Multiwavelength Observations of the BL Lac PKS 2155-304 with the H.E.S.S. Cherenkov Telescopes

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The High Energy Stereoscopic System (H.E.S.S.) has observed the X–ray selected BL Lac object PKS 2155−304 in 2003 between October 19 and November 26 in Very High Energy (VHE) γ-rays ($E \geq 160$ GeV here). Observations were carried out simultaneously for the first time with the PCA on board the RXTE satellite, the *Robotic Optical Transient Search Experiment* (ROTSE) and the Nançay decimetric radiotelescope (NRT). Intranight variability of the order of 80% is reported in the VHE band, the source being detected with a high significance on each night it was observed. More significant variability is found in the X–ray and optical bands on kilosecond timescales along with flux-dependent spectral changes in the X–rays. No correlation can be established between the X–ray and the γ-ray fluxes, or any of the other wavebands, over the small range of observed variability. The average H.E.S.S. spectrum is a very soft power law with a photon index of 3.37 ± 0.07. The energy output in the 2-10 keV and in the VHE γ-ray range are found to be similar, with the X–rays and the optical fluxes at a level comparable to some of the lowest historical measurements indicating that PKS 2155−304 was in a low or quiescent state during the observations. Both a leptonic and a hadronic model are used to find the underlying physical parameters that can be found with these observations. These parameters are found to be sensitive to the model of Extragalactic Background Light (EBL) that attenuates the VHE signal at the redshift considered here.

1. INTRODUCTION

PKS 2155−304 is probably the most prominent and best-studied blazar-type AGN in the Southern Hemisphere. The emission of PKS 2155−304, possible variability patterns, as well as correlations across all wavebands, have been studied exhaustively during the past 20 years (see e.g. [25]). It has also been classified as a TeV blazar, like the northern hemisphere BL Lac objects Mkn 421, Mkn 501, H 1426+428 or 1ES 1959+605. Its redshift of $z = 0.117$ makes it the second most distant TeV blazar after H 1426+428 ($z = 0.129$). PKS 2155−304 was the brightest BL Lac object in the EUVE all-sky survey [16]. The first TeV detection of PKS 2155−304 came from the Durham Mk VI telescopes [6]. It was subsequently confirmed as a high energy gamma-ray emitter by H.E.S.S. [5], AH04 hereafter) at the 45σ significance level.

Here we report on simultaneous H.E.S.S. VHE γ-ray, RXTE/PCA X–rays, ROTSE optical and NRT decimetric observations of PKS 2155−304 during the dark periods of October and November 2003. No simultaneous multi-wavelength campaign had before included an Atmospheric Cherenkov Telescope (ACT) that could sample the evolution of the high energy component of the spectral energy distribution (SED) of this object. We also include EGRET archival data, and other archival data obtained from the NASA/IPAC Extragalactic Database (NED).

2. OBSERVATIONS

In its phase I the H.E.S.S. array consists of four Atmospheric Cherenkov Telescopes operating in stereo mode, but the data shown here were taken before completion of the system with the first 2 telescopes and one more as of mid-September 2003. The forth and final telescope was added to the array in December 2003, therefore the results presented here consist of a configuration of both 2 and 3 telescopes. Each telescope is made up of a tesselated 12m-diameter (107m^2 surface area) mirror which focuses the Cherenkov light from the showers of secondary particles created by the interaction of gamma-rays in the asmosphere onto a camera in the focal plane. This camera consists of 960 photomultipliers with a 0.16° pixel giving a field of view of 5°, a gamma-ray trigger threshold of ≈ 160 GeV and a spectral threshold of 300 GeV with an energy resolution $\simeq 15\%$. It is located in the Khomas highlands in Namibia, (23° S, 15° E, 1800m a.s.l.). For details on the camera calibration see [4].

