On the intrinsic spectrum of PKS 2155-304 from H.E.S.S. 2003 data

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Abstract. In 2003, PKS 2155-304 has been significantly detected by H.E.S.S. at Very High Energies (VHE), with an average spectrum of $\Gamma = 3.3$. Due to absorption by the Extragalactic Background Light (EBL), the intrinsic spectrum is heavily modified both in shape and intensity. To correct for this effect, and locate the Inverse Compton (IC) peak of the Spectral Energy Distribution (SED), we used three EBL models (representatives of three different flux levels for the stellar peak component). The resulting TeV spectrum has a peak around 1 TeV for stellar peak fluxes above the Primack (2001) calculation, while the spectrum is steeper than $\Gamma = 2$ (thus locating the IC peak < 200 GeV) for fluxes below. With bulk Lorentz factors $\delta = 20-30$ (typically used for this object), in the first case the IC peak is in the Klein-Nishina transition region, while in the other case it is in the Thompson regime, and in agreement with the commonly fitted source parameters (e.g. [17]). The constraint on δ given by transparency to 2 TeV photons is $\delta > 19$ (for historical SED fluxes and 2 hours variability timescale).

INTRODUCTION

PKS 2155-304 ($z = 0.116$), at present the second most distant TeV source BL Lac, has been significantly detected ($\sim 45\sigma$) by H.E.S.S. during its commissioning phase [3, 13], allowing for the first time a very good measure of its average spectrum up to ~ 2 TeV (stereo data, June-Sept. 2003 [3, 13]). The interpretation of these data in the context of the blazars Spectral Energy Distribution (SED), however, is not straightforward due to the effects of absorption of high energy photons by the Extragalactic Background Light (EBL), through $\gamma-\gamma$ collision and pair production. As for any extragalactic object of non-negligible redshift, the high (and energy dependent) optical depths determine a heavy modification of the intrinsic spectrum both in shape and intensity. Unfortunately, at present the EBL knowledge is still affected by large uncertainties, on both direct measurements and models [16, 11]. 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 the shape of three different EBL models, as representatives of three different flux levels for the 'stellar' light component of the EBL SED (Fig. 1), which is the one most affecting the H.E.S.S. spectrum. Our goal is not to investigate all possible EBL shapes, or provide a detailed modelling of the possible blazar's SEDs, but to highlight some simple and direct implications of the few important EBL parameters on the source intrinsic properties.

