THE SPECTRAL ENERGY DISTRIBUTION OF NEW TEV BLLACS

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ABSTRACT

Tev blazars studies have been hindered until now by the uncertainties in reconstructing the intrinsic TeV spectra due to absorption from the the diffuse Extragalactic Background Light (EBL), and by the small number of sources. The most recent H.E.S.S. results have now changed this situation, with the discovery of 3 new objects, and providing strong circumstantial evidence for a low intensity of the EBL. Here we present some first results of XMM and RXTE observations performed in coordination with H.E.S.S., which give information on the overall Spectral Energy Distribution of these objects during the epoch of the TeV detections, and discuss some implications of the absorption-corrected TeV spectra in the context of the leptonic SSC scenario.

Key words: LaTeX; XMM; X-rays; TeV; BL Lacs.

1. INTRODUCTION

TeV blazars are presently the most interesting and challenging objects to test the emission models and the physical conditions in blazars jets, since they are characterized by the most energetic electrons in the whole class (synchrotron radiation dominating and often peaking in the X-ray band) and by peculiar phenomenology (e.g. rapid variability at high energies, wide changes in the synchrotron peak energy, and different types of correlation between the synchrotron and inverse Compton emissions). Simultaneous X-ray–TeV observations represent therefore a fundamental diagnostic tool, since the bulk of the luminosity is emitted in those bands and they are supposed to sample electrons of similar energy (radiating through synchrotron and IC processes).

Such studies however have been hindered by the uncertainties in the reconstruction of the intrinsic TeV spectra due to absorption by $\gamma-\gamma$ collisions and pair production on the diffuse Extragalactic Background Light (EBL), and by the small number of objects (until very recently only 4 were well studied).

With the start of operations in 2004 of the Cherenkov telescope H.E.S.S. in full array, the situation is now changing, and 3 new TeV BLLacs have been recently discovered, two of which at relatively high redshift.

The hard spectra of the two most distant sources have provided the strongest constraints up to date on the level of the EBL (Aharonian et al. (2005c), which can now be used to reconstruct and study the blazars SED with less uncertainty than in the past.

2. EBL ABSORPTION

The EBL SED at Opt–NIR frequencies is dominated by thermal radiation produced by stars (which is then partly absorbed and re-emitted by dust at longer wavelengths) over the entire history of evolution of galaxies. Gamma-ray photons from 0.1 up to few TeV (the band detected in these objects) are mainly absorbed by (and thus sample) the EBL up to few microns, whose SED is shown in Fig. 1. The energy dependence of the optical depth $\tau(E_\gamma$ gives origin to a strong modification of the incident spectrum (see Fig. 2), resulting in a steepening of the original slope up to 2-3 TeV (for all expected EBL SEDs, i.e. peaked around 1-2μm). This creates a direct link between the blazar spectrum and the EBL SED: for a given observed TeV spectrum, higher O–NIR EBL fluxes requires harder source spectra. Unfortunately, the large uncertainties on the EBL knowledge (see Fig. 1) leave room to a wide range of possible source spectra, while conversely data from the synchrotron peak alone are not sufficient to univocally constrain the blazars TeV emission, thus hindering the possibility to disentangle absorption from intrinsic features.

A breakthrough in this classic "one equation – two variables" problem is now provided by the H.E.S.S. results on 1ES 1101-232 and H 2356-309 Aharonian et al. (2005c): their observed spectra are unexpectedly hard for their given redshifts. As described in Aharonian et al. (2005c), with the high O–NIR values suggested by the "direct" EBL measurements (i.e. after modelling and subtraction of the much brighter foregrounds, in particular zodiacal light), the reconstructed spectra are extremely hard (pho-

