CONSTRANTS ON ENERGY SPECTRA OF BLAZARS BASED ON RECENT EBL LIMITS FROM GALAXY COUNTS

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ABSTRACT

We combine the recent estimate of the contribution of galaxies to the 3.6 μm intensity of the extragalactic background light (EBL) with optical and near-infrared (IR) galaxy counts to set new limits on intrinsic spectra of some of the most distant TeV blazars, 1ES 0229+200, 1ES 1218+30.4, and 1ES 1101–232, located at redshifts 0.1396, 0.182, and 0.186, respectively. The new lower limit on the 3.6 μm EBL intensity is significantly higher than the previous one set by the cumulative emission from resolved Spitzer galaxies. Correcting for attenuation by the revised EBL, we show that the differential spectral index of the intrinsic spectrum of the three blazars is 1.28 ± 0.20 or harder. These results present blazar emission models with the challenge of producing extremely hard intrinsic spectra in the sub-TeV to multi-TeV regime. These results also question the reliability of recently derived upper limits on the near-IR EBL intensity that are solely based on the assumption that intrinsic blazar spectra should not be harder than 1.50.

Subject headings: BL Lacertae objects: individual (1ES 1218+30.4, 1ES 1101–232, 1ES 0229+200)

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1. INTRODUCTION

The absorption of TeV photons on intergalactic distance scales via γ→ee by the diffuse radiation from the EBL is crucial for the understanding of TeV γ-ray sources with significant redshift (Gould & Schréder 1967). Direct measurements of the EBL at near- to mid-IR wavelengths are greatly hampered by the presence of strong foreground emission from interplanetary dust and diffuse Galactic emission from unresolved stars and the interstellar medium. Consequently, our knowledge of the EBL consists mostly of lower limits derived from ground- and space-based galaxy counts or direct measurements prone to substantial systematic uncertainties (Hauser & Dwek 2001; Kashlinsky et al. 2005).

The catalog of TeV blazars now contains more than 20 objects (see, e.g., Hinton 2007) spanning a range of redshifts between 0.03 and 0.536. Their observed energy spectra have therefore passed through different path lengths resulting in different degrees of attenuation. The observed TeV energy spectra of blazars therefore contain information about their intrinsic spectra convolved with the absorption due to the EBL in the near-IR and mid-IR. Separating the intrinsic blazar spectra from the absorption effect to derive the constraints to the EBL has proven a difficult task (see Stecker et al. 1992, 2007; Dwek & Krennrich 2005; Aharonian et al. 2006; Mazin & Raue 2007) and may require a significantly larger sample of TeV blazars. However, if successful, the potential of providing constraints on the EBL density using TeV energy spectra provides complementary information to direct measurements of the EBL (see, e.g., Coppi & Aharonian 1999).

Galaxy counts provide a firm lower limit on the EBL, and therefore a strong lower limit on the magnitude of absorption present in a blazar spectrum. Figure 1 presents 0.36, 0.45, 0.67, 0.82, 1.1, 1.6, and 2.2 μm lower limits on the EBL determined from ground-based and Hubble Space Telescope (HST) observations (filled triangles) presented by Madau & Pozzetti (2000, hereafter MP00). At 3.6, 4.5, 5.8, and 8.0 μm (open squares), lower limits arise from galaxy counts using the IRAC instrument on the Spitzer infrared space observatory (Fazio et al. 2004), and the 15 and 24 μm Spitzer/MIPS data, obtained by Metcalfe et al. (2003) and Papovich et al. (2004), respectively (open circle and diamond). Recently, Levenson & Wright (2008, hereafter LW08) used profile-fitting techniques to estimate the contribution of the faint fuzzy fringes of galaxies to the total contribution of resolved galaxies, increasing the 3.6 μm lower limit from 5.4 to 9.0 ± 1.7 nW m⁻² sr⁻¹. This correction has brought the galaxies’ contribution to the EBL to within ~1σ of the EBL intensity determined from measurements made with the Cosmic Background Explorer (COBE) satellite (Dwek & Arendt 1998). In the following we treat the constraint by LW08 purely as a lower limit to the EBL at 3.6 μm.

