ABSTRACT

Context. High-energy \( \gamma \)-rays propagating in the intergalactic medium can interact with background infrared photons to produce \( e^+e^- \) pairs, resulting in the absorption of the intrinsic \( \gamma \)-ray spectrum. TeV observations of the distant blazar 1ES 1101-232 were thus recently used to put an upper limit on the infrared extragalactic background light density.

Aims. The created pairs can upscatter background photons to high energies, which in turn may pair produce, thereby initiating a cascade. The pairs diffuse on the extragalactic magnetic field (EMF) and cascade emission has been suggested as a means for measuring its intensity. Limits on the IR background and EMF are reconsidered taking into account cascade emissions.

Methods. The cascade equations are solved numerically. Assuming a power-law intrinsic spectrum, the observed 100 MeV - 100 TeV spectrum is found as a function of the intrinsic spectral index and the intensity of the EMF.

Results. Cascades emit mainly at or below 100 GeV. The observed TeV spectrum appears softer than for pure absorption when cascade emission is taken into account. The upper limit on the IR photon background is found to be robust. Inversely, the intrinsic spectra needed to fit the TeV data are uncomfortably hard when cascade emission makes a significant contribution to the observed spectrum. An EMF intensity around \( 10^{-8} \) nG leads to a characteristic spectral hump in the GLAST band. Higher EMF intensities divert the pairs away from the line-of-sight and the cascade contribution to the spectrum becomes negligible.

Key words. Radiation mechanisms: non-thermal – BL Lacertae objects: individual: 1ES 1101-232 – intergalactic medium – diffuse radiation – Gamma rays: observations
and B intensities such that pairs are expected to be isotropised by the EMF for energies. Various EMF intensities is indicated by dashed diagonal lines. The HESS 2006 and Primack 2005 EBL derive from a simulation of galaxy formation (Primack et al. 1999, 2005, respectively). The Spitzer 2006 EBL is a best fit to available observations (Dole et al. 2006, from which the measurements shown here were also taken).

The created pairs can be deflected from the line-of-sight by an extragalactic magnetic field (EMF). Faraday rotation and synchrotron emission in radio yield estimates of magnetic fields in galaxies (roughly > 10 nG), or in clusters (≤ 0.1 – 1 nG) and even some super-clusters (≤ nG) (Kronberg 1994, Widrow 2002; Vallée 2004). The EMF outside these structures is unconstrained and may be as low as 10⁻¹⁹ nG (Fan et al. 2003, and references therein). For such very weak EMFs, the deflection of electrons due to IC interactions is negligible and the cascade occurs along the line-of-sight with a short delay of the secondary emission (Plaga 1995; Cheng & Cheng 1996; Dai et al. 2002). Diffusion on a stronger EMF creates a halo around γ-ray sources and isotropises the cascade emission (Aharonian et al. 1994). This occurs when the gyroradius $R_L$ of the pairs is much lower than their Compton cooling length $C_{IC} = E(dE/d\gamma)_{IC}^{-1}$. Since mostly CMB photons are upscattered, the minimum $B$ required to isotropise pairs of energy $E$ is $3 \times 10^{-6} E_{1000}(1+z)^{4} nG$. Much of the isotropic re-emission is lost to the observer and the pairs diffuse on a scale ~ $(R_L C_{IC})^{1/2}$. For intermediate EMFs, the TeV electrons in the beamed relativistic jet are deflected by ~ $C_{IC}/R_L$. Halo sizes ≥ 0.1° could be resolved by γ-ray detectors and used to estimate the EMF intensity (Neronov & Semikoz 2006). Photons in 0.1° haloes have propagation times varying by ~ 10⁵ years, averaging out any time variability (Fan et al. 2003). In the following, the cascade emission is assumed to be unresolved from the source and delays are not considered. The TeV emission detected by HESS from IES 1101-232 appears to be at a low flux level with no significant variability.

