be very compact here, with a size $\lesssim 10$ light-hours if one assumes a typical value of 10 for the geometric Doppler factor (which reduces the time-scale in the observer frame).

Fig. 2(a) shows the spectral energy distributions (SEDs) of Mkn 501 and Mkn 421. Mkn 501 showed a clearly curved spectrum in 1997, with a $\gamma$-ray peak lying above the CAT threshold. Mkn 421 is less extreme since its spectra do not show any significant curvature. In the framework of leptonic models (Tavecchio, these proceedings), which successfully explain the SED of Mkn 501 in the X-ray and VHE $\gamma$-ray ranges (see also our fit in Fig. 2(b), which is based on a homogeneous Synchrotron Self-Compton model), these results imply that the peak energy of the inverse Compton contribution of Mkn 421 SED is significantly lower than the CAT detection threshold. This is not surprising since the corresponding synchrotron peak is known to be lower than that of Mkn 501, and since leptonic models predict a strong correlation between X-rays and $\gamma$-rays.

As can be seen in Fig. 2(a), there is in fact some indication of curvature for the 2000 time-averaged spectrum of Mkn 421. This result is further discussed in Piron et al. (2001).
Figure 4: Spectral energy distributions (SEDs) of Mkn 501 and Mkn 421. VHE spectra are represented by an area showing the 68% confidence level contour given by the likelihood method with the assumption of a curved spectrum. (a) VHE SEDs as measured by CAT; (b) Mkn 501 X-ray and VHE SEDs for April 7th and 16th, 1997, as simultaneously measured by Beppo-SAX and CAT. Full lines come from a homogeneous SSC model.

4 Conclusion

Although the observations of Mkn 501 and Mkn 421 are quite numerous, alternative scenarios other than leptonic models are still successful in interpreting their SEDs. In the future the study of the dynamic aspects of blazar jet emission, including the temporal and spectral correlations between various wavelengths, is thus required in order to accurately constrain existing models, and to understand the particle acceleration and cooling processes occurring at the sub-parsec scale in jets. It should help to discriminate between these models and allow, in particular, to address more deeply the crucial problem of the plasma jet content.

For instance, Beppo-SAX and CAT have observed a correlated X-ray and γ-ray spectral hardening during the flares of Mkn 501 in 1997 (see Djannati-Ataï et al. (1999)). This behaviour is illustrated in Fig. 4(b) by the shift of the entire SED between April 7th and 16th. A simple correlation has been observed many times for Mkn 421, but always in terms of integrated (and not differential) fluxes due to the lack of statistics. Moreover, the VHE spectral variability of Mkn 421 has not been clearly proven yet (we discuss this problem in Piron et al. (2001)). Hopefully, the recent huge bursts recorded from this source in the beginning of 2001 should help to clarify this point.

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