The same considerations that have resulted in a significant underestimate of the contribution of resolved galaxies to the 3.6 μm EBL may also apply to the estimated integrated light from resolved galaxies obtained from standard aperture photometry (Bernstein et al. 2002; Wright 2001; Yoshi 1993; Bernstein et al. 2007). The galaxies’ contribution to the EBL could therefore be higher than the reported lower limits of MP00. The combination of the new limit at 3.6 μm with potentially higher limits at shorter wavelengths (MP2.0+ LW+ MIR; see below for nomenclature) will imply more attenuation for γ-ray spectra at TeV energies and harder intrinsic spectra.

Only a limited number of blazar spectra at TeV energies at sufficiently high redshift, and consequently substantial absorption, are available. This leads us to select the energy spectra of 1ES 1218+30.4 (Albert et al. 2006) detected over the 0.08–0.7 TeV range, and also recently detected by VERITAS over an energy range of 0.18–1.5 TeV (Fortin et al. 2008); 1ES 1101–232 (Aharonian et al. 2006) detected over the 0.18–2.9 TeV range, and 1ES 0229+200 (Aharonian et al. 2007a) detected over the 0.6–11.5 TeV range. Note that 3C 279, the most distant blazar at a redshift of 0.536, has only been observed over a very limited spectral range from 80 to 485 GeV, and has considerably larger statistical errors than those presented above (Albert et al. 2008). Other blazars with adequately measured energy spectra are 1ES 1011+496 (Albert et al. 2007) and 1ES 0347–121 (Aharonian et al. 2007b) with redshifts of

¹ We use the VERITAS spectrum as it extends to higher energies than that of MAGIC.
The three selected blazars constrain the EBL in different wavelength regimes, so that the combination of the three, simultaneously probing different EBL scenarios in the near-IR to mid-IR, provides the strongest constraint to their intrinsic spectra. The methodology to find a limit to the intrinsic spectra of these three by applying EBL scenarios goes as follows: we look for the hardest spectral index that any of the three blazars show for a given EBL scenario and then search for the EBL that allows for the softest spectrum among those.

The results are presented in Table 1 showing the spectral indices $\Gamma_i$ for power-law fits to the absorption-corrected (also referred to as intrinsic) energy spectra of 1ES $1101-232$, 1ES $1218+30.4$, and 1ES $0229+200$ for a range of EBL scenarios.

To give the reader an idea about the dependence of spectral index on EBL density, we also show scenarios that fall below limits from galaxy counts, e.g., the LLL scenario. Those are

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**2. THE INTRINSIC BLAZAR SPECTRA FOR DIFFERENT EBL SCENARIOS**

In order to obtain the intrinsic spectrum of a blazar, the measured spectrum must be corrected for the effects of the EBL. Figure 1 shows a wide range of EBL intensities (shaded area) considered for unfolding the intrinsic spectra. The lower limits from galaxy counts restrict the possible EBL density as a function of wavelength. A convenient parameterization of EBL scenarios and a wide range of EBL spectra was provided by Dwek & Krennrich (2005) and are used in this study. For illustrative purposes we use a low EBL scenario that is called LLL for Low near-IR, Low mid-IR, Low far-IR which is consistent with the limits from MP00 but falls significantly below the galaxy counts in the mid-IR. Furthermore, we have considered a variety of EBL scenarios with different spectral indices and shapes that are within the boundaries of the shaded area in Figure 1. The upper bound is somewhat arbitrary; however, as will become apparent, uniformly higher density EBL scenarios lead to even harder intrinsic spectra and are moot. The shaded area also covers the EBL wavelength regime that is most sensitive to the blazar energy spectra in question; nevertheless, for completeness we also include the limits at 15 and 24 $\mu$m.

