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TeV Gamma-Ray Spectra Unfolded for IR Absorbtion for a Sample of Low and High Red-Shifted AGN

A. Konopelko[a,b], A. Mastichiadis[c] and F.W. Stecker[d]

(a) Institute of Physics, Humboldt-University for Berlin, D-12489 Berlin, Germany
(b) Max-Planck-Institute of Nuclear Physics, Postfach 103980, Heidelberg, Germany
(c) Department of Physics, University of Athens, Panepistimiopolis, GR 15783 Athens, Zografos, Greece
(d) NASA Goddard Space Flight Center, Laboratory for High Energy Astrophysics, Code 662, Greenbelt, MD 20771
Presenter: A. Konopelko (Alexander.Konopelko@mpi-hd.mpg.de), ger-konopelko-A-abs3-og23-poster

The H.E.S.S. collaboration recently performed the accurate measurements of the γ-ray spectra above 200 GeV for two BL Lac-type AGN in the Southern sky: PKS 2155-304 and PKS 2005-489. The TeV spectrum of the BL Lac object 1ES 2344+514 has also been recently measured by the Whipple collaboration. Using the results of phenomenological calculations of the SED of the EBL we have extracted the intrinsic γ-ray spectra of these blazars. Consequently we have shown that these spectra can be fitted well by means of a synchrotron self Compton model.

1. Introduction

The ground-based very high energy (VHE) γ-ray astronomy, exploiting imaging atmospheric Čerenkov telescopes, continues to enlarge the sample of BL Lac objects detected at energies above 100 GeV. Six of such objects, i.e. Mkn 421, Mkn 501, 1ES 2344+514, 1ES 1959+650, H 1426+428, and PKS 2155-304, have been confirmed in observations with at least two instruments. The latter was recently detected with the H.E.S.S. system of four imaging atmospheric Čerenkov telescopes in the Namib desert [1]. Another high-frequency peaked BL Lac PKS 2005-489 was discovered by H.E.S.S. in the 2004 observational campaign [2]. The VHE γ-ray fluxes of these sources are highly variable with a few clear indications of variations of the spectral shape with the flux level, which seems to be a generic feature of the objects of this class.

The measured TeV γ-ray spectra of extragalactic objects could be strongly modulated due to absorption by interacting with diffuse interstellar or intergalactic infra-red (IR) radiation. Such attenuation caused by pair-production highly depends on redshift of a TeV γ-ray source. Owing to the lack of direct measurements of the IR background radiation in the wavelength range 1-50 μm, a computation of the opacity of the intergalactic medium to TeV γ rays remains model dependent.

In a simplified approach the most recent data on the extragalactic background light (EBL) can be used to construct different realizations representing all possible permutations between EBL limits and the detections in the different wavelength regions [3]. In general these realizations could help to explore numerous possibilities of the intrinsic spectra of TeV blazars. However, distinct absorbtion models (e.g. [4, 5]) have inferred various observational constrains and additional astrophysical information (e.g. galaxies IMF), which finally mold a shape of the spectral energy distribution (SED) of the EBL. Considering theoretically uncoerced realizations of the SED of the EBL does not contribute much to the absorption model and in particular to compiling a self-consistent theory of emerging of TeV γ-rays out of blazar environment and their propagation in the interstellar medium. Here we adopted a different approach [6]. We have folded the distributions of the EBL derived in [4, 7] to construct the intrinsic spectra using sets of TeV data for a number of blazars. These spectra taken along with the contemporaneous X-ray data can be fitted with a homogeneous synchro-self-Compton (SSC) model [8, 6]. One can tightly constrain the absorbtion model by testing it for an extended sample of TeV blazars. Improved absorbtion model would reveal, in turn, an appropriate information on the blazar intrinsic spectra.

2. Observations

The stereoscopic arrays of imaging atmospheric Čerenkov telescopes (IACTs), such as HEGRA and H.E.S.S., have achieved a very good energy resolution of less than 10% for spectral measurements at energies above 100 GeV. Stereoscopic observations allow also to tightly narrow down the systematic errors in the measured energy spectra. Ultimately the accuracy of the spectral measurement is determined by the statistics of the γ-ray events above the cosmic ray background, which depends, in turn, on source emission state and observational exposure.

