Modeling the IR de-absorbed γ-ray spectra of TeV BL Lacs

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1. Abstract

A sample of the BL Lac objects detected so far in TeV γ-rays consists of four well established sources, in particular Mkn 501, Mkn 421, 1ES 1426+428, and 1ES 1959+650. The energy spectra of these objects at TeV energies show the steepening in the spectral slope, which can be attributed to the γ-ray absorption onto extra-galactic infra-red (IR) background light. Based on the empirically based model of the IR spectral energy distribution (SED) we have unfolded the intrinsic spectra of two BL Lac objects: Mkn 501 and Mkn 421 and modeled the TeV γ-ray emission in the synchrotron-self Compton (SSC) scenario.

2. Introduction

It was suggested long ago that TeV γ-rays could be absorbed by interacting with diffuse interstellar or intergalactic IR radiation [1]. Owing to the lack of direct measurements of the IR background radiation in the wavelength range 1-50 μm [2], a computation of the opacity of the intergalactic medium to TeV γ-rays must be based on a model of the diffuse radiation field. Here, we use the distributions of the extra-galactic background light (EBL) given by [3] to estimate both the magnitude and the uncertainty in the IR absorption and construct intrinsic spectra of TeV BL Lac objects. Having constructed the intrinsic spectrum we use the SSC model described by [4] to obtain a fit. The SSC model provides a reasonable fit for recent data on TeV γ-ray spectra measured from two BL Lacs Mkn 501 and Mkn 421 (i.e. for Mkn 421 in low and high state of activity).

3. IR opacities

There have been a number of attempts in past to measure the SED of EBL in the mid-IR range, which is most relevant for interaction of the γ-rays of

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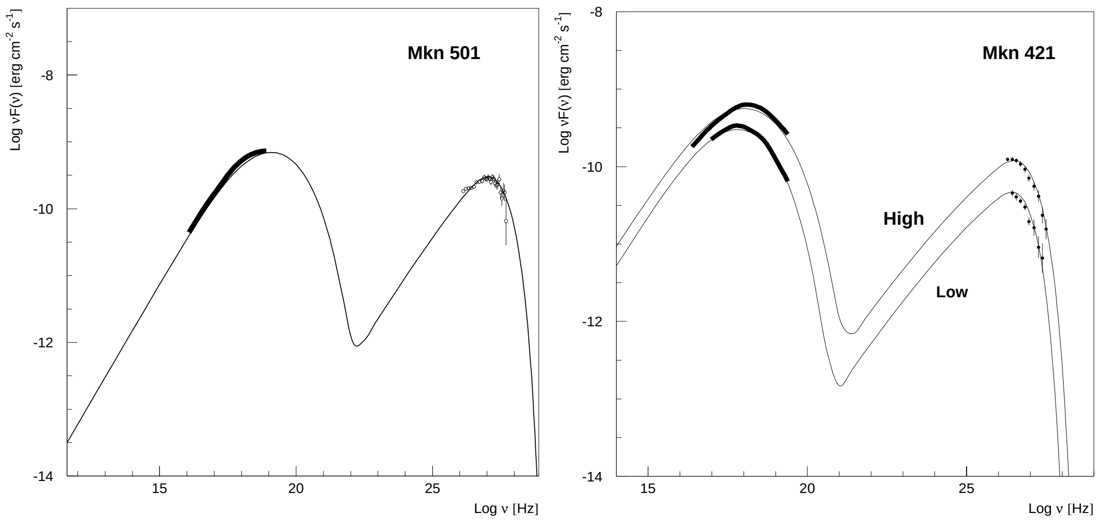

Fig. 1. The de-absorbed spectra of Mkn 501 (left panel), and Mkn 421 in high and low states (right panel) together with the best fit SSC models.

energy from 300 GeV to 20 TeV. However, such direct measurements are usually hampered by unavoidable foreground emission [2]. Recently [3] reconsidered empirically based model for the EBL starting from the near-IR and extending to the far-IR range. This model is consistent with all currently measured lower and upper limits in the mid-IR range as well as with the COBE-FIRAS fluxes given at $140\mu m$ and $240\mu m$. This model can be extended towards ultraviolet (UV) wavelengths using the galaxy counts in the Hubble Deep Field data taken with Hubble Space Telescope [5]. This so-called *hybrid* model gives a smooth distribution of the EBL over the 1-$300\mu m$ wavelength range.

