Observations of Very High Energy Gamma-Radiation from Markarian 421

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Abstract

This article intends to summarize the observational data on the first extragalactical object to be discovered as a VHE Gamma-ray source, the BL Lac object Mkn 421. After a historical overview, the present situation is reviewed. As an intermediate conclusion it can be stated that while the source's existence and strong variability is firmly established, its spectral behaviour at energies above ≈ 3 TeV, especially in the quiescent state, is not known to a satisfactory precision.

1. A brief history of Mkn 421

Between 1967 and 1981, the armenian astronomer Benyamin Yerishevich Markarian with his assistants compiled a catalog of 1515 galaxies with a UV continuum (i.e. a UV spectrum with no (or very faint) emission or absorption lines indicating non-thermal processes). The objects were simply numbered: Mkn 1 - Mkn 1515 (as catalog name also "Mrk", "Mkr", "Mk" and "Mark" are used). The complete catalog was published as the "First Byurakan Survey" in Markarian et al. (1989) and parts of it beforehand in Astrofizika volumes 3 to 17. In volume 8 (1972), the objects Mkn 421 and Mkn 501 are named[1].

Already in the same year, Mkn 421 and Mkn 501 were identified with radio sources from the second Bologna survey: B2 1108+38 and B2 1652+39 (Colla et al., 1972). In 1975, Ulrich et al. identified both sources as BL Lac objects and measured their redshift: $z = 0.031$ for Mkn 421 and $z = 0.034$ for Mkn 501. Until today Mkn 421 is the closest BL Lac object with well measured z. For most other Mkn-Galaxies the redshift has been measured, too, but only a small part of them are BL Lac objects. Mkn-Galaxies are mostly Seyfert or starburst galaxies.

Mkn 421 and 501 cointinued their leading role in 1978 by being the first BL Lac objects which were identified with X-ray sources (Mkn 421 = 2A 1102+384 (Cooke et al. 1978), Mkn 501 = 4U 1651+39 (Schwartz et al. 1978)). Several multi-wavelength campaigns followed. Both sources were observed up to energies of several 10 keV (e.g. Mufson et al. 1984, Mufson et al. 1990, Fink et al. 1991). From archival plates, Miller obtained already in 1975 an optical light curve of Mkn 421 which contains measurements for almost every year between 1900 and 1975. This curve shows strong variability on timescales of months or less, but also over timescales of several years with a maximum-to-minimum change by a factor of 76 (4.7^m). In other observations, optical variability on timescales down to hours was seen with amplitudes of 1.4^m (GuangZhong et al. 1988). The average apparent luminosity of Mkn 421 is $\approx 14^m$.

Mkn 421 has not yet been detected at energies between 100 keV and 100 MeV (as opposed to Mkn 501 which has been detected by OSSE during the source's 1997 high state). Above

[1] Although I am going to focus on Mkn 421, the object Mkn 501 will be mentioned when authors were examining the two objects in one publication.

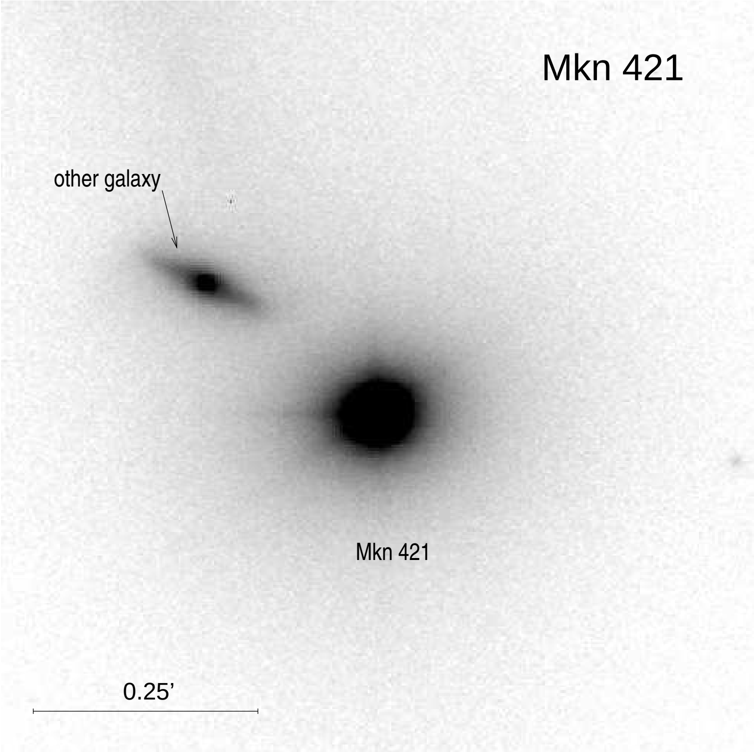

Fig. 1: Optical image of Mkn 421 and a neighbouring galaxy taken by A. Sillanpää and L. Takalo (University of Turku, Finland) with the Nordic Optical Telescope, La Palma, in 1995.