We also show results for an EBL spectrum that was presented in Aharonian et al. (2006) and is dubbed AHA0.65 (P0.65 in the original paper). In addition, we widen our range of EBL scenarios allowing for a scaling factor in $\nu_l$ which follows the name of the EBL scenario. Finally, we also consider effects on the intrinsic energy spectra imposed by lower limits at 15 and 24 $\mu$m. Those scenarios carry the suffix “MIR”. Also note that in the semi-logarithmic scale, the two different EBL scenarios show two different spectral slopes while both spectra intersect with the lower limit at 3.6 $\mu$m. We also show a scenario $\text{MP} + 0.7\text{LW} + \text{MIR}$ which falls substantially below the limit at 3.6 $\mu$m. Two different EBL codes were used to derive the intrinsic spectra, which allowed us to test and verify the results independently. The $\gamma$-ray spectral indices for the different EBL scenarios are listed in Table 1.
marked with an asterisk in Table 1 and are not viable, e.g., the LHL0.76, the LLL, and the LLH scenarios. The ones that are still compatible with the lower limits from galaxy counts are shown in the two lower sections of Table 1 (separated from the upper section by a double line) and the absorption corrected \( \gamma \)-ray spectra collectively give a lower limit to the hardness of these blazar spectra. We furthermore show three additional scenarios (below the single line in Table 1) that take into account lower EBL limits from galaxy counts at 15 and 24 \( \mu m \): AHA0.65 + MIR constitutes the standard AHA0.65 scenarios up to 10 \( \mu m \) plus an MIR component consistent with lower limits. The MP + LW + MIR scenario is based on a fit through the MP00 data, the LW08 data point, and the MIR data. The MP2.0 + LW + MIR differs from the last case by its level in the near-IR with the MP00 values scaled up by a factor of 2.

For example, when just considering 1ES 1218 + 30.4 by itself, its softest intrinsic spectrum among all EBL scenarios that obey the galaxy count limits is described by a power law with index \( \Gamma_{\text{intrinsic}} = 1.83 \pm 0.40 \) and corresponds to the LHL1.25 scenario. However, for the same EBL scenario, the spectrum of 1ES 0229 + 200 would be extremely hard showing a power-law index of \( \Gamma = 0.59 \pm 0.34 \). By searching for the combination of intrinsic spectra of these three sources that yield the softest spectral indices, one finds that the AHA0.65 scenario gives a spectral index \( \Gamma = 1.28 \pm 0.20 \) for 1ES 1101–232, \( \Gamma = 1.30 \pm 0.38 \) for 1ES 1218 + 30.4, while 1ES 0229 + 200 gives \( \Gamma = 2.40 \pm 0.13 \). The spectral index of \( \Gamma = 1.28 \pm 0.20 \) corresponds to the least hard spectral index of all EBL scenarios (shaded region) consistent with the lower limits. In other words, any other EBL scenario compatible with the lower limits from galaxy counts results in one of the three blazar spectra to be harder than \( \Gamma = 1.28 \pm 0.20 \). The lower limit from LW08 is an important new constraint to the intrinsic spectra; the same analysis carried out with the lower limits provided by Fazio et al. (2004) lead to a spectral index of \( \Gamma = 1.78 \pm 0.20 \) making it significantly less constraining than the LW08 limit.