As is generally the case with ACT experiments, data can only be taken in dark-sky, moonless conditions at the site. Such telescopes are pointed instruments, and only sources within the 5° field of view can be detected (~ 0.006 sr). The intrinsic advantage of such detectors is the large collection area (~ 50000 m^2); though the rejection of the background from the showers initiated by charged cosmic rays can make source detection complicated. Early reports of H.E.S.S. have been given elsewhere (see e.g. [10]).

The results presented here are based on observations carried out in 2003 between October 19 and November 26, when a clear 5 σ level detection by H.E.S.S. was achieved in an hour in the beginning of the observation period, triggering thereby an approved RXTE ToO on this target.

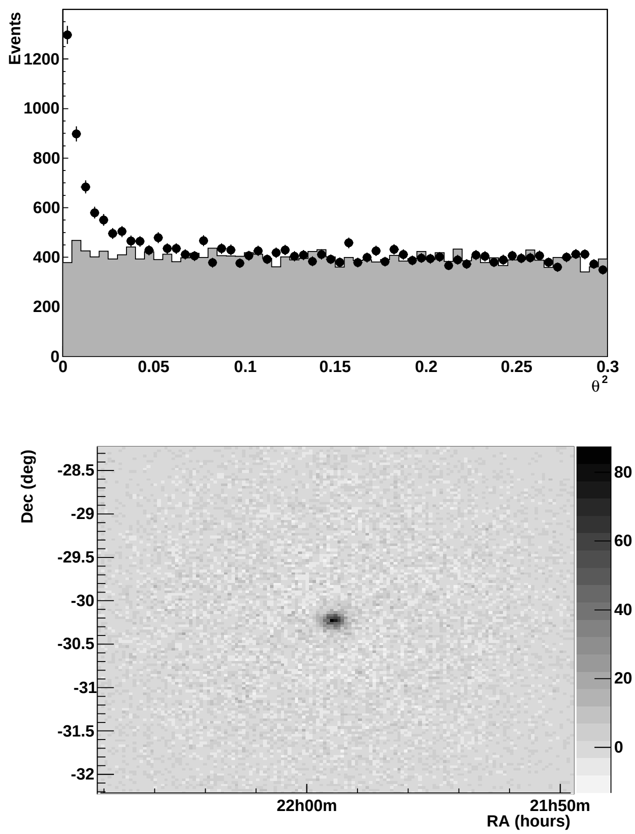

Figure 1: Top: The distribution of θ^2 for on-source events (points) and normalized off-source events (shaded) for the observations in October and November 2003. Bottom: The two dimensional distribution of excess events observed in the direction of PKS 2155-304.

3. SED MODELING

The broadband spectral morphology of PKS 2155−304 is typical of the BL Lac type with a double humped structure in νF_ν representation, exhibiting a low-energy and a high-energy component. Its broadband emission is usually attributed to emission from a beamed relativistic jet, oriented in a direction close to the line of sight. Whereas the current models seem to agree that the low-energy component is dominated by synchrotron radiation coming from nonthermal electrons emitted in collimated jets, the high-energy emission is assumed to be either inverse Compton scattering off the synchrotron photons (Synchrotron Self-Compton) or by external photons. A hadronic origin of the VHE emission using the Synchrotron-Proton blazar (SPB) model with a dominating proton synchrotron component at high energies in a proton-electron plasma is also able to produce a double humped SED.

The high-energy component above ≈ 100 GeV is attenuated by interactions with the Extragalactic Background Light (EBL) and is probably a lower limit for the intrinsic spectrum (see e.g. [8, 24]). The energy budget at X–rays and VHE γ-rays is comparable, though the maximum output at the peak energy in the high-energy component is likely to be lower than the one in the lower-energy component. The connection between EGRET archival data and VHE data through a maximum located > 10 GeV would be natural through the high-state EGRET data. A connection using the Catalog data extrapolated to VHE energies with a power law falls below the H.E.S.S. data and therefore requires 2 inflexion points in the SED.

