Effect of intergalactic absorption in the TeV γ-ray spectrum of Mkn 501

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Abstract. We discuss an effect of the intergalactic absorption of the TeV γ-rays in time-averaged spectrum of Mkn 501 measured by the HEGRA collaboration. Analysis of the spectral behavior, variability time scale and relevant calculations of TeV γ-ray emission allow to conclude the presence of a noticeable absorption of the TeV γ-rays in the Mkn 501 energy spectrum.

INTRODUCTION

The ground-based detectors, utilizing the so-called imaging air Čerenkov technique, offer an effective tool to study the cosmic TeV γ-rays. Recently, a number of celestial objects has been identified as TeV γ-ray emitters by use of such technique [1]. Among them there are two active galactic nuclei (AGN) – Mkn 421 and Mkn 501 – which for almost similar redshift of 0.031 and 0.034 respectively, have very different properties of a TeV γ-ray emission. In particular, TeV γ-ray fluxes from Mkn 421 and Mkn 501 differ in variability time scale and spectral behavior. Mkn 421 has shown significant flux variations within a time period as short as 15 minutes [2] whereas Mkn 501 may outburst during a period of 6 months with an extraordinary high γ-ray flux of more than 3 Crabs on average [3]. The energy spectrum of Mkn 501, as measured in the energy range from 0.5 TeV up to 20 TeV, shows evident curvature ($dJ_\gamma/dE \propto E^{-1.9} exp(-E/6.2)$) and the spectrum shape does not depend on the flux level [4]. At the same time the Mkn 421 energy spectrum is very steep and consistent with the pure power law ($dJ_\gamma/E \propto E^{-3.1}$) over the energy range 0.5-7 TeV, at least during low state of emission [5]. All that shows an apparent intrinsic difference in the mechanism of the TeV γ-ray emission which is widely believed to be an inverse Compton scattering of electrons within a relativistic jet directed along the observer line of site (for review see [1]). In addition the measured spectra of TeV γ-rays from such distant sources as Mkn 421 and Mkn 501 might be affected by the γ-ray absorption on the diffuse intergalactic infrared (IR) background. Here we discuss how important might be the effect of

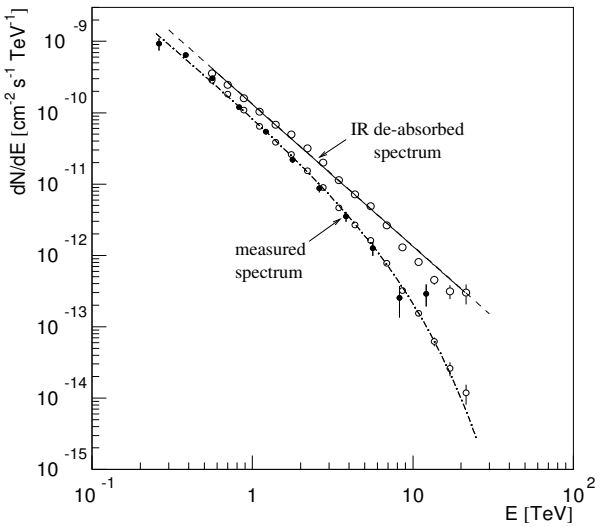

FIGURE 1. The energy spectrum of Mkn 501 as measured by the HEGRA IACT array (open circles) [4]). The combined fit (power law plus exponent) of the HEGRA data is shown by the dotted-dashed curve. The Mkn 501 spectrum measured by the Whipple group (filled circles) is from [6]. The "de-absorbed" HEGRA data and a power law fit (solid line) are shown also.

such absorption on the spectra of two observed AGNs in particular Mkn 501 which shows a spectacular shape of its spectrum.

OBSERVATIONS

During an extraordinary outburst of TeV γ-rays from Mkn 501 in 1997 observation period this object was monitored by several ground-based imaging air Čerenkov telescopes (IACTs) [3]. The HEGRA stereoscopic system of 4 IACTs has observed Mkn 501 for a total exposure time of 110 hours [4]. The unprecedented statistics of about 38,000 TeV photons, combined with the good energy resolution of $\sim 20\%$ allowed determination of a spectrum over the energy range from 500 GeV up to 24 TeV. The shape of the spectrum does not depend on intensity of the source. It justifies the determination of the time-averaged Mkn 501 spectrum. The energy spectrum of Mkn 501, as measured by the HEGRA group, shows apparent curvature over entire energy range. The shape of the spectrum may be well described by the power law with an exponential cutoff. A fit of the data gives:

$$\mathrm{d}N/\mathrm{d}E = 10.8 \cdot 10^{-11} E^{-1.92} \exp\left[-E/6.2\right], \ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1} \qquad (1)$$

The detailed systematic analysis of the fit parameters has been discussed in [4]. The HEGRA data are also shown in Figure 1.

