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A low density of the Extragalactic Background Light revealed by the H.E.S.S. spectra of the BLLac objects 1ES 1101-232 and H 2356-309

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Abstract The study of the TeV emission from extragalactic sources is hindered by the uncertainties on the diffuse Extragalactic Background Light (EBL). The recent H.E.S.S. results on the blazars 1ES 1101-232 and H 2356-309 represent a breakthrough on this issue. Their unexpectedly hard spectra allow an upper limit to be derived on the EBL in the optical/near-infrared range, which is very close to the lower limit given by the resolved galaxy counts. This result seems to exclude a large contribution to the EBL from other sources (e.g. Population III stars) and indicates that the intergalactic space is more transparent to $\gamma$-rays than previously thought. A discussion of EBL absorption effects and further observational tests with Cherenkov telescopes are presented.

Keywords $\gamma$-rays · AGN · EBL · extragalactic · diffuse background · blazar

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1 Introduction

The diffuse Extragalactic Background Light (EBL) contains unique information about the epochs of formation and the history of evolution of galaxies, since it consists of the sum of the light produced by all extragalactic sources over cosmic time. Its Spectral Energy Distribution (SED, Fig. 1) is characterized by two broad bumps [1], produced by thermal emission contributed directly from stars at optical (Opt) and near infrared (NIR) wavelengths, and by dust which partly absorbs and re-emits the starlight at longer wavelengths (FIR). The Opt-NIR range has gained special interest in recent years because some direct measurements between 1 and 3 $\mu$m have suggested the presence of a significant excess above the contribution of normal galaxies, which has been intriguingly interpreted as the signature of redshifted UV light from heavy Population-III star formation at $z \sim 10$ [2] (though with severe energy-budget problems, see [3]). Unfortunately, direct EBL measurements are subject to possible large systematic uncertainties due to the difficulty of an accurate modelling and then subtraction of the bright foregrounds, mainly consisting of zodiacal (interplanetary dust) light [1].

An alternative approach [4] is provided by the measurement of very high energy (VHE) $\gamma$-rays from extragalactic sources, through the detection and identification of absorption features in the VHE spectra caused by the interaction with EBL photons ($\gamma\gamma \rightarrow e^+e^-$). High-
energy peaked blazars (HBL) represent to this respect excellent sources of $\gamma$-ray beams, thanks to their prominent TeV emission and high apparent luminosity, which makes them detectable from large distances and/or with good photon statistics. The “downside” is that they are highly variable and characterized by a very wide range of possible spectra. Though a lot has been learned about them, the present understanding of their radiation processes is not yet complete enough to reliably predict the intrinsic TeV spectra, and thus to disentangle absorption from intrinsic features. Conversely, the still large uncertainties on the EBL prevent a sufficiently accurate reconstruction of their intrinsic spectra in order to constrain the emission models. The studies of blazars and EBL are therefore tightly coupled, in a classic case of “one equation, two variables” problem [17].

So far, only hints and guesses could be made from the TeV detected objects (in particular from the more distant 1ES 1426+428 [8] and PKS 2155-304 [9,10]), since the reconstructed spectra could be generally explained also as blazars’ intrinsic features. The surprising hardness of the H.E.S.S. spectra of 1ES 1101-232 and H 2356-309 [5,6] represent a breakthrough in this respect, posing the problem of conflict between blazar spectra and EBL estimates in a much more severe and compelling way.

2 EBL effects on TeV $\gamma$-ray spectra

To illustrate the effects of absorption, as reference shape for the EBL SED we adopted the phenomenological curve used in [18] (labelled P1.0 in Figure 1), which is designed to be in general agreement with the EBL spectrum expected from galaxy emission [11] (modulo normalization). Such EBL SED imprints a specific shape onto the original spectrum, as illustrated in Fig. 2 (center panel): above $\sim$0.1 up to $\sim$1-2 TeV it causes a strong steepening, followed by a flattening between 2 and $\sim$7 TeV, where the observed spectrum partially recovers the original slope (owing to the decline approximately $\propto \lambda^{-1}$ above few microns, which causes the optical depth to become nearly constant with energy [4]). Further on, a sharp cut-off occurs above $\sim$8-10 TeV caused by the EBL SED rising again above 10 $\mu$m.