To calculate opacities we made integration over the angle between the photons, red shift, and energy of the soft photon field, according to the prescription e.g. given in [6]. For this we used a discretised representation of the IR SED with approximately 40 bins per decade of energy. When integrating over the soft photon energy ϵ we interpolated the background SED $log\epsilon F_\epsilon$ as a linear function of $log\epsilon$. We calculated opacities for both IR SED given in [5] for *fast* and *baseline* evolution models. Applying these two sets of opacities to the measured spectra we interpreted the results as upper and lower values of the de-absorbed intrinsic flux, as 3σ deviations from the true value, and add this error to that attached to the original TeV point.

4. SSC model

To model the multi-wavelength spectra of the BL Lac objects in a homogeneous SSC scenario we use an approach described in [4]. This method involves

Table 1. Characteristic features of Mkn 501 and Mkn 421.

Source:	Mkn 501	Mkn 421
Time variability:	20 min	15 min
Relative flux variability:	$\simeq 10$	$\simeq 10$
Peak of synchrotron emission:	up to 100 keV	$\simeq 1$ keV
Peak of intrinsic IC emission:	$\simeq 7$ TeV	1-2 TeV

prescribing an injection function for relativistic electrons and solving the two time-dependent kinetic equations for the electron and photon distributions source. All relevant physical processes are taken into account in the code, i.e., synchrotron radiation, inverse Compton scattering (both in the Thomson and Klein-Nishina regimes), photon-photon pair production, and synchrotron self-absorption. Seven model parameters are required to specify a source in a stationary state. They are the Doppler factor δ of emitting blob, the radius R of the spherical source, the magnetic field strength B, the index s of the electron injection spectrum, $\gamma_{\rm max}$, the Lorentz factor at the cut-off of the injection spectrum, the amplitude of the injection spectrum $q_{\rm e}$, and $t_{\rm esc}$, the effective escape time of relativistic electrons. We used here a physically motivated strategy to arrive at reasonable starting values for these seven parameters as suggested in [4]. For all models considered here we used $t_{esc} = t_{cross} = R/c$.

5. Data

The HEGRA system of 5 imaging Čerenkov telescopes has achieved a very good energy resolution of about 10% for each individual γ-ray shower [7] using stereoscopic observations. This unique energy resolution allowed to deliver the high precision spectral data for Mkn 501 [8] during its outburst in 1997, Mkn 421 [9] in its high and low states during 2000-2001 observational period. In addition, we use here the data taken with *BeppoSAX* in observation period of April 1997 [10] for Mkn 501, and X-ray spectra of Mkn 421 measured with the *BeppoSAX* in 2000 for low and high states of the source [11]. These two BL Lac objects have rather different intrinsic features, which are summarized in Table 1. Mkn 421 is extremely highly variable source, where as Mkn 501 has an extremely hard X-ray spectrum.

6. Results

The de-absorbed spectra for Mkn 501 and Mkn 421 shown in Figure 1 can be fitted reasonably well by the homogeneous SSC model using physics parameters listed in Table 2. The two AGNs modeled have definitely different intrinsic spectra

Table 2. Physical parameters used for the SSC models.

Source	State	δ	R (cm)	s	γ_{max}	l_e	B (G)
Mkn 501	-	35	1.5×10^{15}	1.60	1.5×10^6	6.50×10^{-5}	0.20
Mkn 421	high	55	1.5×10^{15}	1.75	2.8×10^5	1.85×10^{-5}	0.45
Mkn 421	low	55	1.5×10^{15}	1.70	1.7×10^5	1.15×10^{-5}	0.40

as well as slightly different variability scales, which is shorter for Mkn 421. This leads to a slightly higher value of Doppler factor for Mkn 421 as well as a higher magnetic field and a lower value of γ_{max}. The energy spectra of Mkn 421 in high and low states can be fitted by changing the γ_{max} and luminosity parameters, whereas the Doppler factor and the magnetic field remain unchanged.

Note that our fits are characterized by higher values of the Doppler factor ($\delta \geq 35$). In fact, the recent studies of the variability and velocity of superluminal sources [12] based on radio observations indicate the existence of such large Doppler factors for some BL Lac objects.

We argue here that a logically consistent SSC model of X-ray and TeV γ-ray emission can be constructed for both AGNs, Mkn 501 and Mkn 421, taking into account the IR absorption. Accurate spectral data are needed for other AGNs, in particular for the newly discovered 1ES 1426+428 and 1ES 1959+650, in order to test the consistency of this model for AGNs at different red-shifts.

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