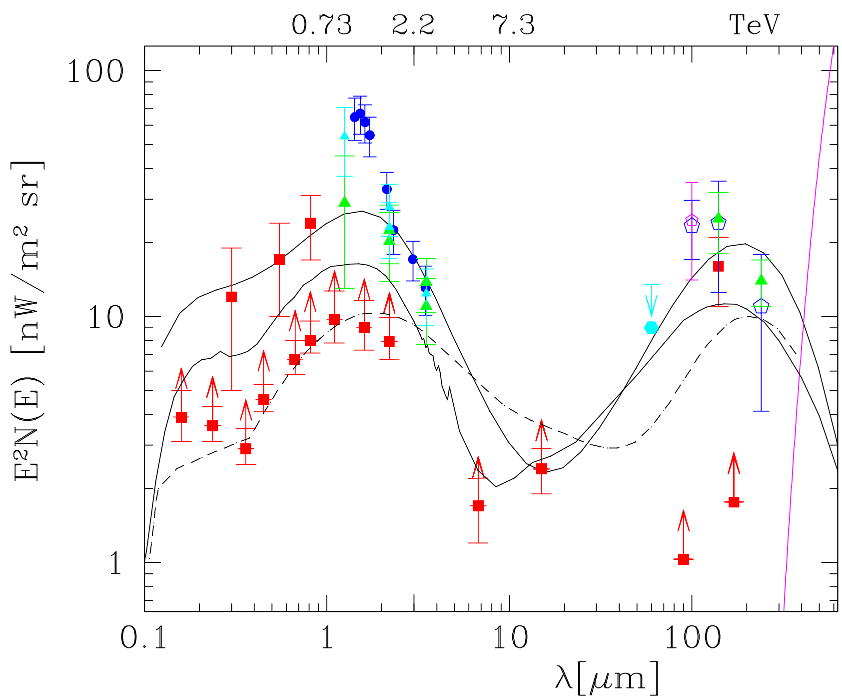

FIGURE 1. Spectral energy distribution of the of the Extragalactic Background Light (EBL). The compilation of measurements have been taken from [11], updated with recent publications (full refs. in [2]). Lower limits are from HST and ISO source counts [14, 8, 9] Above 400μm the CMB contribution starts to dominate. The two continuous lines represent the EBL shapes based on the Primack model: the original Primack 2001 calculation[16] (lower one), and the one presented in Aharonian et al. 2003 [2]. The dotted line is the Malkan & Stecker "baseline" model [15]. The upper scale shows the corresponding VHE photon energies for interactions at the peak of the $\gamma-\gamma$ crossection: at 1,3 and 10 μm , respectively.

EBL MODELS

The three models are showed in Fig. 1, and can be sorted according to the different peak fluxes at the 1–2 μm . The middle one is the original Primack calculation in 2001 [16], for a Salpeter initial mass function (which we will label *Primack01*). The higher flux one is the phenomenological shape used in Aharonian et al. 2003 [2] (there labelled Prim01), which is based on the Primack calculation but smoothed and scaled up to match the data points below 1 μm (*Ahar03*). The lower flux one is the model by Malkan & Stecker 2001 (MS, [15]), with "baseline" evolution (*MSbaseline*). With respect to the Primack ones, the MS models are also characterized by a very different shape above 3 μm (much flatter than λ^{-1}), implying a different dependence of the optical depth τ with energy (see Fig. 2): in particular, the absence of 'flattening' between 1 and 8 TeV. The present H.E.S.S. data, however, not having detection above $\sim$ 3 TeV, are not very sensitive to this difference, since the peak of the $\gamma-\gamma$ cross section for such photons is at 3–4 μm (Fig.1). In our case, therefore, the three models differ mainly for the flux levels below 3 μm , which directly corresponds to a different amount of steepening they imprint on the incident spectrum.

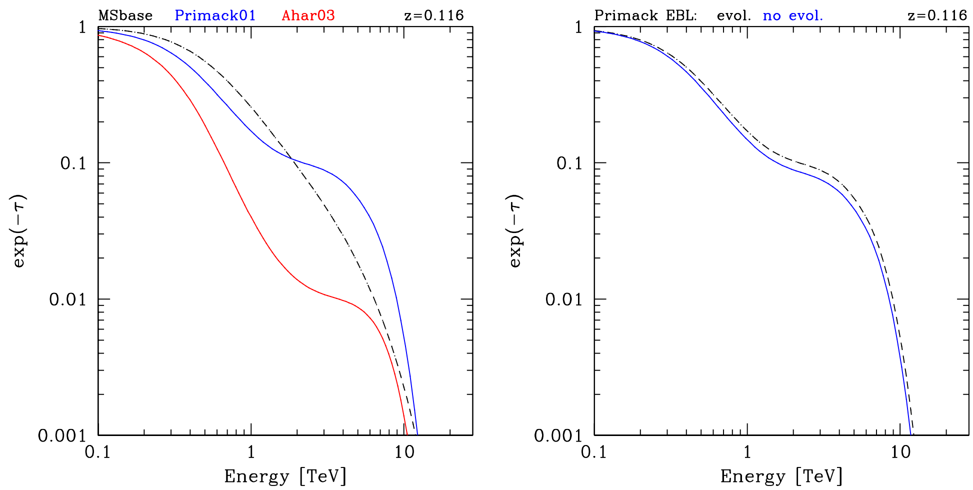

FIGURE 2. Left: attenuation factors for the three EBL shapes, calculated for the PKS 2155-304 redshift (z=0.116) and assuming no evolution. Full lines: Primack-like models. Dotted line: MSbaseline. The curves may be thought as the observed TeV spectrum resulting from an intrinsic power-law one with flat slope. Right: attenuation factors for the Primack01 model only, with (dotted line) or without (full line) evolution, as given in [16]. The difference is still small, and negligible compared to the models differences and EBL flux uncertainties (although not for a detailed spectral study).