This yields two consequences: a) with the current systematic uncertainties of Cherenkov telescopes (CT), if the intrinsic spectrum is a power-law the observed spectrum can still be well approximated by a power-law model in the range 0.2-2 TeV, but of steeper spectral index ($\Gamma_{\text{obs}} > \Gamma_{\text{int}}$); b) measuring a spectrum above $\sim$200 GeV, no cut-off is expected from EBL absorption up to $\sim$6-7 TeV: any cut-off measured by CT in such energy range is more likely to be intrinsic (unless considering an EBL NIR spectrum much flatter than $\propto \lambda^{-1}$). Note also that in the range 0.2-10 TeV breaks or cut-offs in the emitting particle distribution of blazar jets are quite common, as shown by the corresponding synchrotron emission in the Opt–X-ray range. Such intrinsic steepening might cancel out the expected flattening due to EBL absorption. In other words, the absence of such flattening in the TeV spectra of some blazars does not imply an evidence for a different EBL spectrum. To detect such feature, a power-law (and possibly hard) intrinsic TeV spectrum over $\sim$2 decades is generally needed (e.g. 1ES 1426+428 [8]).

Figure 2 shows the effect of a change of the EBL normalization “$P^\prime$” and of source redshift: $\Delta \Gamma$ (the difference between observed and intrinsic slope) increases with both normalization and redshift. The two dependencies combine, so that at higher redshifts an equal change of EBL density yields a much stronger effect (Fig. 2, right panel). Redshift thus provides leverage: more distant ob-
The effects of changing the EBL spectral shape (increasing the flux selectively at 1-2 µm or at 0.2-0.3 µm, left panel) on the attenuation factor, for fixed redshift. Center panel: an increase only at 1-2 µm strongly steepens the spectrum, since it increases the optical depth at ∼ 1 − 2 TeV without affecting the 0.2-0.3 TeV range (since below threshold). Instead, a higher EBL flux in the UV range alone increases absorption at 0.2 TeV more than at 1-2 TeV, thus reducing the energy dependence of the optical depth (right panel). As a result, the spectrum suffers less steepening, at the price of an overall higher attenuation.

Figures 3 shows instead the effects of a change in the EBL spectrum with respect to our template, namely increasing the flux in the 1-3 µm range (as would be required to match some direct estimates, and expected in the Pop III stars scenario) or in the 0.1-0.3 µm range. In the first case the steepening gets stronger, while in the second case it is reduced, because of a lower contrast in optical depth between 0.2 and 1 TeV photons (though at larger absolute values). Note that a decrease of the UV-opt fluxes would not reduce the steepening, since it increases the contrast between the two energies while reducing the absolute values.

It is also worth to highlight an important consequence of EBL absorption on blazar interpretation: if the EBL is high, sources at z ≳ 0.1 would be so heavily absorbed that their intrinsic Inverse Compton (IC) luminosity and peak energy become always much higher than the observed ones. The absorption-corrected values can easily reach IC peak energies > 3-10 TeV and luminosities in excess of 10^{47−48} erg cm^{-2}s^{-1}, with a Compton dominance of 10-100. Therefore, the bulk of their luminosity would be emitted at high energies, alike FSRQ. In other words, they would represent the famous “high-energy peaked, high-luminosity” blazars that would invalidate the blazar sequence scenario[12,13] (though it would remain the issue of why their radio luminosity is so low compared to FSRQ). These objects would not have been recognized as such counter-examples simply because their luminosity would be largely underestimated, being dispersed in the intergalactic space due to γ − γ absorption. Though now this seems not the case (see Sect. 3), this possibility still remains also with a low EBL level, considering objects at significantly larger redshift (but which are likely beyond the horizon of the present generation of CT).

Fig. 4 The HESS spectra of 1ES 1101-232, corrected for absorption with three different EBL SEDs, as labelled (from [5] see ). Red: observed data. Blue: absorption-corrected data. The lines show the best fit power-laws to the reconstructed spectrum, and the corresponding shape after absorption correction.