100 MeV, however, EGRET was able to detect 7 out of the 24 known BL Lac objects with $z < 0.2$ (Lin et al., 1996). The first one among these was Mkn 421 (Lin et al., 1992). Its integral flux above 100 MeV is stated in the Second EGRET Catalog as $(1.57 \pm 0.24) \times 10^{-7}$ $\mathrm{cm^{-2}s^{-1}}$. It is compared to other EGRET-detected objects a weak source with a flat spectrum (differential spectral index $\alpha = 1.7 \pm 0.2$ (Thompson et al., 1995)). There is only insignificant time-variability.

The Whipple-Observatory started in 1991 to systematically observe objects which had been detected by EGRET. In addition, further AGN and especially close BL Lac objects were observed. The detection of γ-radiation above 500 GeV from Mkn 421 (Punch et al. 1992) was the first evidence for the existence of VHE-γ-ray sources outside our galaxy. In a later publication, a flux of $(1.59 \pm 0.20) \times 10^{-11}$ $\mathrm{cm^{-2}s^{-1}}$ above 500 GeV was derived (Schubnell et al., 1996).

In the observation season 1993/94, Mkn 421 was again observed by the Whipple group. The source showed an average flux which was about 50 % of its level in 1992, approx. 20 % of the Crab flux. Between 11 and 15 May 1994, however, a rise of the flux by a factor 9 ± 1.5 was observed. Two weeks later, the flux was nearly back to it's low "preburst" level. It was not possible to actually observe the decay because of the lack of moonless night. On 7 June 1994 a second flare followed with approx. half the intensity of the first one and a rise time of two days. Both flares are described in Kerrick et al. (1995). Fortunately, the first of these two flares occured during a multi-wavelength campaign in which also the HE-γ-ray (EGRET), X-ray (ASCA), the UV (IUE), IR (UKIRT), mm (JCMT) and Radio (UMRAO) emission was monitored (Macomb et al. 1995). A significant increase in the emission, however, occured only in the X-ray band. Also EGRET saw a slight increase, which gives together with the data in the other wavebands a coherent picture of the spectral energy distribution of Mkn 421: The radiation power has two major peaks, one at $\approx 5 \times 10^{17}$ Hz (X-rays) and one between 10^{24} and 10^{26} Hz (in the region between 10 and 200 GeV which is so far unexplored). During a TeV flare, the radiation power changes mainly in a region from two orders of magnitude in frequency below each peak up to a few orders of magnitude above. At low energies, no significant change takes place. Both peaks are very similar in energy flux (of the order of 10^{-10} ergs cm^{-2} s^{-1}), and seem to be strongly correlated with small time-lags. The time-lags, however, are still under investigation.

In 1995, for the first time other Cherenkov telescopes besides the Whipple Observatory were able to detect the source at TeV energies and in this way confirmed the existence of the source: The Cherenkov telescopes CT1 and CT2 of the HEGRA collaboration obtained from altogether 97 h of observations at zenith angles $< 45°$ a signal with 6 σ significance. This detection was reported at the last Workshop "Towards a major atmospheric Cherenkov detector" in Padua (Petry et al. 1995).