3.1. EBL corrected spectrum

For objects at non-negligible redshifts, the high and energy dependent optical depths determine a heavy modification of the emitted spectrum both in shape and intensity. Unfortunately, at present the EBL knowledge is still affected by large uncertainties, on both direct measurements and models ([21]). In order to see what the intrinsic spectrum could look like, and thus to locate the Inverse Compton (IC) peak of the blazar's SED, we have used three EBL models as representatives of three different flux levels for the stellar peak component. This is the EBL energy range which mostly affects the H.E.S.S. spectrum: with data up to 3–3.5 TeV, the peak of the $\gamma-\gamma$ crossection is obtained with soft photons $\lesssim 5$ μm .

The three models used here are the phenomenological shape used in [3], which is based on the original [21] calculation but smoothed and scaled up to match the data points below 1 μm and at 2–3.5 μm (hereafter *Phigh*); the original [21] calculation, for a Salpeter initial mass function (hereafter *Primack01*); and the new 2004 calculation ([20], hereafter *Primack04)*, which takes advantage of the recent improvements on the knowledge of the cosmological parameters and of the local luminosity function of galaxies.

The optical depths are calculated from the EBL SED shapes taking into account only the cosmology (H_0 = 70 km/s/Mpc, $\Omega_{\rm Mat} = 0.3$ and $\Omega_\Lambda = 0.7$). To treat all the three shapes on the same level, no evolution has been introduced yet. This corresponds to a "maximum absorption" hypothesis (i.e., as z increases, constant instead of decreasing EBL comoving energy density). But at these redshifts (~ 0.1) and, for example, assuming the evolution given in [21], the difference is still small ($\Delta\Gamma < 0.1$ in the range 0.3–1 TeV), and negligible compared to the differences between models.The resulting absorption-corrected spectra are shown in Fig. 3, together with the observed ones. The intrinsic spectra are all well fitted by a single power-law model, with a hard slope for Phigh ($\Gamma \approx 1.5$), and steep ones for Primack01 and Primack04 models ($\Gamma \approx 2.3$ and $\Gamma \approx 2.8$, respec-