3. Cascade equations

The cascade is described by a set of two coupled equations involving the photon energy density $n_P(E)$ and the electron (positron) energy density $n_E(E)$:

$$c \partial_t n_P = -\frac{1}{\lambda_{PP}} n_P + c_B \int E G_{PP}(E, n_P(E)) de$$  \hspace{1cm} (1)

$$c \partial_t n_E = -\frac{1}{\lambda_{IC}} n_E + 2 \int E G_{IP}(E, n_P(E)) de$$  \hspace{1cm} (2)

The first term in both equations is the sink term due to PP (Eq. 1) or IC losses (Eq. 2). $\lambda_{PP}$ and $\lambda_{IC}$ are the mean free path for each interaction. The second term is the source term corresponding to cascade emission (Eq. 1) or pair creation (Eq. 2) with a factor 2 for the pair). The cascade emission factor $c_B$ is 1 when the EMF is ignored, and approximated to 0 when the electron population is considered isotropised. The pair production term is written in terms of $G_{PP}(E, n_P)$, where $d\sigma_{PP}$ is the differential cross-section and $u$ is the photon background energy density (EBL+CMB). The IC radiation term $G_{IC}(E, n_E)$ is defined similarly. The third term in Eq 2 reflects IC cooling of electrons from higher energies. All of these terms are functions of $z$.

The integrated cross-sections for PP and IC on isotropic target photons are taken from Gould & Schréder (1966) and Jones...
A priori served spectra as power-laws, the e−1 limit on the EBL responsible for attenuation. Current theoreti-
scale of energies (Thus ζ = (10^11/10^13)^1/250). To ensure energy conserva-
integrals on G_{PP} and G_{IC} are calculated as

\[ \int G_{IC}(e, e) n_E(e) de = \sum_k V_{k,E} \int_{\zeta^{1/2}}^{\zeta^{-1/2}} \frac{e^{\delta k u} G_{IC}(e^{\delta k u}, e) du}{\zeta^{1/2} - \zeta^{-1/2}} \]  

The cascade equations may then be rewritten as a matrix \( P \) acting on the vector \( V : V(t + \delta t) = \exp(\delta t P)V(t) \) (exp is de-
attenuated by the HESS 2006 EBL (without cascade, \( c_B=0 \)) and the data is shown in Fig. 3, reproducing the results of \( \text{Aharonian et al.} \ (2006) \). Attenuated spectra taking into account the full cascade emission with \( c_B=1 \) (i.e. a null EMF) are also shown for various values of the maximum energy \( \epsilon_M \) to which the intrinsic power-law extends. Since cascades initiated at higher energies increase the photon populations in lower ones, one might expect the final spectra to appear harder than for pure absorption. However, because IC occurs predominantly on the CMB, the cascade emission accumulates below 100 GeV, softening the spectrum between 100 GeV and 1 TeV. High values of \( \epsilon_M \) lead to more cascading and more softening. The \( \chi^2 \) values suggest \( \epsilon_M < 15 \) TeV, although further observations, particularly above 1 TeV, would be necessary in order to confirm this.

For such low \( \epsilon_M \) values, not many photons initiate cascades. For higher \( \epsilon_M \), the softening is such that a lower EBL would be needed to match the data. Thus the HESS 2006 upper limit found by \( \text{Aharonian et al.} \ (2006) \) holds strong, even in this extreme limit where all the cascade emission is received by the observer.

Inversely, the intrinsic \( \gamma \)-ray spectrum at the source can be obtained given some assumption on the intervening EBL. Using the lower limit on the EBL set by galaxy counts (\( \text{Primack} \ 2005 \) in Fig. 1) gives a limit on how soft the intrinsic spectrum can be. For pure absorption, the best fit has \( \Gamma = 1.95 \pm 0.19 \) (Fig. 4). As expected, this is softer than the \( \Gamma = 1.5 \) assumed above, yet still suggests that a good fraction of the \( \gamma \)-ray energy

cal understanding of shock acceleration limits the intrinsic par-
intrinsic spectral index, increasingly so with EBL intensity.