2. Results published since the Padua Workshop 1995

The major new piece of information to be mentioned here consists of the two unextectedly large outbursts of γ-radiation above 300 GeV which were observed by the Whipple telescope on 7 May 1996 (MJD 50210) and 15 May 1996 (Gaidos et al. 1996). During the first of these bursts, the flux rose from 2 Crab to about 10 Crab within 2 hours (an order of magnitude faster than in the 1994 burst). Within the next half hour of observations, the beginning of a decay seems to be visible, then the observations were stopped because of the rising moon. On 8 May 1996, the flux was back to its quiescent value of 0.3 Crab. The second burst (on 15 May 1996) reached a peak flux of 5 Crab and was only about 30 minutes in duration. Since here the duration of the burst could be clearly determined, upper limits to the source size can be calculated based on causality arguments. Gaidos et al. (1996) give an upper limit of 10 light hours on the spacial extent of the emission region assuming a jet Lorentz factor δ of about 10.
- Further new results were:
(a) The summary of Whipple results on Mkn 421 for the years 1991 - 1994 (Schubnell et al., 1996).
(b) The flux measurement above 1 TeV for the 1995 season from the data of HEGRA CT2 (Petry et al. 1996). Nearly simultaneous observations of the Crab nebula showed Mkn 421 to be a moderately weak source ($F(E > 1\,\mathrm{TeV}) = 7.6(\pm 1.8)_{\mathrm{stat}}(+6.4 - 3.1)_{\mathrm{syst}} \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1} \approx$ 50 % of the Crab flux above 1 TeV) with a spectrum which is probably steeper than that of the Crab (differential spectral index 3.6 ± 1.0, i.e. larger than 2.3 with 90 % confidence level).
(c) The analysis of another multi-wavelength campaign on Mkn 421, this time taken during a relatively small flare in 1995 (VHE peak on MJD 49834, 27 April 1995). The members of the campaign were the Whipple group, ASCA, EUVE and the Landessternwarte Heidelberg. The results indicate a clear correlation between the flux above 300 GeV and the emission in the 1-7 keV X-ray, the 6 - 17 nm UV and the 650 nm optical wavebands (Buckley et al., 1996).
(d) Investigation of large zenith angle data from between 18 June and 1 July 1995 shows that the emission of Mkn 421 extends to above 5 TeV (Krennrich et al. 1997).

3. New results presented at the 25th ICRC

Six of the papers presented at the 25th International Cosmic Ray Conference at Durban (just before this workshop) are concerned with observations of Mkn 421:

OG 4.1.4: (Bhat et al., manuscript not in the ICRC proceedings but available from Dr. Bhat) The observations of Mkn 421 (29.3 h of observations made in April-May 1997) by the only recently commissioned TACTIC experiment (Mt. Abu, India, see Koul et al. (1997)) yield a conservative 3σ upper limit to the photon flux above 0.7 TeV of $F(E > 0.7\,\mathrm{TeV}) < 2.2 \times 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which is consistent with all earlier measurements of the quiescent state flux. Figure 2 shows the ALPHA-distributions as obtained by this observation after Gamma-Hadron separation cuts.

OG 4.3.1: (Petry et al.) Together with five other AGN, Mkn 421 was observed by HEGRA CT1 in 1996. The average observed flux is $F(E > 1.5\,\mathrm{TeV}) = 2.7(\pm 0.6)_{\mathrm{stat}}(+3.1 - 0.9)_{\mathrm{syst}} \times 10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (this value is the final one presented at the conference). The light curve shows no significant deviation from constant emission. Especially on MJD 50210, just about 6 hours before the largest flare observed by the Whipple group, the emission above 1.5 TeV is measured to be less than the Crab flux with 95 % confidence level. The spectrum of Mkn 421 between 1.5 TeV and 10 TeV is consistent with a differential spectral index of 3.0 ± 0.5.

OG 4.3.4: (McEnery et al.) Apart from the results already mentioned in section 2., this presentation showed a measurement of the spectrum of Mkn 421 during the flare of 7 May 1996: $F(E) = 2.24(\pm 0.12)_{stat}(\pm 0.7)_{syst} \times 10^{-10} E^{-2.56 \pm 0.07 \pm 0.1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. The spectrum at other non-flaring times may be softer. During the flare, it continues to at least 8 TeV. Concurrent optical observations show a significant increase in the optical emission of Mkn 421 which starts several days before the flare and continues until several days after (figure 5). In the 1997 season, Mkn 421 has been in a low state with one significant flare on 1 February 1997.

OG 4.3.6: (Acharya et al., manuscript not in the ICRC proceedings) This group presented preliminary results from the Pachmarhi distributed Atmospheric Cherenkov Array. The main result is that while no significant emission was observed on several nights of observations in March and April 1996, a clear peak in the excess rate is visible on 15 May 1996. The duration is less than 80 minutes. The measurements seem to agree with those of the Whipple and HEGRA group.