The addition of an MIR component consistent with the 15 and 24 \( \mu m \) constraints does not change the result significantly. Finally, we show the absorption-corrected (AHA0.65) energy spectra of 1ES 1218 + 30.4, 1ES 1101–232, and 1ES 0229 + 200 in Figure 2. The former two appear to have their peak energy above 2 TeV. Since the EBL used for correcting for absorption is the AHA0.65 scenario, which is somewhat above the lower limits from \( HST \) galaxy counts, it is entirely possible that the source spectra of those two blazars are softer; however, in that case the source spectrum of 1ES 0229 + 200 would have to be significantly harder, again bringing the peak energy of 1ES 0229 + 200 well above 10 TeV. Also note the presence of a bump in the corrected spectrum of 1ES 0229 + 200, although the probability for a power-law fit is 5.5\%. The sharpness of this feature indicates that this feature is likely due to an over correction for EBL absorption. However, neither the AHA0.65 + MIR nor the MP + LW + MIR, the MP2.0 + LW + MIR, and the MP + 0.7LW + MIR show a significant bump, suggesting that this feature is only an artifact that disappears when the EBL is extended to include the mid-IR limits. Our result for the intrinsic energy spectra of blazars is entirely based on observational data and therefore provides a firm limit to the hardness of the energy spectra of some of the most distant TeV blazars. The simultaneous application of EBL scenarios to blazar spectra that provide sensitivity to two different EBL wavelength regimes, the 0.2–3.6 \( \mu m \) (1ES 1101–232, 1ES 1218 + 30.4) and the 0.7–14 \( \mu m \) (1ES 0229 + 200) combined with the new lower limit at 3.6 \( \mu m \) leads to much stronger and unambiguous constraints to the intrinsic spectra than any previous study.

3. CONCLUSIONS

In this Letter we have presented observational evidence that the absorption corrected energy spectra of individual TeV blazars are extremely hard, exhibiting spectra with an index of \( \Gamma = \)

![Image](http://example.com/image.png)

**TABLE 1**

| Scenario       | 1ES1101 | 1ES1218 | 1ES0229 |
|----------------|---------|---------|---------|
| AHA0.45*       | 1.78 ± 0.20 | 1.86 ± 0.37 | 2.43 ± 0.13 |
| LLH*           | 2.01 ± 0.22 | 2.07 ± 0.35 | 2.12 ± 0.20 |
| LHL*           | 2.04 ± 0.20 | 2.08 ± 0.39 | 0.94 ± 0.32 |
| LHL0.76*       | 2.23 ± 0.21 | 2.32 ± 0.37 | 1.30 ± 0.29 |
| MHL0.70*       | 1.26 ± 0.19 | 1.34 ± 0.36 | 1.35 ± 0.21 |
| MP+0.7LW+MIR*  | 1.80 ± 0.21 | 1.82 ± 0.38 | 1.43 ± 0.16 |
| LLL*           | 2.06 ± 0.16 | 2.20 ± 0.34 | 2.11 ± 0.20 |
| HHH            | −0.67 ± 0.12 | −0.72 ± 0.29 | 0.90 ± 0.17 |
| LLL2.4         | 1.10 ± 0.17 | 1.12 ± 0.34 | 1.67 ± 0.19 |
| MHL1.10        | 0.40 ± 0.20 | 0.33 ± 0.36 | 0.70 ± 0.19 |
| AHA0.65        | 1.28 ± 0.20 | 1.30 ± 0.38 | 2.40 ± 0.13 |
| LHL1.25        | 1.85 ± 0.24 | 1.83 ± 0.40 | 0.59 ± 0.34 |
| AHA0.65+MIR    | 1.29 ± 0.20 | 1.31 ± 0.38 | 1.70 ± 0.15 |
| MP+LW+MIR      | 1.87 ± 0.22 | 1.77 ± 0.42 | 1.01 ± 0.17 |
| MP2.0+LW+MIR   | 1.18 ± 0.20 | 1.20 ± 0.38 | 1.53 ± 0.15 |

**Notes** — Note that many EBL scenarios contain a suffix that represents a scaling factor in \( m \). Scenarios marked with an asterisk are inconsistent with lower EBL limits.

**Fig. 2** — Shown are the measured (filled circles) and absorption corrected (filled squares) energy spectra of 1ES 1101–232 (Aharonian et al. 2006), 1ES 1218 + 30.4 (Fortin et al. 2008), and 1ES 0229 + 200 (Aharonian et al. 2007a) using the AHA0.65 EBL. Note that the latter two have been scaled in absolute flux for clarity. The intrinsic spectra of 1ES 1101–232 and 1ES 1218 + 30.4 are extremely hard, with \( \Gamma \) smaller than the limiting value of 1.5.