Mkn 501 & Mkn421. The TeV energy spectra of two BL Lac objects Mkn 501 and Mkn 421 have been studied in great detail with the HEGRA system of five IACTs at La Palma, Canary Island. In 1997 Mkn 501 was in an unprecedented high state for almost 6 months. An extremely high statistics of the accumulated TeV γ rays (>30,000) provided very accurate measurement of the spectrum, which reveals a gradual steepening towards the higher energies [9]. The energy spectrum of Mkn 421 was measured with HEGRA in different states of emission at TeV energies up to 20 TeV. The energy spectrum of Mkn 421 is evidently curved at higher energies, whereas data at energies below 3 TeV show significant variations of the spectral slope depending on the flux level [10]. The measured energy spectra of both Mkn 501 and Mkn 421 over the energy range from 500 GeV up to 20 TeV were used to reconstruct the IR de-absorbed intrinsic source spectra, which were then fitted along with contemporary X-ray data in an homogeneous SSC model [6]. In [6] a logically consistent model of X-ray and TeV γ-ray emission was constructed for both AGN, Mkn 501 and Mkn 421, taking into account IR absorption according to the SED of the EBL as given in [4, 7].

PKS 2155-304. PKS 2155-304 has been observed with a single telescope and the system of two H.E.S.S. telescopes, during construction phase of the experiment, in a few exposures during year 2002 and 2003 for a total observational time of about 52 hrs [1]. The overall significance of the γ-ray signal is of 45σ and about 4,500 excess events registered above 160 GeV. This unique data sample of PKS 2155-304 provided very accurate measurement of the TeV energy spectrum. The energy resolution for each individual γ event was better than 15%. The data clearly indicated high variability of PKS 2155-304 in TeV γ-rays between 10% and 60% of constant Crab Nebula flux, but no evidence found that the spectral index varies with time. It justified the measurement of the time-averaged spectrum, which is rather steep in the energy range from 200 GeV up to 2.5 TeV. The spectrum can be well fitted by pure power-law with a spectral index of 3.32 ± 0.06. Despite that the residuals at high energies are in fact smaller for a power-law fit with an exponential cutoff at $\simeq$1.4 TeV, this PKS 2155-304 data does not reveal a statistically firm indication of the exponential cutoff at TeV energies. The shortest variability time scale was found to be of half an hour. We used here this time-average spectrum of PKS 2155-304 measured by H.E.S.S. [1] to extract the intrinsic emission spectrum by unfolding the IR absorption. The steep TeV energy spectrum of PKS 2155-304 caused by IR absorbtion was predicted in [11].

PKS 2005-489. Recently the γ rays above 200 GeV with the 2.5% flux of that from the Crab Nebula has been detected from another high-frequency peaked BL Lac PKS 2005-489 using the full H.E.S.S. array of IACTs in the 2004 observational campaign for an exposure of 24.2 hrs [2]. The statistical significance of the signal was of 6.7σ with about 300 excess events. The energy spectrum is consistent with a pure power-law with an exponent of 4.0 ± 0.4. These data do not allow conclusions on any sophisticated spectral shape as well as on the time variations of the spectral slope. Non-detection of PKS 2005-489 with H.E.S.S in 2003 observational campaign ascertained a clear variability of the source in TeV γ rays, even though this data can not be effectively used to establish a shortest variability time scale. The spectral data points given in the energy range expanding up to 2.3 TeV [2] are characterized by rather large statistical errors at high energies, which can be naturally explained by the low statistics of γ-ray events in the corresponding energy bins. We have used this data for the consistency check of the IR absorption model.

Table 1. Summary of the measured TeV γ-spectra $(dN/dE)_m$ for a concurrent sample of seven BL Lac objects. ν_{TeV} corresponds to the estimated IC peak position for the IR de-absorbed spectra.

Object	Redshift	$(dN/dE)_m$	Ref.:	$log\ \nu_{TeV}$ [Hz]
Mkn 421	0.031	$\propto E^{-1.92}e^{-E/6.2\ TeV}$	[10]	$\simeq$26.5
Mkn 501	0.034	$\propto E^{-2.19}e^{-E/3.6\ TeV}$	[9]	$\simeq$27.5
1ES 2344+514	0.044	$\propto E^{-2.54}$	[12]	$\simeq$26
1ES 1959+650	0.048	$\propto E^{-2.83}$	[13]	$\simeq$26
PKS 2005-489	0.071	$\propto E^{-4.0}$	[2]	$\leq$25.5
PKS 2155-304	0.117	$\propto E^{-3.32}$	[1]	$\leq$25.5
H 1426+428	0.129	$\propto E^{-3.5}$	[14]	$\leq$25.5

1ES 2344+514. The BL Lac object 1ES 2344+514 is an established source of TeV γ-rays (see [12] and references herein). The brightest outburst in TeV γ rays from this object was detected with a 10 m VERITAS telescope on the night of December 20, 1995. During this flare the γ-ray flux exceeded by about a factor of two the flux of the Crab Nebula, which provided the detection of 128 excess events at the confidence level of 5.3σ. So far this is the best data sample available for the spectrum evaluation of the 1ES 2344+514. The resulting spectrum between 0.8 TeV and 12.6 TeV can be described by a power-law of spectral index of 2.54 ± 0.17, with given error as the statistical one. For the energy resolution of VERITAS telescope at Mt. Hopkins of about 40% and very small signal, rather coarse bins are preferable for the spectral data presentation (four bins per decade). Detailed studies of spectral evaluation procedure allowed to substantially limit all possible systematic energy biases [12]. Note that both 1ES 2344+514 and 1ES 1959+650 are located at almost the same redshift. Taken together they form a second pair of TeV blazars at the same redshift after a famous pair of Mkn 501 and Mkn 421.