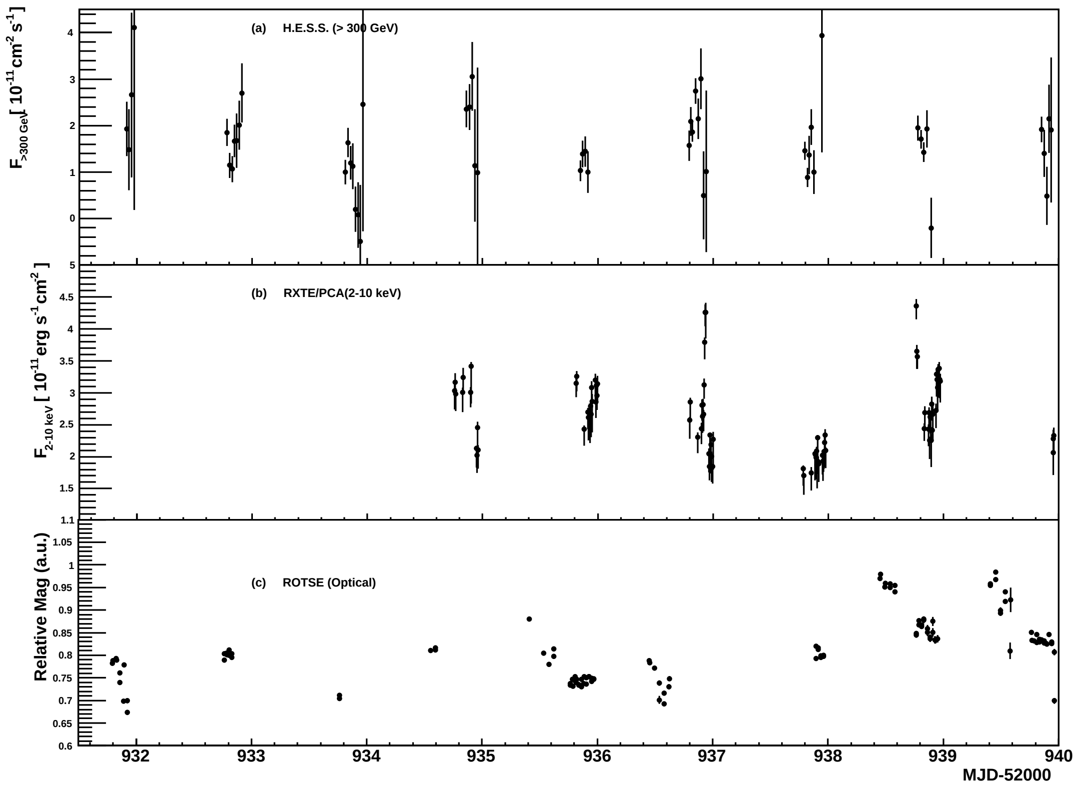

Figure 2: (a) October 2003 Lightcurve from HESS binned in run lenghts averaging 25 minutes each. (b) Lightcurve expressed as flux in the 2-10 keV band for the RXTE observations, in 400 s bins. (c) Lightcurve derived from the ROTSE optical data.

tively). In the following, we will discuss both scenarios for the SED modelling, using the Phigh and Primack2004 curves as the two ends of the possible range of values for the “Primack-type” shape (i.e. between the claimed EBL direct measurements at few microns and the lower limits from galaxy counts).

3.2. Leptonic interpretation

Interpretation by a single zone SSC model of the SED of PKS 2155−304 has already been proposed in the literature using two different assumptions. In [13] the low energy tail of the SSC model is used to account for the low-energy component up to the optical in the SED. That component is decomposed in two sub-components by [7] where the radio to optical emission has an other origin than the X–ray part which is assumed to come from the jet. These two different interpretations are used here in the context of the leptonic model described in [11] which has already been applied to Mkn 501 and Mkn 421 ([12]). To constrain this model only the simultaneous data are used, since the archival data reported in the SED of Fig. 4 are likely to not represent the state of this source (see e.g. the difference in optical flux and the ROTSE measurement).

When using the Primack04 absorption, the model used here can reproduce the X–ray through VHE part of the SED, but the H.E.S.S. spectrum constrains it such that the radio measurement can not be included in the synchrotron bump predicted by the single-zone model. As for Mkn 421 and Mkn 501 adding a more extended component than the VHE emitting zone can provide an explanation for this. The origin is probably the compact VLBI core which has a radio core to lobe ratio of ≈1 ([15, 19]) and a typical size of 10^{18}cm, more than two orders of magnitude larger than the VHE emitting zone. This VLBI feature dominates the spectrum at low energy and is included in the SED modeling here. An uncertainty remains which is the high frequency cutoff of this VLBI component. The host galaxy contribution to the optical flux is estimated to be $\approx 10^{-11}$ erg cm^{-2} s^{-1}, deduced from the magnitudes given by [14] and assuming a low-redshift solar metallicity elliptical galaxy of age equal to 13 Gyr (R-H=2.4), corresponding to a mass of $5 \times 10^{11} M_{\odot}$ ([9]). So even at the measured low activity state of PKS 2155−304 the host galaxy is not contributing much in the optical range.

If the absorption correction is well described by the

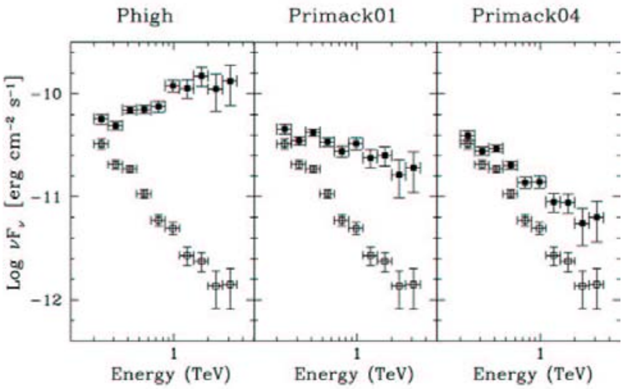

Figure 3: PKS 2155−304 absorption corrected spectra, along with the observed one, for each EBL model considered and in a νF_ν plot (i.e. a zoom in the blazar's SED). Open squares: H.E.S.S. observed spectrum. Filled squares: reconstructed intrinsic one. All spectra from "Primack-type" models are compatible with a power-law shape, with different slopes: hard (Phigh) and steep (Primack01, Primack04), locating the intrinsic SED peak for the high component above 1–2 TeV or below 200 GeV, respectively.