4. Application to 1ES 1101-232

The SED of the attenuating EBL can be deconvolved from \( \gamma \)-ray observations of extragalactic sources (TeV blazars), given \textit{a priori} knowledge on the intrinsic spectra. Modelling observed spectra as power-laws, the effect of PP is to soften the intrinsic spectral index, increasingly so with PP intensity. Hence, using observations of the farthest TeV blazar and assuming the hardest possible intrinsic spectrum puts an upper limit on the EBL responsible for attenuation. Current theoretical understanding of shock acceleration limits the intrinsic par-
ticle distribution in blazars to a power-law of index no harder than a 1.5 and correspondingly, an intrinsic photon spectrum \( dN \propto E^{-\Gamma} dE \) with \( \Gamma \geq 1.5 \) (\text{Aharonian et al.} 2006).

1ES 1101-232, at \( z = 0.186 \), is currently the farthest known TeV source and was used by the HESS collaboration to set an upper limit to the EBL corresponding to the HESS 2006 SED shown in Fig. 1. The comparison between a \( \Gamma=1.5 \) power-law attenuated by the HESS 2006 EBL (without cascade, \( c_B=0 \)) and the data is shown in Fig. 3, reproducing the results of \( \text{Aharonian et al.} \ (2006) \). Attenuated spectra taking into account the full cascade emission with \( c_B=1 \) (i.e. a null EMF) are also shown for various values of the maximum energy \( \epsilon_M \) to which the intrinsic power-law extends. Since cascades initiated at higher energies increase the photon populations in lower ones, one might expect the final spectra to appear harder than for pure absorption. However, because IC occurs predominantly on the CMB, the cascade emission accumulates below 100 GeV, softening the spectrum between 100 GeV and 1 TeV. High values of \( \epsilon_M \) lead to more cascading and more softening. The \( \chi^2 \) values suggest \( \epsilon_M < 15 \) TeV, although further observations, particularly above 1 TeV, would be necessary in order to confirm this.

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in 1ES 1101-232 is output above a TeV. A hard $\Gamma \leq 2$ intrinsic spectrum is needed if cascade emission is to contribute significantly to the low-energy continuum (Aharonian et al. 2002). 1ES 1101-232 is the first blazar where the intrinsic spectrum is constrained to be hard enough for this, even in the minimal EBL limit.

Including cascade emission in the fit (Fig. 4) hardens even more the intrinsic spectrum as the cutoff $\epsilon_M$ increases and cascades contribute more and more to the observed spectrum. For higher $\epsilon_M$, the best fit $\Gamma$ increases again to mitigate the pronounced softening from the strong cascading but the fit worsens. This also holds for (implausibly) high values of $\epsilon_M > 100$ TeV, for which cascade emission largely dominates at a few TeV. The hard intrinsic spectra found here, assuming the Primack 2005 is indeed the minimum possible EBL, suggest either that $\epsilon_M$ is not greater than a few TeV, so that there is little cascade emission in the TeV range, or that a large part of the cascade emission is lost due to diffusion on the EMF.

As discussed in §2, the electron diffusion on the EMF depends on the ratio $R_L/C_{IC}$. The effect on the observed spectra is now taken into account by setting $c_B=0$ when $R_L/C_{IC}<300$ (corresponding to a maximum deviation on the line-of-sight of $0.1^{-0.2}$ equal to the best GLAST angular resolution) and $c_B=1$ otherwise. For example, an EMF of $10^{-6}$ nG means that emission from electrons of energy $E \lesssim 20$ TeV is suppressed. This will lead to low-energy cutoff in the cascade spectrum as only emission from pairs above a certain energy reaches the observer. The overall spectrum appears as a hump between $\gamma^2\nu_{CMB}$ (with $\gamma$ the Lorentz factor of the electrons for which $R_L = 300C_{IC}$) and 100 GeV (above which absorption dominates). Hence, a non-zero EMF leads to a reduction of the overall cascade emission seen by the observer (compared to Figs. 3-4) but can also lead to a well-defined signature above the continuum.