OG 4.3.7: (Aiso et al.) Here, one of the first results from observations with telescopes from the future Telescope Array (TA) is presented. Mkn 421 has been observed by two TA telescopes (based at Akeno) at a threshold of about 2 TeV. The preliminary analysis of the data did not show a a significant signal on any of the 11 days except on 12 May 1996 (MJD 50215.6), when a 5.5 σ signal was obtained from 35 minutes observation time. The corresponding flux is estimated to be between 5 and 11 Crab (very preliminary).

OG 4.3.16: (Amenomori et al.) The Tibet collaboration presents improved upper limits on the emission of Mkn 421 at above 10 TeV and 30 TeV.

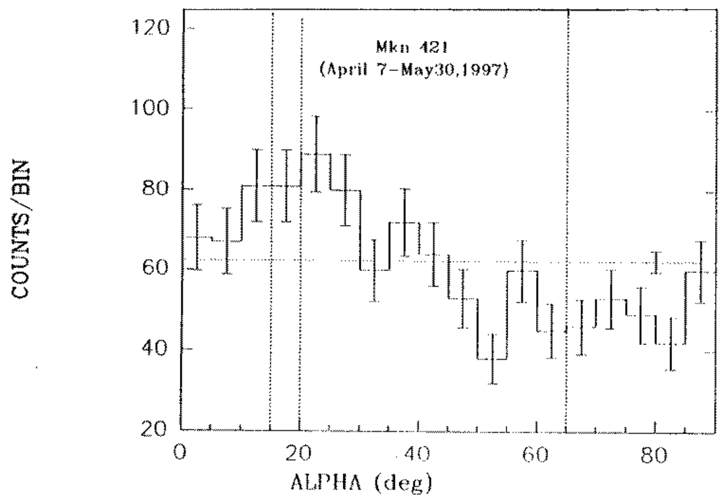

Fig. 2: The ALPHA-distribution after Gamma-Hadron separation cuts (except the cut on ALPHA) obtained by the TACTIC experiment from 29.3 hours of observations of Mkn 421 in 1997. No significant signal is observed in the Gamma domain at ALPHA $< 15°$.

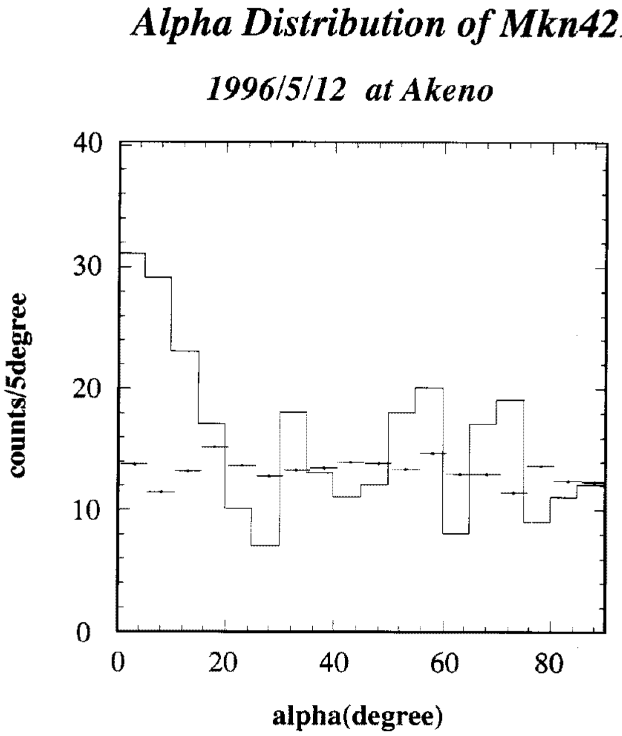

Fig. 3: The ALPHA-distribution after Gamma-Hadron separation cuts (except the cut on ALPHA) obtained by two Telescope Array prototypes from a 35 minute observation on 12 May 1996. Shown is the sum of the single telescope distributions.

4. Conclusion

With the many positive detections both by Cherenkov telescopes and EGRET, Mkn 421 is now together with Mkn 501 the first firmly established extragalactic source of VHE Gamma-rays. Also the strong variability of the source's intensity on short timescales is clearly proven.