Fig. 2 shows the attenuation factors for the three EBL shapes, at the redshift of PKS 2155-304 ($z = 0.116$). The optical depths are calculated from the EBL SED shapes taking into account only the cosmology ($H_0 = 70$ km/s/Mpc, $\Omega_{Mat} = 0.3$ and $\Omega_{\Lambda} = 0.7$). To treat all three cases 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 [16] (Fig.2 right), the difference is still small, negligible with respect to the difference between models, and doesn’t change relevantly our results.

THE IC PEAK OF PKS 2155-304

Fig. 3 shows the observed average H.E.S.S. spectrum of PKS 2155-304 (June-September 2003 data), together with the reconstructed one according to the three EBL models. The observed spectrum can be fitted by a single power-law with photon index $\Gamma = 3.32 \pm 0.06$ (statistical errors only; $\chi^2 = 10.8/7$ d.o.f.), with marginal improvements provided by a broken power-law or exponential cut-off models (with breaks around 0.7–1.4 TeV; full details in [3, 13]). Observed and reconstructed spectra are also plotted in Fig. 4, which shows the historical SED of PKS 2155-304.

The mere fact that we observe VHE emission up to ~ 2 TeV implies that the source is itself transparent to $\gamma - \gamma$ interactions, posing a strong limit on the energy density of

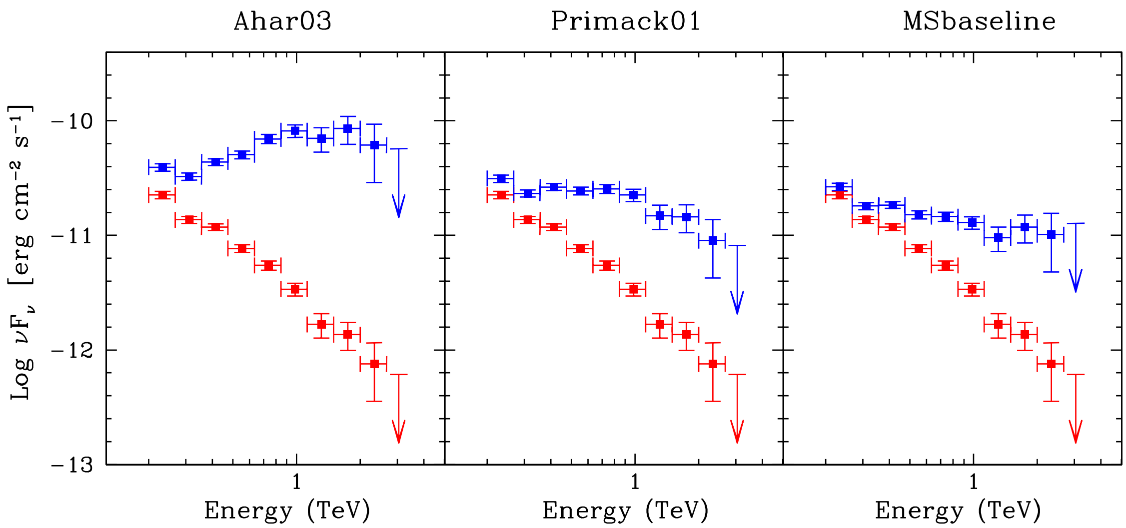

FIGURE 3. H.E.S.S. average spectrum of PKS 2155-304 from June-September 2003 data (configuration: 2-3 telescopes, stereo data; details in [13, 3]). Upper limit 90%. Red: observed data. Blue: absorption corrected spectra. Both "Primack-like" shapes present a break in the spectrum around 1 TeV, while the MSbaseline remains compatible with a (steep) single power-law spectrum. EBL fluxes above the Primack01 level (as Ahar03) imply a hard spectrum, which shifts the IC peak at higher energies with respect to lower EBL fluxes.

the soft radiation in the emitting region. From this limit one can obtain then a lower limit on the Doppler factor δ. Following [7], we can then update the limits given in [17] for this object ($\delta > 14$). We assumed an optical (V) flux of $log(\nu F_\nu) \approx -9.8$ (see Fig. 4) with a spectral index of ~ 0.9, and a variability time of 2 hours, as often shown by this source during optical monitoring (and confirmed also in 2003 data by the ROTSE III telescope on the H.E.S.S. site). With such values, the condition of transparency to 2 TeV photons implies a lower limit on $\delta > 19-20$. This value is at the lower end of the range usually obtained from SSC modelling [17, 12]. Such constraint is valid under the usual assumption that the region emitting the SED optical flux (i.e., the target photons) is cospatial with (or at least embeds) the high energy emitting region.