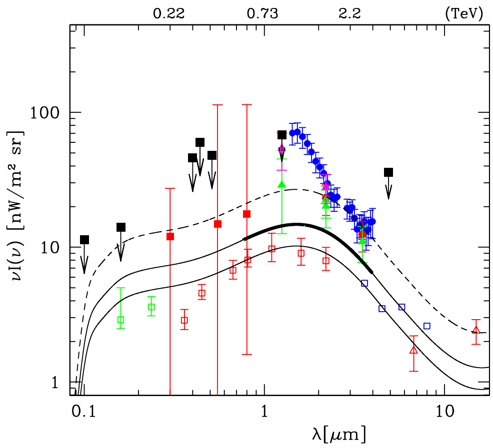

Figure 1. EBL Spectral Energy Distribution. Open points: integrated light from resolved galaxy counts, and thus has to be considered lower limits for the EBL. Full points, direct estimates (see Aharonian et al. (2005c)). The two filled lines correspond to the range of the EBL flux levels used to deabsorb the TeV data. Details in Aharonian et al. (2005c). The dashed line, as well as the NIR peak over galaxy counts, are considered very unlikely since imply intrinsic TeV spectra with photon indexes $\Gamma < 0$. *The upper axix shows the TeV energies corresponding to the peak of the* $\gamma - \gamma$ *cross-section.*

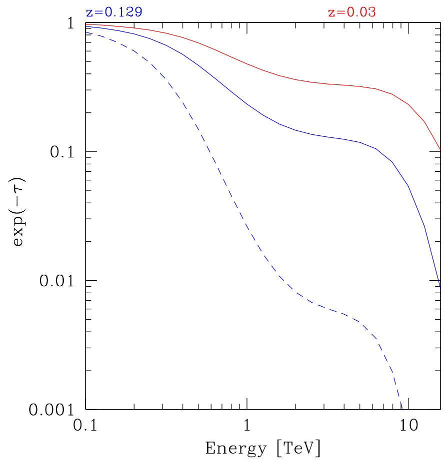

Figure 2. Attenuation factors for two different redshifts for the lowest curve in Fig 1 (full lines), and for the same redshift (z=0.129) but with the higher EBL curve in Fig. 1 (dashed line). The above curves can be thought as the observed spectrum resulting after absorption if the incident one is a power-law with flat slope.

ton index $\Gamma \lesssim 0$). Such values have never been previously seen in the blazar emission, are not explained with the accelerated particle spectra obtained in the standard shock acceleration models, and are generally difficult to reproduce in the standard leptonic or hadronic scenarios.

They are not impossible in principle (and in fact some mechanisms have already been envisaged, seeAharonian (2001)), but if they were a real, newly discovered feature of the blazar TeV emission, they should become directly visible in the observed spectra of the closer, less absorbed objects like Mkn 421 and Mkn 501 ($\Gamma_{obs} \lesssim 0.5$), so far not seen. Unless assuming an improbable fine tuning of the source parameters with redshift, so that such "line-like" features always disappear due to EBL absorption.

High EBL fluxes in the NIR band, if due to redshifted UV radiation from Pop III stars in the early universe, are also disfavoured by recent theoretical results on this scenario (Madau & Silk (2005); Dwek et al. (2005)), due to the extreme energetic requirements and fine-tuning necessary not to overproduce the mean metallicity or the soft X-ray background presently observed.

A lower EBL intensity, instead, in agreement with the expectations from standard galaxy evolution models (e.g. Primack et al. (2005)), would avoid such problems.

Given also the fact that the "direct" EBL estimates can be affected by large systematic uncertainties due to the difficulties in the accurate modelling of the bright foregrounds, in particular zodiacal light (which has the same spectrum of the NIR excess between 1 and 4 micron, Dwek et al. (2005)), a low EBL intensity seems at present the simplest and most natural conclusion.

Although not yet the "smoking gun", the H.E.S.S. results on these two objects provide strong circumstantial evidence for a very low EBL. Therefore, unless/untill further data will change this picture (e.g., the direct measurement of very hard spectra in nearby TeV blazars, or the detection of spectra of objects at high redshift, z=0.3-0.5, incompatible even with the galaxy counts limits), we will adopt for the TeV spectra reconstruction the range between the upper limit derived in Aharonian et al. (2005c), and the lower limits represented by the integrated light from resolved galaxies.