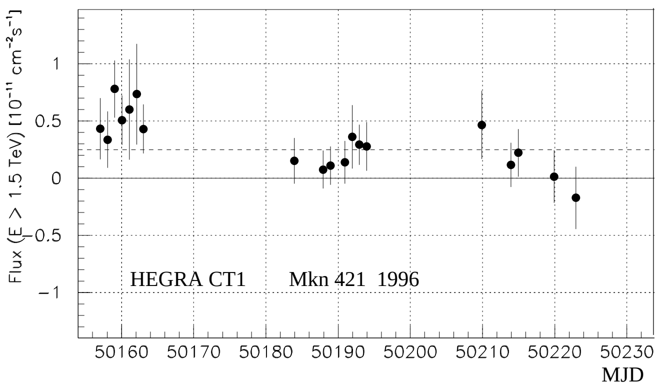

Fig. 4: The lightcurve of Mkn 421 as measured by HEGRA CT1 in 1996 (March to May) with the errorbars only indicating the statistical errors. For comparison, the Crab flux above 1.5 TeV as measured with the same telescope and analysis technique is 0.82 ± 0.1 *in the units of this plot.*

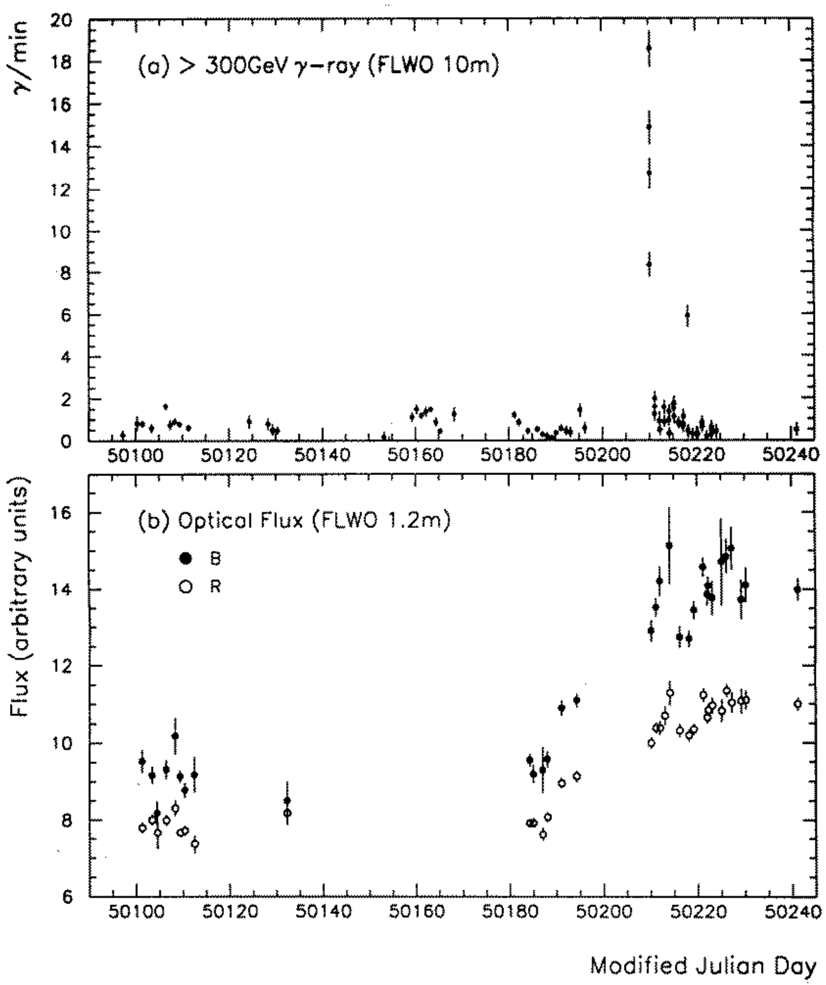

Fig. 5: The Mkn 421 lightcurve from January to May 1996 as observed by the Whipple Cherenkov telescope and a 1.2 m optical telescope which is part of the Whipple Observatory. Each point is an average over 28 minutes observation time.

The main interest focusses now on the exact shape of Mkn 421's energy spectrum and on the question whether there is spectral variability. As can be seen from figure 6, our knowledge of the spectrum above a few TeV is still far from satisfactory. While it is clear that there is a spectral break or roll-off between EGRET energies (differential index 1.7) and TeV energies (differential indices larger than 2.3) it is still unknown if and how strongly this steepening continues at energies above $\approx 3\,\mathrm{TeV}$. This inconclusiveness is caused by the weakness of the source in its so-called quiescent state and the still large systematic uncertainties of spectral measurements with Cherenkov telescopes. One of the hopes for improving the situation seems