3 EBL upper limits from H.E.S.S. spectra

The intrinsic TeV spectra were reconstructed directly from the observed ones, using the optical depth calculated for the assumed EBL SED. In this way no a priori assumption on the blazar spectrum is required. The reconstructed spectra are compatible with a power-law model, but high EBL fluxes yield extremely hard photon indices (Γ_{int} ≲ 0), for both 1ES 1101-232 (Fig. 4) and whole SED in Fig. 5) and H 2356-309 (see [5]). Such hard spectra have never been seen in the closest, less absorbed objects (e.g. Mkn 421 and Mkn 501, Γ_{int} ≈ 1.5 − 2.8 for the same EBL SEDs) and are difficult to explain within the standard leptonic or hadronic scenarios[4] for blazar emission. Assuming instead more typical values for the intrinsic spectrum as expected from the currently known blazar physics and phenomenology, namely that the true average VHE spectrum during the H.E.S.S. observations...
was $\Gamma_{\text{int}} \gtrsim 1.5$ (as obtained under most circumstances if the index for the particle spectrum in shock acceleration models is $s \gtrsim 1.5$, [14]), the EBL SED has to be scaled down to the level of P0.45, very close to the galaxy counts limit (details in [5]). This represents the upper limit for the EBL in the Opt-NIR range which does not require dramatic changes for the blazar physics or in the scenarios for the underlying particle spectra. Accounting for galaxy evolution and for the statistical and systematic uncertainties on the H.E.S.S. spectral measurement, the limit corresponds to $\lesssim (14 \pm 4) \text{nW m}^{-2} \text{sr}^{-1}$ (i.e. $\lesssim P_{0.55} \pm 0.15$; Fig. 6). Of course, a different limit can be derived according to different hypotheses, and depending on their overall plausibility. But only strong spectral differences would qualitatively change this result (see Sect. 4); for example, even the case of a particle spectrum with $s = 1$, which has been argued as asymptotically possible in finite-Mach-number shocks under certain conditions (see e.g. [15][16]), would raise the limit only slightly (for 1ES 1101-232, the change of scaling factor $P$ is approximately $\Delta P \simeq 0.34 \Delta \Gamma$).

### 4 Alternative scenarios

Another way to avoid such hard spectra is to reduce the energy dependence of the optical depth by increasing absorption at low $\gamma$-ray energies, i.e. with high UV-Opt fluxes. However, the huge fluxes required to have $\Gamma = 1.5$ (> 300 nW m$^{-2}$ sr$^{-1}$, see [5] and Fig. 3 left) are in contrast with measurements [17], even when interpreted as upper limits, and could hardly be accomodated within any reasonable cosmological model. Unless considering even more exotic scenarios like violation of Lorentz invariance or the non-cosmological origin of blazars’ redshift, at present the most viable alternative is that such hard spectra are a real, newly discovered feature of the blazar emission. Possible mechanisms have already been envisaged [4]. Bulk-motion Comptonization in the deep Klein-Nishina regime of a narrow-band photon field (such as a Planck-type distribution) by cold plasma with a very large Lorentz factor may lead to very hard spectra with a sharp pile-up, reproducing spectra like the ones in Fig. 4.5 (see [4]). A “pile-up” (i.e. relativistic Maxwellian) particle distribution seems also expected as outcome of turbulent acceleration (see e.g. [18][19] and refs therein). In this case, however, even suppressing cooling and considering a purely monoenergetic distribution (or a distribution with a similarly sharp low energy cut-off at $\gamma_{\text{min}} > 10^5$ [20]), the resulting synchrotron and SSC spectrum would be at most $\propto \nu^{1/3}$, i.e. $\Gamma \gtrsim 0.66$ [20]. If so, the EBL P0.45 upper limit would be shifted to $\approx \gamma_{0.72}$. Note that to make this scenario feasible it is necessary to always hide the hard synchrotron emission of these particles below a second, broader component which dominates the blazar emission at low energies, in order to account for the simultaneous SED (Fig. 5).

However, even if theoretically feasible, also this alternative seems highly unlikely. If intrinsic, such pile-up features should be directly visible in the observed VHE spectra of closer, less absorbed HBLs like Mkn 421 and Mkn 501 (if $\Gamma_{\text{int}}$ was $\approx 0$, they should show $\Gamma_{\text{obs}} \lesssim 0.5$). This is in contrast with observations, unless assuming a dependence of the source parameters on redshift such that the corresponding features always disappear due to EBL absorption. It is difficult to justify such a fine-tuning on a relatively small redshift range, even assuming an evolution of blazar properties. Though the sample of objects is still too limited to settle this issue definitively, growing data seem to corroborate this conclusion. Figure 7 shows the observed photon indices of all TeV blazars detected so far as a function of redshift, in comparison with the expected index for a $\Gamma = 1.5$ intrinsic spectrum. If the EBL density is high, the very strong dependence

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**Fig. 5** SED of 1ES 1101-232 [25], for an EBL spectrum equal to P1.0. At lower energies, XMM data (blue) and RXTE data (green) have been taken in the same epoch of the H.E.S.S. observations (Aharonian et al. 2006, in prep.). Magenta: historical SAX observations [25].