3. X-RAY DATA

The XMM observations were performed as simultaneous campaigns with H.E.S.S. at fixed epochs (given the narrow overlap of the visibility windows for simultaneous coverage), while the XTE observation was performed as ToO, but the campaign was hindered by bad weather conditions (thus the short exposures). Strict simultaneity has been possible only for the XMM observation of 1ES 1101-232, while for the others only within 1-2 days, due to bad atmospheric conditions on the H.E.S.S. site. The TeV flux levels however were not high enough to allow a study of the flux or spectral properties within one night of data.

The XMM data were analysed with the SAS 6.5 (6.0 for OM), according to the XMM Handbook and calibration instructions (and correspondingly for the XTE data), with

Table 1. Main parameters of the H.E.S.S. observations and campaigns, with the results of a single powerlaw fit. Errors are 1 sigma statistical. H.E.S.S. results taken from Aharonian et al. (2005a,b,c); Benbow et al. (2005); Pita et al. (2005); Tluczykont et al. (2005)

Name	z	X-ray obs.	TeV obs.	H.E.S.S. results detection	livetime	Γ_{obs}	N_0 ($cm^{-2}s^{-1}TeV^{-1}$)
PKS 0548-322	0.069	XMM 20/10/04	10 2004	(2.1σ)	4.1 hrs	-	$<$ 2.2% Crab
PKS 2005-489	0.071	XMM 4/10/04	6-7/8-9 2004	6.7σ	24.3 hrs	4.0 ± 0.4	1.9e-13
H 2356-309	0.165	XTE 11/11/04	6-12 2004	10σ	40 hrs	3.06 ± 0.21	4.4e-13
1ES 1101-232	0.186	XMM 8/6/04	3-6 2004-05	12σ	43 hrs	2.88 ± 0.17	3.1e-13

Table 2. X-ray data spectral parameters of the best fit models, for single and broken powerlaw ones. Preliminary analysis, full details in Aharonian et al. 2006, Costamante et al. 2006, in preparation. The column density was fixed at the galactic values. Errors are at 90% confidence level for 1 and 3 parameter of interests. The last column gives the range of possible slopes for the intrinsic TeV spectrum using the limits in Fig. 1, as derived in Aharonian et al. (2005c).

Name	exposure ks	Γ_1	E_{break} keV	Γ_2	Flux (2-10 KeV) erg cm^{-2} s^{-1}	intrinsic TeV Γ
PKS 0548-322	35	1.76 ± 0.05	0.81 ± 0.1	1.99 ± 0.01	3.28 e-11	-
PKS 2005-489	12	3.09 ± 0.02	-	-	1.03 e-12	3.5-3.6
H 2356-309	2.8	2.44 ± 0.25	-	-	1.0 e-11	2.0-2.3
1ES 1101-232	18	1.97 ± 0.04	1.3 ± 0.1	2.19 ± 0.03	3.88 e-11	1.5-1.8

the standard recipies for exclusion of background flares intervals, pile-up and background subtraction (details in Costamante et al. 2006, Aharonian et al. 2006, in preparation). The spectra were then analysed with XSPEC V11.3.1. The observations were performed in *small window* mode for MOS2, and in *timing* for PN. The main X-ray and TeV data parameters are summarized in Table 1.

No variability has been observed in these objects: all X-ray and OM light curves for the different filters are well fitted by a constant, as well as the hardness ratios among different energy bands. We therefore fitted the whole datasets, with free normalization between the the MOS2 and PN spectra. The preliminary results of single and broken-powerlaw fits are shown in Table 2. The N_H was fixed to the galactic values, but no evidence for higher values was found with free N_H.