4 The power-law indices of the blazar spectra of 1ES 1101–232, 1ES 1218 + 30.4 are primarily dominated by \( \gamma \)-ray energies of 0.18–1 TeV considering the statistical uncertainties making these spectra mostly sensitive to 0.2–1.2 \( \mu m \) while the spectral index of 1ES 0229 + 200 is dominantly determined by photon energies between 1 and 4 TeV making it mostly sensitive to 1.2–5 \( \mu m \); the spectral coverage at \( \gamma \)-ray energies translates into complementary spectral constraints in the EBL wave band.
1.28 ± 0.20 or harder. In fact the spectra are likely even harder considering that the lower limits from MP00 do not take into account the faint and fuzzy fringes of resolved galaxies. If their lower limits will be scaled up by a factor of 2, then MP2.0 + LW + MIR may be a more realistic EBL scenario, yielding a slightly harder intrinsic spectral index for 1ES 1101−232 with an index of $\Gamma_i = 1.18 \pm 0.20$. One should also note that this EBL scenario is similar to the EBL model from Primack et al. (2005) used in Aharonian et al. (2006). The results of our studies show that the intrinsic spectral index for at least one of the three blazars is in the range of $\Gamma_i = 1.18 \pm 0.20$, and no softer than $1.29 \pm 0.20$ (AHAO,65+MIR). These results are a direct consequence of the new limit on the EBL, and pose a significant challenge to models that suggest that intrinsic blazar spectra cannot be harder than $\Gamma_i = 1.5$. This result concurs well with a recent paper by Stecker & Scully (2008) in which the authors show that the energy spectral index of the blazar 1ES 0229+200 could have a hard intrinsic spectral index between 1.1 ± 0.3 and 1.5 ± 0.3 if their EBL models are correct. We confirm the hardness of the energy spectral indices based on a new observational constraint and a new analysis method.

Franceschini et al. (2008) provided a very detailed compilation of the EBL based on a vast amount of survey data and a backward evolution model. They applied their model EBL that includes redshift evolution to the blazar data from 1ES 1101−232 yielding a spectral index of $\Gamma_i = 1.6$. However, the EBL model did not consider the recent limit from LW08. As a consequence, our result of $\Gamma_i = 1.28 \pm 0.20$ for the intrinsic spectra of the three blazars and their result are not conflicting, since the former is based on theoretical modeling and our result is based on observational constraints.

The notion of potentially hard intrinsic TeV blazar spectra and their implications for EBL constraints and relativistic jets has been extensively discussed in the literature with emphasis on theoretical models (Aharonian et al. 2006; Malkov & Drury 2001; Stecker et al. 2007; Katarzyński et al. 2006; Böttcher et al. 2008; Aharonian et al. 2008). Gamma-ray spectra of blazars with $\Gamma \leq 1.5$ were considered inconsistent with TeV spectra that originate from processes that involve diffusive shock acceleration (Aharonian et al. 2006; Malkov & Drury 2001). Recent numerical simulations performed by Stecker et al. (2007), however, seem to indicate that sufficiently hard electron spectra could be generated by diffusive shock acceleration at relativistic shocks. Even for a hard spectrum electron population, it is argued by Böttcher et al. (2008) that in a synchrotron self-Compton (SSC) scenario the resulting GeV–TeV $\gamma$-ray spectra would experience substantial softening from Klein-Nishina effects making $\Gamma_G \leq 1.5$ difficult to model. Another solution to the problem was proposed by Katarzyński et al. (2006); a high low-energy cutoff in the electron distribution could give the appearance of a hard $\gamma$-ray spectrum for a given energy regime. Aharonian et al. (2008) show that $\gamma\gamma$ absorption in the source due to narrowband emission from the AGN could lead to unusually hard TeV spectra.