1ES 1959+650. The BL Lac 1ES 1959+650 was detected with the HEGRA system of IACTs in a high state during May-June 2002 with the flux at TeV energies exceeding of that from the Crab Nebula [13]. The 8.5 hrs exposure provided detection of 255 γ rays at the significance level of 25.5σ. In the energy range between 1.5 Tev and 10 TeV the data were fit to a power law, which results in the spectral index of 2.83 ± 0.22. At the same time the power law fit of spectral index of 1.83 ± 0.23 with the exponential cutoff of about 4.2 TeV describes equally well the data. For given statistical and systematic errors of the power-law spectral index the energy spectra of 1ES 1959+650 measured with HEGRA in high and low states are marginally undistinguishable.

H 1426+428. The H 1426+428 has the largest redshift, z=0.129, among all of the so far established TeV blazars. The energy spectrum of H 1426+428 as measured by VERITAS collaboration [14] is a power law with a spectral index of 3.5 ± 0.4 in the energy range from 250 GeV up to 2.5 TeV. Such steep energy spectrum is consistent with the spectrum for another BL Lac object PKS 2155-304 (see above) located at similar redshift of z=0.117. However, observations of H 1426+428 with the HEGRA system, characterized by rather low γ rays statistics of about 200 events and signal significance of about 6σ, revealed very peculiar spectral shape above 1 TeV [15], which constitutes for a statistically significant deviation of the spectrum from a power law. It is apparent that further observations of this source are needed in order to reexamine its TeV energy spectrum. We have omitted discussion of these data in this paper.

3. Discussion on the IR de-absorbed spectra

We have used here the empirically based model for the EBL developed in [4, 7]. This model is consistent with all available data on the EBL over the 1-300 μm wavelength range taking into account the statistical and

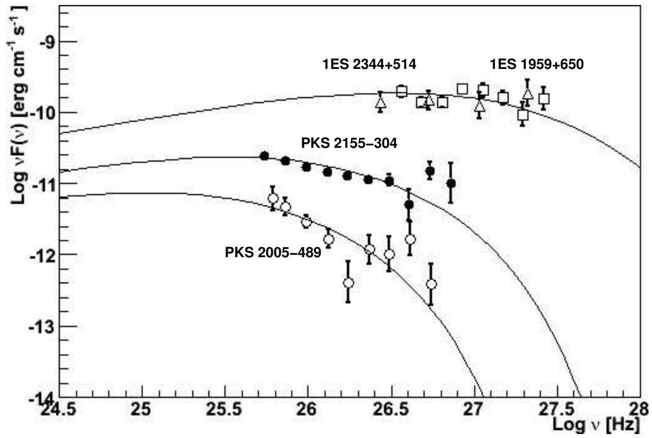

Figure 1. The de-absorbed TeV γ-ray spectra of four BL Lac type objects: PKS 2005-489, PKS 2155-304, 1ES 2344+514 (△), 1ES 1959+650 (□). The IC spectra computed in the homogeneous SSC model are also shown.

systematic errors of those measurements. The SED of the EBL was used to compute the opacity of TeV γ-rays, $\tau(E,z)$, as described in [6]. Finally we have reconstructed the intrinsic source spectrum using the measured spectrum as $(dN_\gamma/dE)_i = (dN_\gamma/dE)_m \cdot exp[\tau(E,z)]$. The IR de-absorbed spectra are shown in Figure 1. We do not observe any non-physical features, e.g. sharp upturns etc, in any of the de-absorbed spectra. All spectra are well consistent with a generic IC TeV spectrum. Thus the X-ray and TeV γ-ray data for PKS 2155-304, which is the most distant BL Lac from those discussed here, can be well fitted in the homogeneous SSC model using parameters: $\mathrm{B} = 0.5\,\mathrm{G}$, $\delta = 50$, and $\gamma_{max} = 2 \times 10^5$. Such values of the model parameters are very close to the corresponding values obtained for Mkn 421 and Mkn 501 [6]. We note that there is an apparent trend in steepening of the measured TeV spectra with the enlargement of the redshift. We plan to examine this more closely in a forthcoming paper. However, the preliminary results presented here show that the IR-absorption/SSC model developed in [6] for two low redshift BL Lac objects, Mkn 421 and Mkn 501, can be applied as well to the new set of extragalactic TeV sources.

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