4. TEV BLAZARS SEDS

We used all the available data (optical, X-ray and TeV) to build the source SEDs corresponding to the overall epoch of the TeV detections. Although derived from very different timescales (hours for the X-ray data, average over several months for the TeV data), the lack of significant variability also in the TeV band, and the fact that the X-ray data were taken in an epoch corresponding to the average TeV flux, suggests that these SEDs can likely represent the status of the source during a relatively quiescent period, even if of course variability in the unobserved epochs cannot be excluded (although not high enough).

The H.E.S.S. data were corrected for absorption as decribed in in Aharonian et al. (2005c): i.e. between the EBL upper limit corresponding to $\Gamma_{\rm TeV} \geq 1.5$ for 1ES 1101-232 and the absolute lower limit represented by the resolved galaxy counts (P0.4). The range of the derived spectra is shown in Table 2.

The OM data taken in the different filters (V, B, U, UVW1,UVM2) were corrected for galactic extinction according to the Cardelli's curve, and using the A_B values from NED (Schlegel et al. 1998), but no host galaxy subtraction was performed.

4.1. PKS 0548-322

This source was not detected by H.E.S.S. around the XMM pointing, so only an upper limit is derived Aharonian et al. (2005b), but given the short exposure (4 hrs) and assuming that the observed excess of 2.5σ is not due to background fluctuations, the detection level ($\sigma/\sqrt{hr}$) and flux estimate is comparable to that of the other objects (around 1% of the Crab).

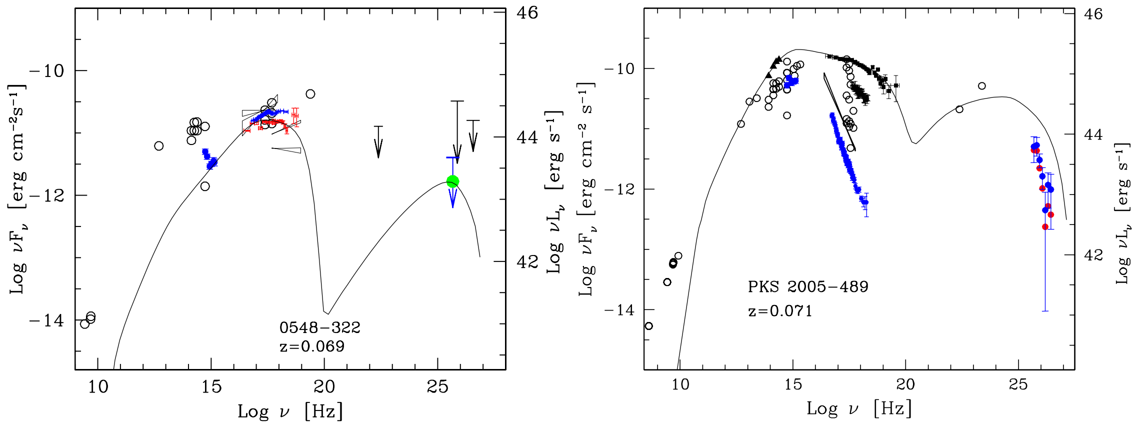

Figure 3. SED of the two HBL with very similar redshifts (~ 0.07). The new "sam epoch" data are shown in blue. In the TeV range: left, the point corresponds to the flux estimate on the excess, assuming it's not a fluctuation; right, the data are corrected with the middle curve in Fig. 1 (i.e. the one that implies $\Gamma = 1.5$ for the 1ES 1101-232 TeV spectrum). In black, historical data. The lines correspond to an old SSC modelling to the BeppoSAX data (see Costamante et al. (2001); Tagliaferri et al. (2001); Perlman et al. (1999)). An updated modelling is in preparation. The Y axis on the right shows the luminosity scale for these objects. For all calculations, a flat ΛCDM cosmology with $H_0 = 70$ km/s/Mpc, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ is adopted.