As shown in Fig. 3, the absorption corrected spectra are characterized by very different slopes, but yield two simple different scenarios for the location of the high energy peak. The Primack01 model, giving a slope ~ 2.1 below 1 TeV, represents approximately the dividing line: EBL models with stellar peak fluxes above it (as Ahar03) imply a hard ($\Gamma < 2$) intrinsic spectrum, with an IC peak at (for Primack-like shapes) or above 1 TeV. EBL models with fluxes at or below it (as MSbaseline), imply instead a steep intrinsic spectrum ($\Gamma > 2$), thus locating the IC peak below the observed energy range (< 200 GeV).

In the first case, the IC peak is given by electrons with at least $\gamma \gtrsim 2 \times 10^6/\delta$. With $\delta = 20-30$ the limit for IC scattering still in the Thompson regime is with photons $h\nu < 5-8$ eV. For a synchrotron peak at $\sim 10^{16}$ Hz (~ 40 eV, see Fig. 4), the source would be in the transition region between Thompson and full Klein-Nishina regimes.

In the second case, instead, the source properties are similar to those obtained in

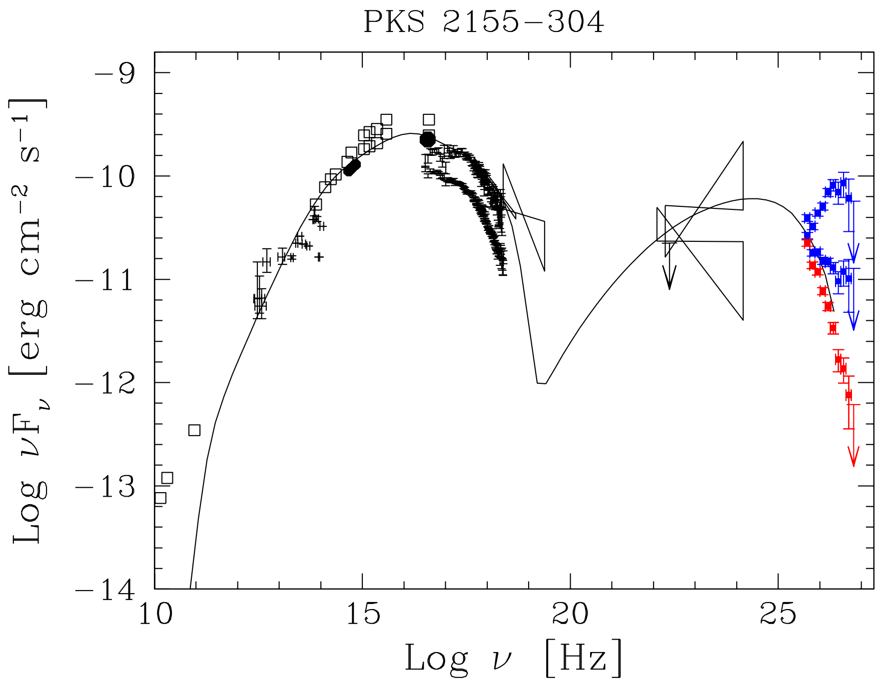

FIGURE 4. SED of PKS 2155-304 (historical data and SSC modelling, from [6]), with superimposed the H.E.S.S. average spectrum of June-Sept. 2003: observed (red, lower points) and absorption corrected with Ahar03 and MSbaseline models (blue, upper and middle points, respectively). The EGRET data plotted are from the 3EG catalogue (steeper spectrum) and a re-analysis of the VP4040 (previously reported in [18]). Updated modelling, with quasi-simultaneous optical and X-ray data, is in preparation (for the data from the multiwavelength campaign in October and November 2003 [13])

the past by many authors, (i.e., within the Thompson limit), who assumed for their modelling an IC peak around $\sim 10^{25}$ Hz (10–100 GeV). See e.g. [17, 10, 4, 12], with typical values $\gamma_{\rm peak} \approx 10^{4.5}$, $\delta = 20-30$, $B = 0.1-0.4$ Gauss.