Phigh model, the slope of HESS data at high energy implies that the peak of the TeV emission bump is located above 4 TeV (or 10^{27} Hz). Such a high frequency peak emission imposes a strong constraint for single-zone SSC scenario, especially since the peak of the synchrotron bump has to remain below 1 keV (or $10^{17.5}$ Hz) as requested by the slope of the RXTE data. High values of both the jet Doppler factor and the maximal Lorentz factor of radiating particles are requested to reach the necessary energy for the IC bump, namely $\gamma_{\max}\delta > 8 \times 10^6$. On the other hand to keep the synchrotron peak below 1 keV imposes an upper limit to the magnetic field. Within these constrains, the best fit we obtain is shown in Fig. 5. We can notice that none of the high energy tails are well accounted for. This fit somehow reproduces the observed X-ray and γ-ray data but is not as satisfactory than the one obtained with the Primack04 absorption correction and in any case it is impossible to give account for the ROTSE optical point. The main changes in parameters between the two fits consist in enhancing the boosting, which then becomes somewhat extreme, while reducing the density and magnetic field for the Phigh absorption correction.

3.3. Hadronic models

Generally, the leptonic models constitute the preferred concept for TeV blazars, basically because of two attractive features: *(i)* the capability of the (relatively) well understood shocks to accelerate electrons to TeV energies ([18, 23]) and *(ii)* effective conversion of the kinetic energy of these relativistic electrons into the X-ray and TeV γ-ray emission components through the synchrotron and inverse Compton radiation channels. The so-called hadronic models are generally lacking in these virtues. These models assume that the observed γ-ray emission is initiated by accelerated protons interacting with ambient matter,photon fields (PIC model), magnetic fields or both.

The models of TeV blazars involving interactions of protons with photon and B-fields require particle acceleration to extreme energies exceeding 10^{19} eV which is possible if the acceleration time is close to $t_{\rm acc} = r_{\rm g}/c$ ($r_{\rm g}$ is the gyro-radius, and c is the speed of light). This corresponds (independent of a specific acceleration mechanism) to the maximum (theoretically possible) acceleration rates ([2]) which hardly can be achieved by the conventional diffusive shock acceleration mechanism. On the other hand, the condition of high efficiency of radiative cooling of accelerated particles requires extreme parameters characterising the sub-parsec jets and their environments, in particular very high densities of the thermal plasma, radiation and/or B-fields. In particular, the so-called proton-synchrotron models of TeV blazars require highly magnetized ($B \gg 10$ G) condensations of γ-ray emitting clouds of Extremely High Energy (EHE) protons, where the magnetic pressure dominates over the pressure of relativistic protons ([1]).

Below we use the hadronic Synchrotron-Proton Blazar (SPB) model to model the average spectral energy distribution (SED) of PKS 2155−304 in October/November 2003. A detailed description of the model itself, and its implementation as a (time-independent) Monte-Carlo/numerical code, has been given in [17] [22].

Flux variability provides an upper limit for the size of the emission region. To allow for a comparative study between leptonic and hadronic models we fix here the comoving emission region to $R \sim ct_{\rm var}\delta = 6 \times 10^{13}\delta$ cm. We assume that the optical through X-ray emission and the gamma ray output stems from the same region of size R.