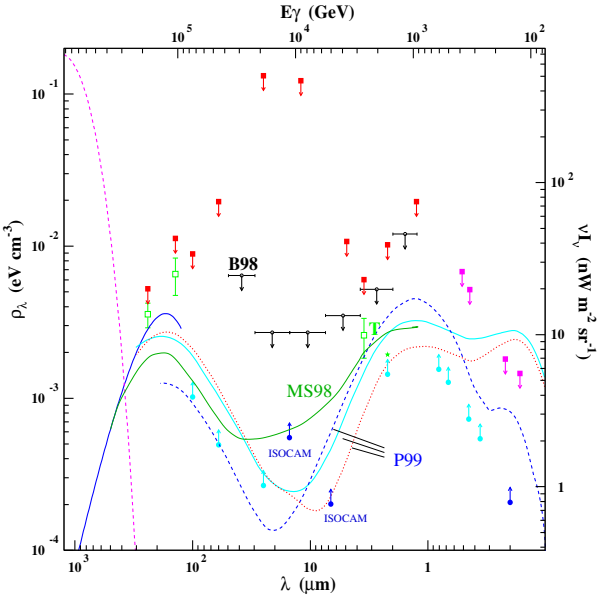

FIGURE 2. Compilation of data and models for a spectral energy distribution of the diffuse intergalactic background taken from [1] (adapted). The results of calculations using the model [14] for high IR photon field are shown by solid curve and denoted by MS99. Calculations from [15] for different model parameters are shown by dotted, dashed, thin solid curves and denoted by P99.

DISCUSSION ON SPECTRUM SHAPE

The curvature in Mkn 501 energy spectrum may be caused by several reasons. The curved energy spectrum of TeV γ-rays may be attributed to (i) the intrinsic spectrum of TeV γ-ray emission within the synchrotron self-Compton or external inverse Compton scenarios; (ii) the curvature might be due to the absorption of TeV γ-rays by the pair production inside the source, or (iii) in intergalactic medium; finally, the observed energy spectrum may be affected by a combination of several reasons noticed above.

The recent calculations based on the synchrotron self-Compton (SSC) and external Compton (EC) models could explain rather well currently established variability time scales of X-ray and TeV emission of Mkn 421 and Mkn 501 (see e.g., [7]). Thus the observation of the variability of TeV γ-ray flux at the level of $\simeq$1 hr [8], at least, limits the Doppler boosting factor of the emitting jet as $\delta \geq 10$. For such big Doppler boosting factor the γ-ray absorption within the sources does not play an important role and γ-ray photons can easily escape from the emitting region [9].

The shape of Mkn 501 energy spectrum as measured by the HEGRA collaboration can not be easily fitted by pure SSC and EC models (see e.g., [9]). In particular, the shape of a spectrum appears to be very steep above 5 TeV. In addition, the observations with Rossi X-Ray Timing Explorer have shown that the spectrum of

Mkn 501 varies strongly with generally a very hard spectral index extending to much higher energies ($\geq$ 100 keV) [10]. On the contrary, the TeV γ-ray spectrum does not show any variations in the spectrum shape [4]. The simultaneous variations in the X-ray and TeV γ-ray fluxes may be well described by a change in the maximum energy to which electrons can be accelerated γ_{max} [11] (hereafter γ_{max} is a corresponding maximum Lorentz factor). Thus the energy spectrum of TeV γ-rays can be extremely soft, e.g., $\alpha \geq 3.0$ (α is an index of a power law energy spectrum), due to the cutoff in the spectrum of emitting electrons. However for that the variations in γ_{max} lead to significant change of the spectrum slope in TeV γ-rays which is not a case for the HEGRA observations. It is more likely that synchrotron photons of approximately 1-20 keV, emitted by the electrons accelerated within the jet, are up scattered by the same electrons to the TeV energies. For such scenario the X-ray variabilities caused by the hardening of the initial electron spectrum not necessarily lead to a variations of the spectrum slope in TeV γ-rays which is relatively flat $\alpha \simeq 2.0$ and remains constant. Interestingly, the TeV energy γ-ray spectrum as measured by HEGRA shows very similar spectrum slope in the energy range below 5 TeV whereas it deviates from the power law strongly in the high energy part. Such behavior might be easily explained by the effect of intergalactic absorption.

IR ABSORPTION IN TEV SPECTRUM OF MKN 501

While propagating in the interstellar medium the TeV γ-rays may attenuate through pair production process in the intergalactic infrared radiation field (IIRF) [12]. The corresponding opacity of intergalactic medium is determined by the spectral energy distribution (SED) of the IR photon field (see Figure 1). The absorption of γ-rays in the energy range from 0.5 to 20 TeV rely on IR SED of photon field between 1 to 50 mkm. Recently measurements as well as low upper limits of SED strongly constrain the shape of SED in the range relevant to the TeV γ-rays. Compilation of present data is shown in Figure 1. We also show two models of SED from [13] and [14]. Note that the recent tentative detection of IR photons at 3.5 mkm by COBE [15] is consistent with both models whereas the ISOCAM lower limit on IR photon field, if true, favour model from [13] with rather flat SED at mid IR region. An optical depth of γ-ray absorption as a function of energy and redshift, $\tau = \tau(E_\gamma, z)$, was calculated in [16] using the predictions on SED of intergalactic IR photon field according to [13]. As such these data may be used to unfold the Mkn 501 energy spectrum measured by the HEGRA group, $(dN_\gamma/dE)_m$, in order to get a "de-absorbed" intrinsic energy spectrum of Mkn 501, $(dN_\gamma/dE)_i$.