Another interesting and potentially verifiable solution was given by Böttcher et al. (2008). They introduce an additional radiation component that arises from Compton upscattering of ambient photons from the cosmic microwave background, occurring in a kiloparsec-scale jet. In this case, a substantial fraction of the jet power is transported by hadrons to the outer regions of the jet, where they are dissipated into ultrarelativistic electrons. Such a hard radiation component would be associated with the large scale of the kpc jet without exhibiting the time variation that is typically seen in TeV emission from blazars. Observations of 1ES 1101−232 (Aharonian et al. 2006), 1ES 1218+30.4 (Albert et al. 2006; Fortin et al. 2008), and 1ES 0229+200 (Aharonian et al. 2007a) in fact do not show flux variations, not inconsistent with this scenario. However, the flux levels are only a few percent of the Crab, making the detection of flares at that level difficult. More observations are required and could provide a means of searching for a hadronic component in TeV blazars.

The observational limit presented in this Letter puts the notion of the possibility of extremely hard TeV blazar spectra on substantially more solid footing as we provide an observational limit of $\Gamma_G \leq 1.28 \pm 0.20$ to the intrinsic spectra of a sample of three TeV blazars. As this limit relies on the validity of recent lower limits of galaxy counts and the assumption of EBL absorption taking place in intergalactic space, it constitutes indirect evidence for extremely hard spectra of distant TeV blazars.

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REFERENCES

Aharonian, F. A., et al. 2006, Nature, 440, 1018
———. 2007a, A&A, 475, L9
———. 2007b, A&A, 473, L25
Aharonian, F. A., Khangulyan, D., & Costamante, L. 2008, MNRS, 387, 1206
Albert, J., et al. 2006, ApJ, 642, L119
———. 2007, ApJ, 667, L21
———. 2008, Science, 320, 1752
Bernstein, R. A., et al. 2002, ApJ, 571, 56
———. 2007, ApJ, 666, 663
Böttcher, M., Dermer, C. D., & Finke, J. D. 2008, ApJ, 679, L9
Coppi, P. S., & Aharonian, F. A. 1999, ApJ, 521, L33
Dwek, E., & Arendt, R. 1998, ApJ, 508, L9
Dwek, E., & Krennrich, F. 2005, ApJ, 618, 657
Fazio, G. G., et al. 2004, ApJS, 154, 39
Fortin, P., et al. 2008, preprint (arXiv:0810.3030)
Franceschini, A., Rodighiero, G., & Vaccari, M. 2008, A&A, 487, 837
Gould, R. J., & Schrédter, G. P. 1967, Phys. Rev. Lett., 155, 1404
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Hinton, J. 2007, Proc. 30th Int. Cosmic Ray Conf. (Merida) (arXiv: 0712.3352v1)
Kashlinsky, A., et al. 2005, Phys. Rep., 409, 361
Katarzyński, K., et al. 2006, MNRS, 368, L52
Levenson, L. R., & Wright, E. L. 2008, ApJ, 683, 585 (LW08)
Madau, P., & Pozzetti, L. 2000, MNRS, 312, L9 (MP00)
Malkov, M. A., & Drury, L. 2001, Rep. Prog. Phys., 64, 429
Mazin, D., & Raue, M. 2007, A&A, 471, 439
Metcalfe, L., et al. 2003, A&A, 407, 791
Papovich, C., et al. 2004, ApJS, 154, 70
Primack, J. R., et al. 2005, AIP Conf. Proc., 745, 23
Stecker, F. W., Baring, M. G., & Summerlin, E. J. 2007, ApJ, 667, L29
Stecker, F. W., de Jager, O. C., & Salamon, M. H. 1992, ApJ, 390, L49
Stecker, F. W., & Scully, S. T. 2008, A&A, 478, L1
Wright, E. L. 2001, ApJ, 553, 538
Yoshi, Y. 1993, ApJ, 403, 552