The X-ray spectrum (see Fig. 3, left) shows that the source was characterized by an extreme state, with the synchrotron peak $\approx 5keV$. Compared with the past *Beppo*SAX and ASCA data, the source was in a higher state in the hard X-ray band, approaching the hard spectrum seen with EINSTEIN. Given the nearly identical redshift as PKS 2005-489 (z=0.069 vs 0.071; so that the EBL absorption effects are exactly the same), and the very different X-ray and SED properties (Fig. 3), the comparison between the TeV emission in these two objects will be very interesting, shedding light on the most efficient TeV production conditions. These two objects in fact are characterized by very different ratios between X-ray (tracing TeV electrons) and optical-UV fluxes (giving the seed photons for IC).

Quite interestingly, the spectrum derived from the OM data in the different filters is concave, suggesting that we are seeing the transition zone between the tail of the host galaxy (thermal) emission, and the emerging of the jet synchrotron radiation.

4.2. PKS 2005-489

With PKS 2155-304, this HBL is one of the X-ray brightest BL lacs in the southern emisphere, and is characterized historically by a very large amplitude variability. The X-ray spectrum however has always been steep, even during the exceptional flare of 1998 Tagliaferri et al. (2001); Perlman et al. (1999), locating the peak below the X-ray band (Fig. 3, right)

Quite surprisingly, the X-ray state corresponding to the H.E.S.S. TeV detection is one of lowest and steepest ever observed in this object (2 orders of magnitude less than for the 1998 flare, in the hard X-ray band), suggesting similar properties also in the TeV range, which would explain the very steep TeV spectrum. Given the huge potential dynamic range for the X-ray flux (which traces TeV electrons), this object seems in fact a "dormant TeV vulcano", potentially capable of 10^{-10} erg cm^{-2} s^{-1} TeV fluxes even if the TeV emission would follow only linearly the X-ray one during flares. It is therefore one of the best objects to investigate the correlated variability in the two bands, both on the shortest timescales (thanks to the large fluxes expected in high states), and for long term monitoring studies, since the H.E.S.S. array seems capable to detect it also in a very low state.

The $\Gamma < 2$ slope indicated by the OM photometric data constraints the peak of the synchrotron emission to be located in the UV, around 10^{16} Hz.

4.3. H 2356-309

Compared to the past *Beppo*SAX data (Costamante et al. (2001)), these short XTE PCA observations reveal a significantly steeper spectrum in the hard X-ray band, and at a lower flux level by a factor ~ 3. The TeV spectrum, instead, once corrected for absorption, is flat ($\Gamma = 2.0$) up to 1 TeV using the upper limit EBL, while it is more similar to the X-ray one (within errors) if the EBL is as low as the galaxy counts limit. In the first case, for the usual

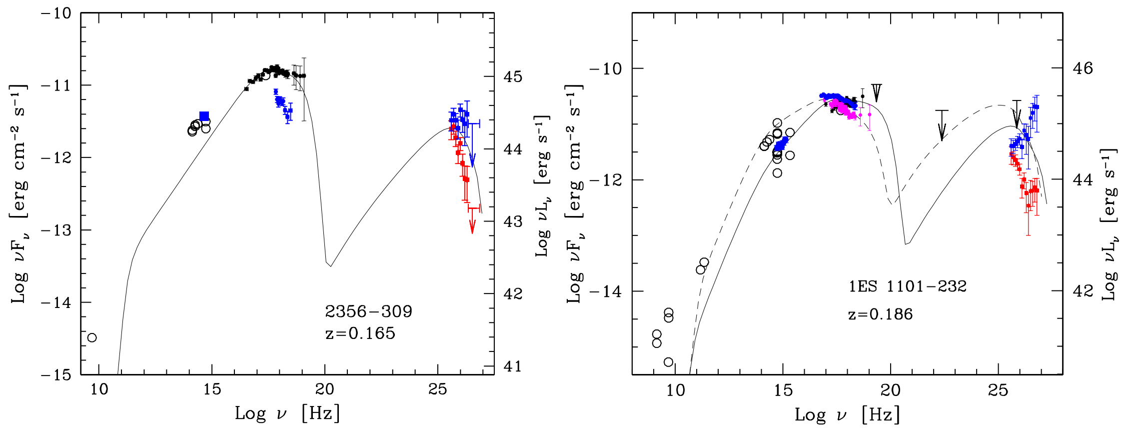

Figure 4. SED of the two most distant TeV blazars presently detected with spectral information. Same labels as in Fig. 3. In the TeV range, the lower point are the observed data, the higher ones are absorption corrected according to Aharonian et al. (2005c).