$$(dN_\gamma/dE)_i = (dN_\gamma/dE)_m \cdot e^{\tau(E,z)} \tag{2}$$

The "de-absorbed" HEGRA data are shown in Figure 1 together with a power law fit. We find [17] that the data points can be well fitted by

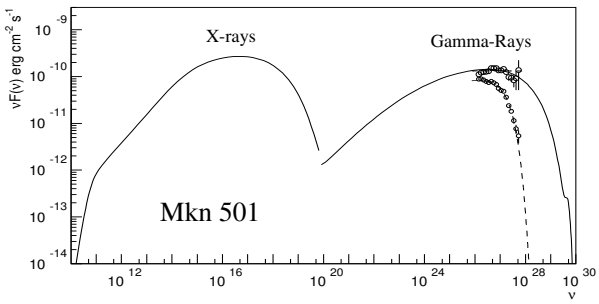

FIGURE 3. Spectral energy distribution of Mkn 501 computed using the homogeneous model [11]. Calculations have been done assuming the variability time scale of $t_{var} = 10^4$s, maximum Lorentz factor of the emitting electrons: $\gamma_{max} = 1.4 \cdot 10^6$, magnetic field: $B = 0.7 \cdot 10^{-3}$G, Doppler boosting factor: $\delta = 80$. The HEGRA data are from [4].

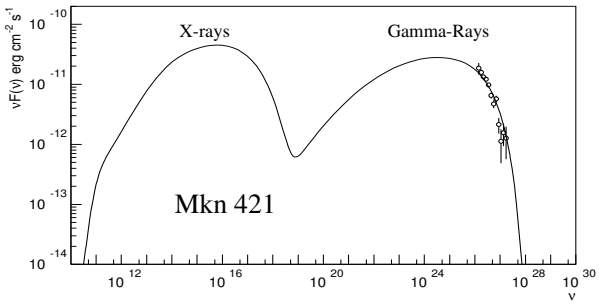

FIGURE 4. Spectral energy distribution of Mkn 421 calculated in [11] ($t_{var} = 10^3$s, $\gamma_{max} = 2 \cdot 10^5$, $B = 2.5 \cdot 10^{-3}$G, $\delta = 47$). The HEGRA data are from [5].

$$(dN_\gamma/dE)_i = (1.32 \pm 0.04) \cdot 10^{-10} (E/1\ TeV)^{-2.0 \pm 0.03}. \quad (3)$$

Note that similar results have been shown at this Workshop by the Telescope Array group using their measurement of the Mkn 501 TeV γ-ray spectrum. We show in Figure 3 the large scale spectral energy distribution of Mkn 501 calculated assuming the absorption.

COMPARISON OF MKN 501 AND MKN 421 SPECTRA

As reported in [18] the spectra of Mkn 421 and Mkn 501, measured by the Whipple group in the high state of emission, show noticeable difference in their spectral shape over the energy range 0.3-10 TeV. The spectrum of Mkn 421 is a power law whereas the spectrum of Mkn 501 is apparently curved. Since two objects Mkn 421 and Mkn 501 have almost the same red shift one may conclude that these two objects have different intrinsic energy spectra of TeV γ-rays [18]. However the Whipple data for the Mkn 421 and Mkn 501 energy spectra at the energies above 1 TeV do not show prominent difference and both could be well fitted by power law. Apparent difference in two spectra is at energies less than 1 TeV, namely in

the range where the absorption of TeV γ-rays in the intergalactic IR photon field does strongly affect the spectra. Similar behavior of both spectra in the energy range above 5 TeV does not contradict the effect of absorption at these energies as stated above.

The spectrum of Mkn 421 as measured by HEGRA collaboration in low state shows power law behavior $dN_\gamma/dE \propto E^{-3.1}$ [5]. The HEGRA data allow to extend the spectral measurements only up to 7 TeV. Such steep spectrum most likely can be attributed to the very soft intrinsic source spectrum and may not disprove the effect of absorption of TeV γ-rays (see Figure 3).

CONCLUSION

We propose a possible scenario explaining the spectral shape of the Mkn 501 energy spectrum as measured by HEGRA collaboration. Strong variations of X-ray emission argue in favor of rather flat intrinsic spectrum of TeV γ-rays. We conclude that absorption in the interstellar IR photon field plays an important role and produces an apparent curvature observed in Mkn 501 spectrum. The SSC fit of the spectral shape constrain rather high value of the Doppler boosting factor of a emitting jet, $\delta > 50$. Future multi-wavelength observations as well as detections of other BL Lac objects will help in future understanding of mechanisms of the TeV γ-ray emission and propagation processes.

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