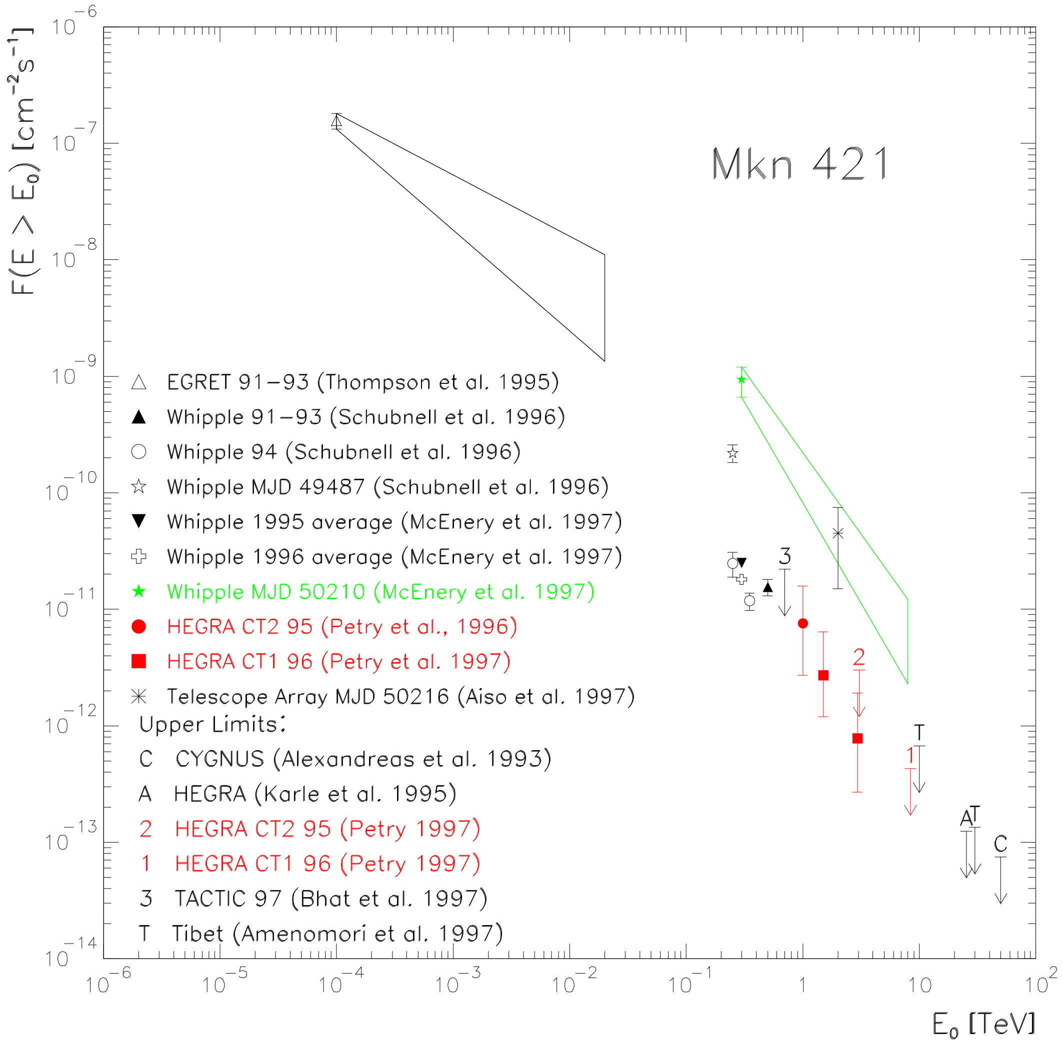

Fig. 6: The integral spectrum of Mkn 421 above 100 MeV. This plot shows essentially all measurements of the photon energy spectrum of Mkn 421 above 100 MeV. Differential measurements were integrated. If single MJDs are stated, the corresponding flux is that of an extreme, short-time high state (flare) on that MJD. All other values are averages over at least a month. Measurements by the Whipple collaboration which were originally given in terms of the Crab flux were converted into an absolute flux using the latest Crab flux published by the same collaboration.

to be the further lowering of the Cherenkov telescopes' energy threshold which leads to the possibility of observing Mkn 421 at large zenith angles while keeping the energy threshold below 1 TeV. The huge collection areas which become possible in this way may provide the necessary sensitivity to explore Mkn 421's quiescent state.

Although Mkn 421 has been studied now at TeV energies for more than five years, it seems that it will remain one of the most interesting objects for several years to come.

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