**Fig. 6** Upper limit for the EBL (black marked region), corresponding to the assumption of an intrinsic 1ES 1101-232 spectrum with photon index $\Gamma \geq 1.5$. It is obtained from the P0.45 curve, when accounting for galaxy evolution effects (details in [5]).
Fig. 7  Observed hardest photon indices of the VHE spectra of all detected TeV blazars as a function of redshift. The lines give the expected observed (i.e. absorbed) photon index of a source with an intrinsic spectrum \( \Gamma = 1.5 \), when fitted in the range 0.2-1 TeV, for different EBL SEDs (as labelled). The dashed line corresponds to an EBL SED as low as the galaxy counts limit, and including galaxy evolution effects (according to [11]). The distance of the points over each curve represents visually the intrinsic hardness of the source spectra. Red: H.E.S.S. data. Blue: MAGIC data. Black: past results. The sources are (from left to right): Mkn 421, Mkn 501, 1ES 2344+514, Mkn 180, 1ES 1959+650, PKS 2005-489, PKS 2155-304, 1ES 1426+428, H 2356-309, 1ES 1218+304, 1ES 1101-232, PG 1553+113 (details in [6], Table 1).

on redshift would require a dramatic change of properties between TeV blazars at \( z \sim 0.2 \) and \( z \lesssim 0.1 \), with all 4 farther objects showing such hard features (which would thus seem rather common) and none of the 8 closer objects. There seems to be no reason why the jet emission mechanisms in blazars should know the level of the EBL with such precision. A low EBL level instead, close to the galaxy counts limit, does not impose such difference, making the TeV properties similar among different HBLs in this redshift range, as observed in all the other energy bands of the SEDs.

5 Observational tests

A straightforward step to test this conclusion is to look for independent evidence that HBLs can indeed have much harder TeV spectra than assumed. This can be done focussing in particular on lower (\( z < 0.1 \)) and higher (\( z > 0.3 \)) redshift objects. A low EBL level instead, close to the galaxy counts limit, does not impose such difference, making the TeV properties similar among different HBLs in this redshift range, as observed in all the other energy bands of the SEDs.

as the galaxy counts limit. This would provide evidence for intrinsically hard spectra, though in such case the possibility of exotic scenarios invoking a modification of the physics of the \( \gamma-\gamma \) interaction would not be formally excluded. With a low EBL level, objects at \( z=0.4-0.5 \) should be well within the possibilities of the current CT generation. Figure 8 shows the optical depth expected for a source at \( z=0.5 \) using the EBL model by [11], when scaled down to match the EBL upper limits. This model was adopted to properly include galaxy evolution effects, which become important at larger redshifts. Though the spectrum is expected very steep, up to 300 GeV the attenuation is not dramatically higher than for the already detected TeV sources, and only a factor \( \sim 2 \) around 150 GeV. Sources at such distances therefore could be detectable by current CT also outside exceptional (and rare) high-flux states.

The best targets for such observations are HBLs with the appropriate declination to be observable by CT at zenith (to take advantage of the lowest possible energy threshold), and with high X-ray brightness (indicating a large number of TeV electrons). Using the BLLac samples and criteria described in [21], a group of 3 objects best matching these requirements have been found in the northern hemisphere (Fig. 9), suited for MAGIC and VERITAS. They are therefore suggested for observations (Table 1). A similar program for the southern hemisphere has been proposed for H.E.S.S.

6 Conclusions

Showing an unexpected hardness for their redshift, the combined H.E.S.S. spectra of the HBLs 1ES1101-232
Fig. 9 BL Lac objects in the radio (5 GHz) and X-ray (1 keV) $\nu F(\nu)$ plane (details in [21]). Sources belonging to different samples have different symbols, as labeled. Black crosses: new TeV detections since the proposal of the X-ray/radio Flux selection criterion (dotted rectangle). Black squares: location of the proposed high-$z$ sources for MAGIC/VERITAS (Table 1). If at redshift $\sim 0.1$, their location would be in the upper part of the rectangle (a change of redshift moves an object approximately along the lines of constant $\alpha_{RX}$).

and H 2356-309 (now supported by two further TeV sources) provide strong circumstantial evidence for a low density of the EBL. With minimal assumptions on the blazar properties, the H.E.S.S. spectra allow the derivation of an upper limit on the EBL in the Opt-NIR range which is very close to the lower limit given by the integrated light of resolved galaxies. This result indicates that the EBL at these wavelengths is strongly dominated by the direct starlight from galaxies, and thus excludes a large contribution from other sources, in particular Pop III stars. At the same time, this result strongly reduces the uncertainty on the reconstruction of the blazar intrinsic spectra (up to few TeV), thus allowing a more accurate modelling and understanding of the overall SED. However, additional detections and monitoring by the new-generation CTs are needed to better sample the blazars’ behaviour at VHE, to further test this conclusion and possibly to pin down the diffuse background also above a few microns.