A reasonable model representation for the simultaneous data assuming a Primack04 model for the VHE absorption is found for the following parameters: magnetic field B=40 G, Doppler factor δ=20, injection electron spectral index $\alpha_e = 1.6$, assumed to be identical to the injection proton spectral index α_p, maximum proton energy of order $\gamma_{p,max} \sim 4 \times 10^9$, e/p-ratio of 0.15 and a near equipartition proton energy density of $u_p = 27$ erg cm^{-3}. The required total jet power is of the order $L_{\rm jet} \sim 1.6 \times 10^{45}$erg s^{-1}. The model includes the Primack04 model for EBL attenuation. When using the Phigh EBL model a reasonable representation of the data may be achieved by increasing the maximum injected proton energy to $\gamma_{\rm p,max} = 10^{10}$ and simultanously increasing the e/p-ratio to 0.24, while all other parameters remain unchanged. Note that here the maximum proton gyro-

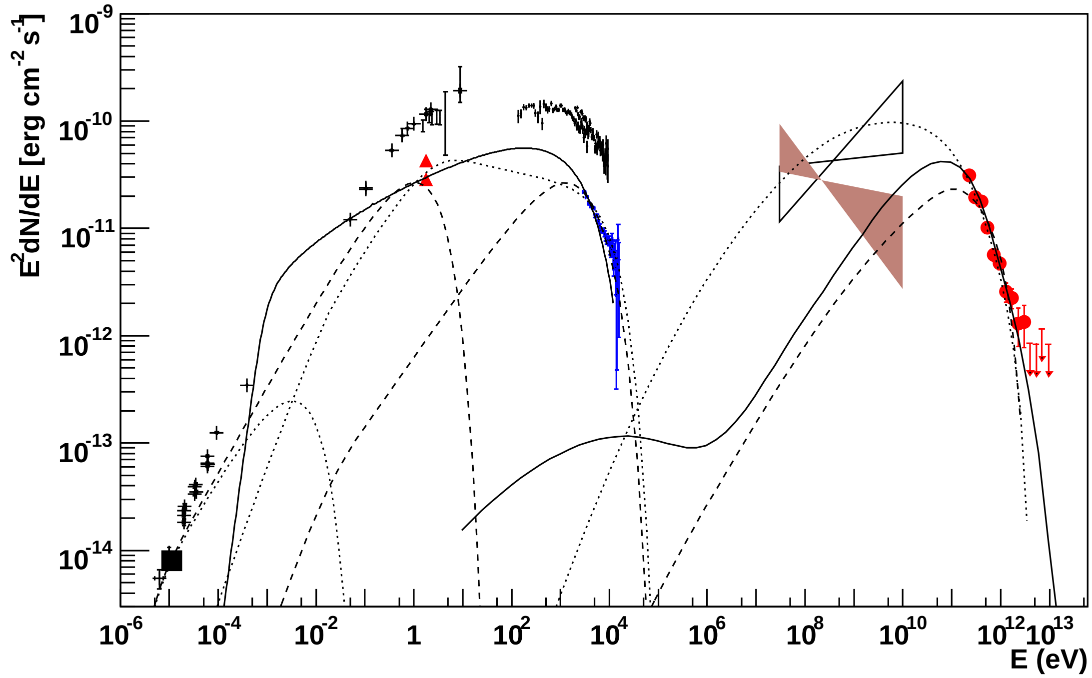

Figure 4: Spectral energy distribution of PKS2155-304. The H.E.S.S. spectrum is derived from October and November 2003 data (*filled circles*) as is the RXTE spectrum. The NRT radio point (*filled square*) is the average value for the observations carried out during this period. The two triangles are the highest and lowest ROTSE measurements for the Oct-Nov observations. Archival SAX data represent the high state observed in 1997. Archival EGRET data are from the third EGRET catalog (shaded bowtie) and from a very high EGRET gamma-ray state (open bowtie). Other data are NED archival data. The solid line is the hadronic model where the VHE gamma-rays are attenuated using the minimal EBL. The dotted and dashed lines are the same leptonic model with the dotted line assuming a common origin for the optical and X–ray synchrotron emission, and the dashed line being the case where the optical emission emanates from the VLBI core.