Even if limited to 2–3 TeV, it is however interesting to note that the observed H.E.S.S. spectrum does not show even a hint of flattening above 1–2 TeV, as seen instead by HEGRA in 1ES 1426+428 ($z = 0.128$) [2], and naturally provided by an EBL shape $\propto \lambda^{-1}$ between 3 and ~ 15 μm (Fig.2). On the contrary, there is marginal evidence for a steepening above 0.7–1 TeV [3, 13]. This effect, however, may be likely due to an intrinsic break of the electron spectrum: with typical values $\delta = 20-30$ and B$= 0.4-0.2$ Gauss, the steepening often seen in X-rays above 3–5 keV translates to a steepening above 2–3 TeV, thus smearing this absorption feature. This dataset is therefore not yet able to even provide an indication for MS or Primack-like shapes: a different source state and simultaneous observations (X-ray data above all) are necessary.

These H.E.S.S. data, in fact, are remarking the importance not only of redshift but also of source properties, for the study of the EBL in that wavelength range. To discriminate among these models, we need a source (or source state) with a simple spectrum and no significant intrinsic breaks in the range between ~ 0.3 and 10 TeV, together with a relatively high flux (for higher statistics) in the 1–10 TeV band. The latter condition points toward objects with hard, single power-law like intrinsic spectra: it's not a case that these are exactly the characteristics of 1ES 1426+428, as shown by its peculiar X-ray spectrum (hard single power-law from 0.1 up to $\sim$ 100 keV, [5]).

Furthermore, not at every redshift such an object could be suited for these studies. Very low redshifts, although easing detectability, provide a low contrast between the steeper and flatter parts of the attenuation factors (Fig. 2) and a smaller difference between the models, which may be more difficult to disentangle from the intrinsic spectral properties even in case of high statistics (e.g. Mkn 501 and 421). On the other hand, large redshifts emphasize the contrasts and models differences, but the "flattening" feature would be seen at increasingly large optical depths, implying a much lower statistics (or even non-detectability) for a given intrinsic flux.

The redshift range between 0.1–0.15 might therefore represent to this respect the "sweet spot" for such studies, given the HEGRA results on 1ES 1426+428. This source, with its nice combination of redshift, TeV emissivity and spectral properties, could turn out to be a more special and precious object than previously thought.

REFERENCES

1. Aharonian F.A. et al., 2002, A&A, 393, 89
2. Aharonian F.A. et al., 2003, A&A, 403, 523
3. Aharonian F.A. et al., 2004, A&A, accepted (astroph ??)
4. Chiappetti et al., 1999, ApJ, 521, 552
5. Costamante L. et al., 2001, A&A, 371, 512
6. Costamante L. & Ghisellini G., 2002, A&A, 384, 56
7. Dondi L. & Ghisellini G., 1995, MNRAS, 273, 583
8. Elbaz D. et al., 2002, A&A, 384, 848
9. Gardner J.P. et al., 2000, ApJ, 542L, 79
10. Ghisellini et al, 1998, MNRAS, 301, 451
11. Hauser M.G. & Dwek E., 2001, ARAA, vol. 39, (astro–ph/0105539)
12. Kataoka J. et al., 2000, ApJ, 528, 243
13. Lemiere A., 2004, these proceedings
14. Madau P. & Pozzetti L., 2000, MNRAS, 312L, 9
15. Malkan & Stecker, 2001, ApJ, 555, 641
16. Primack et al., 2001, AIP Conf. Proc. 558, 463
17. Tavecchio F. et al., 1998, A&A, 509, 608
18. Vestrand et al., 1995, ApJ, 454, L93