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References

1. Hauser, M.G & Dwek, E.: The Cosmic Infrared Background: measurements and implications. ARAA, 39, 249 (2001)
2. Santos, M.R. et al.: The contribution of the first stars to the cosmic infrared background. MNRAS, 336, 1082-1092 (2002)
3. Madau, P. & Silk, J.; Population III and the near-infrared background excess. MNRAS, 350L, 37-41 (2005)
4. Aharonian, F.A.: TeV blazars and the Cosmic Infrared Background radiation. Invited, Rapporteur, and Highlight Papers. Proc. 27th ICRC (Hamburg) (ed Schlickeiser R.), p.250-262 (2001), astro-ph/0112314
5. Aharonian, F.A., et al. (H.E.S.S. collab.): A low level of extragalactic background light as revealed by $\gamma$-rays from blazars. Nature, 440, 1018-1022 (2006)
6. Belikov, M. for the H.E.S.S. collabor., these proceedings.
7. Costamante, L. et al.: Constraining the cosmic background light with four BL Lac TeV spectra. NewAR, 48, 469-472 (2004)
8. Aharonian, F.A. et al. Observations of H1426+428 with HEGRA. Observations in 2002 and reanalysis of 1999&2000 data. A&A, 403, 523-528 (2003)
9. Aharonian, F.A., et al. (H.E.S.S. collab.): H.E.S.S. observations of PKS 2155-304. A&A, 430, 865-875 (2005)
10. Dwek, E. et al: The Near-Infrared Background: Interplanetary Dust or Primordial Stars? ApJ, 635, 784-794 (2005)
11. Primack, J.R., et al.: Probing Galaxy Formation with High-Energy Gamma Rays. AIP Conf. Proc., 558, 463-478 (2001)
12. Ghisellini, G. et al.: A theoretical unifying scheme for $\gamma$-ray bright blazars. MNRAS, 301, 451-468 (1998)
13. Padovani, P., these proceedings.
14. Malkov, M.A. & O’C Drury, L., Nonlinear theory of diffusive acceleration of particles by shock waves. Rep. Prog. Phys., 64, 429-481 (2001)
15. Schlickeiser, R.: Cosmic ray astrophysics. Springer-Verlag, XV+519pp (2002)
16. Vainio, R.: Diffusive Shock Acceleration. Proc. Conf. “Plasma turbulence and energetic particles in astrophysics”, Cracow (Poland), p.232-245, (1999)
17. Bernstein, R.A. et al.: The First Detections of the Extragalactic Background Light at 3000, 5500, and 8000 Å. I. Results. ApJ, 571, 56-84 (2002)
18. Sauge, L. & Henri, G.: TeV Blazar $\gamma$-Ray Emission Produced by a Cooling Pileup Particle Energy Distribution Function. ApJ, 616, 136-146 (2004)
19. Park, B.T. & Petrosian, V.: Fokker-Planck Equations of Stochastic Acceleration: A Study of Numerical Methods. ApJS 103, 255-267 (1996)
20. Katarzynski, K. et al.: Hard TeV spectra of blazars and the constraints to the infrared intergalactic background. MNRAS, 368, L52-L56 (2006)
21. Costamante, L. & Ghisellini, G.: TeV candidate BL Lac objects. A&A, 384, 56-71 (2002)
22. Elbaz, D. et al. The bulk of the cosmic infrared background resolved by ISOCAM. A&A, 384, 848-865 (2002)
23. Dole, H. et al.: The cosmic infrared background resolved by Spitzer. Contributions of mid-infrared galaxies to the far-infrared background. A&A, 451, 417-429 (2002)
24. Mattila, K.: Has the Optical Extragalactic Background Light Been Detected? ApJ, 591, 119-124 (2003)
25. Wolter, A., et al.: X-ray variability and prediction of TeV emission in the HBL 1ES1101-232. A&A, 357, 429-436 (2000)