leptonic SSC scenarios, the IC peak would be located in the TeV band (unless such slope is due to a second component emerging above 200 GeV), and the electrons producing the TeV emission would not correspond to the observed X-ray ones. In the second case, instead, they can be the same electrons, but to avoid the steepening in the TeV band due to the Klein-Nishina effects, the scattering of these electrons has to occur around the Thomson limit and with a sufficiently constant energy density of seed photons, as given for example by a flat slope ($\Gamma 1.9-2$) down to the optical band.

4.4. 1ES 1101-232

Recognized by Wolter et al. (2000), using *Beppo*SAX observations, as an extreme BLLac (with $\nu_{peak} > 10$ keV) and promising TeV source, this object is revealed by the new H.E.S.S. and XMM results as one of the most interesting and puzzling cases for the blazars physics, even after assuming the lowest values for EBL absorption (i.e. galaxy counts). With all possible EBL levels, the intrinsic spectrum is always rather hard (see Table 2). The X-ray spectrum instead, as measured by XMM (at a flux level very similar to the old *Beppo*SAX data in high state), is characterized by a softer slope, nearly flat from 0.2 up to 1 keV and then steepening. The two emissions correspond therefore to two different particle spectra (KN effects tend to steepen the gamma-ray spectrum with respect ot the X-ray one, see e.g. Tavecchio et al. (1998)).

The natural question that arises is therefore: where is the synchrotron emission of the TeV electrons responsible for the TeV spectrum ? From simple energy conservation law, these electrons have

$$\gamma \gtrsim \frac{(1+z)}{\delta}\,\frac{(0.2-3)\mathrm{TeV}}{m_e c^2} \tag{1}$$

corresponding to $\gamma \gtrsim 2\cdot 10^6/\delta$ around 1 TeV. They emit by synchrotron at $h\nu_{sync} \gtrsim 50B(Gauss)/\delta$ keV. So the issue is to find an energy band in the SED with spectra as hard as the TeV ones. The OM data do indicate that the spectrum in the optical-UV band is quite hard, but to shift the TeV electrons synchrotron emission in the O-UV band would require very large beaming factors, $\delta \geq 100$. The alternatives within the SSC scenario are not many, but they can be effectively tested with further simultaneous observations:

- two populations/components, one of which characterized by lower fluxes but higher Compton dominance, so that its (hard) synchrotron spectrum remains hidden below the brighter (and softer) one. This hypothesis has already been proposed to explain the “orphan flares” in 1ES 1959+650 (Krawczynski et al. (2004)). In such case one should not expect correlated variability in the two bands, except for very low amplitude variations in X-rays, and more prominent in the hard bands;

- an electron population with a hard component rising above 10 kev, characterized by a spectrum similar to the TeV one (as in fact not excluded by the *Beppo*SAX PDS data). Such case can be tested with simultaneous observations in the hard X-ray band, although the problem remains on how to avoid the steepening of the gamma-ray spectrum due to the KN effect, since the Optical slope seems rather hard (meaning a rapidly decreasing seed photon energy density for higher energy electrons).

5. CONCLUSIONS

The new results obtained by H.E.S.S. on the high energy emissions of HBLs have opened a new vista on the blazars SED and EBL problems, as well as on the physics of the blazar emission itself. With the universe more transparent to γ-rays than previously thought, detections at larger redshifts become more likely also with the present generation instruments, and the the peculiar SED properties revealed by these X-ray – TeV observations make these objects excellent and very promising laboratories for a deeper understanding of the radiation mechanisms in blazars.

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