radius approaches the size of the emission region. Alternatively, a doubling of the magnetic field to 80 G together with an increase of $\gamma_{\rm p,max}$ to 8×10^9 and a e/p-ratio of unity (leading to $u_B \approx 50 u_p$) represents the SED-data equally well. In conclusion, none of the "Primack-type" EBL models can explicitely be ruled out by the here presented H.E.S.S. data in the framework of the SPB-model. In all cases proton synchrotron emission dominates the (sub-)TeV radiative output. Depending on the Doppler factor part of the proton synchrotron radiation produced may be reprocessed to lower energies. Contributions from the muon and pion cascades lie always below the proton synchrotron component. The low energy component is dominanted by synchrotron radiation from the primary e^-, with a negligible contribution of synchrotron radiation from secondary electrons (produced by the p- and $\mu^{\pm}$-synchrotron cascade).

On the other hand, the synchrotron radiation of secondary electrons resulting from interactions of TeV gamma-rays with low-energy radiation *inside* the source with a modest $\gamma\gamma \to e^+, e^-$ optical depth ($\tau_{\gamma\gamma} \leq 1$), may lead to significant X-ray emission with luminosity comparable to the luminosity of the primary TeV emission [1].

Models involving meson production inevitably predict neutrino emission due to the decay of charged mesons. The SPB-model for PKS 2155−304 explains the high energy emission dominantly as proton synchrotron radiation, making the ν-output completely negligible.

4. Conclusions

This paper reports multi-wavelength observations of the BL Lac object PKS 2155−304 in 2003. Variability on the timescale of a few ks in the 2-10 keV band and of the order of 0.1 d for energies $>$ 300 GeV were observed by RXTE and H.E.S.S. The X–ray data show a correlation of the flux with the spectrum, which becomes harder when the source is brighter. At the level of the observed variability no correlation between the VHE γ-rays, the X-rays and optical was seen. Observations with more important variability are needed before it can be certified that the VHE/X–

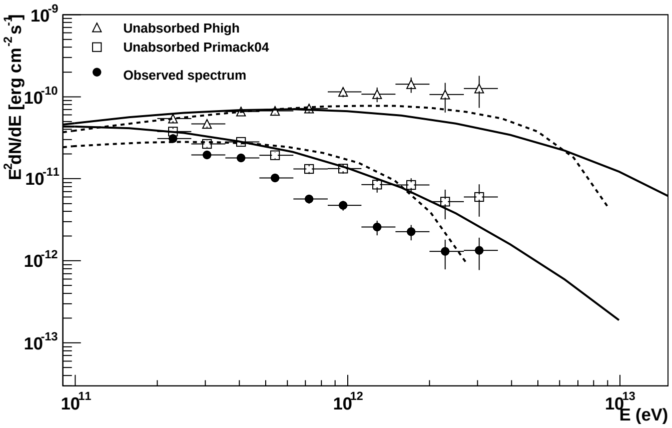

Figure 5: Estimations of the intrinsic PKS 2155−304 VHE spectrum, corrected for either the Phigh or Primack04 models, along with the associated deabsorbed SSC model (dashed lines) and SPB model (solid lines).

ray pattern in PKS 2155−304 is different from other known AGN that are TeV emitters. Since the source was at a low emission state in both the optical and X–rays compared to archival measurements, this lack of correlation has yet to be established for a higher emission state. Simultaneous observations in the X–rays/optical band and VHE γ–rays were never performed in the past on this object. The X–ray fluxes varied during the observations but never reached historically high levels, which implies that the source was probably in a low state even though easily detectable simultaneously by H.E.S.S. on any of its observations since it has been pointed at from the first time (see AH03 for the observation history up to August 2003). The continuous VHE detections makes PKS 2155−304 unique in the TeV BL Lac category and probably indicates that H.E.S.S. has achieved the sensitivity level where it can detect the quiescent state of PKS 2155−304 at any time.

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