Figure 5 shows the observed spectra for a Primack 2005 EBL and for EMF intensities between $10^{-9}$ and $10^{-6}$ nG. The intrinsic power-law index was left free but its cutoff $\epsilon_M$ was fixed at either 10 TeV or 20 TeV. The best fit index $\Gamma$ is then found for each value of the EMF. In both cases, the spectra for an EMF $\gtrsim 10^{-6}$ nG are not much different from the pure absorption case as most of the cascade emission is isotropised and lost to the observer. With $\epsilon_M=10$ TeV, the best-fit intrinsic slopes are flat in $\nu F_\nu$, and the cascade emission is essentially indistinguishable from the GeV continuum for any value of the EMF. The intrinsic emission is assumed here to be a simple power-law over the whole energy range. More realistic modelling would result in a curved intrinsic Compton component. The cascade emission might then be more readily identifiable over an intrinsic continuum rising from GeV to TeV energies.

Stronger cascading, as a result of a higher cutoff energy $\epsilon_M$ and/or a higher EBL density, makes the hump apparent for the same reason. The intrinsic spectrum is then necessarily much harder, enabling the contribution from the cascade to stand out over the continuum. The bottom panel of Fig. 5 shows that EMF intensities of $10^{-9}-10^{-8}$ nG can be identified using GLAST and HESS-2 if $\epsilon_M=20$ TeV. Cascade emission is not diluted for EMF intensities weaker than $10^{-9}$ nG and there is no spectral feature to measure the EMF. Surprisingly, in most cases 1ES 1101-232 is only slightly above the GLAST one-year detection limit. Unless they become active and flaring, low flux state blazars detected by HESS such as 1ES 1101-232 are likely to be difficult to detect with GLAST, illustrating the advantage provided by the large collecting area of ground-based Cherenkov arrays (but at higher energy thresholds). Similar results are obtained by keeping $\epsilon_M$ at 10 TeV but using the stronger HESS 2006 EBL. However, in this case, the fitted intrinsic slopes are very hard ($\Gamma \approx 1.1$) when the EMF intensities are lower than $10^{-7}$ nG.

The softest values of $\Gamma$, which are the most plausible given the present knowledge on blazars, favour values of the EMF higher than $10^{-6}$ nG and/or a cutoff energy below 20 TeV. VHE emission from nearby, little-attenuated blazars can be investigated for evidence of cutoffs at energies $>20$ TeV — although it should be noted that e.g. HESS observations of Mkn 421 ($z = 0.03$) taken at a high flux actually measure an exponential cutoff at 3 TeV (Aharonian et al. 2005). EMF intensities $\gtrsim 10^{-6}$ nG are consistent with measures inside clusters and super-clusters. Such structures may reach 10–50 Mpc in size, which is greater than the attenuation length for $\gamma$-rays above 100 GeV.
Furthermore, the largest voids, where the EMF is expected to be very small, have a size \(20 h^{-1} \text{ Mpc}\) [Patiri et al. 2006], smaller than the distance to IES 1101-232. Hence, cascades are likely to be initiated inside walls. As \(C_{\text{IC}}\) is only of the order of 1 Mpc, such cascades reemit most of their energy within the confines of the clusters, and thus are subject to diffusion. In this case, the cascade emission can only be detected by resolving the faint halo surrounding the \(\gamma\)-ray source.

5. Conclusion
The impact of extragalactic cascade emissions on the GeV-TeV spectrum of IES 1101-232 has been investigated and shown to soften the observed spectrum in the TeV range compared to pure absorption. This occurs because most of the cascade emissions occur at 100 GeV and below. As a result, the upper limits on the EBL determined by HESS are strengthened in the sense that taking cascades into account would lead to harder intrinsic spectra than judged plausible, or to a reduced EBL upper limit. Inversely, using lower limits on the EBL coming from galaxy counts, the intrinsic spectrum of IES 1101-232 is found to have \(\Gamma \leq 1.95\), with very hard values if there is an important contribution from cascade emission. This is at odds with current theoretical and observational understanding of blazars. A cutoff \(\lesssim 10\text{ TeV}\) in the intrinsic spectrum would limit the cascade contribution. This contribution would also be quenched if the EMF intensity is greater than \(10^{-6}\) nG, as expected away from voids. A lower EMF increases the amount of cascade emission reaching the observer in the GeV band, with a signature in the GLAST band for intensities \(\sim 10^{-8}\) nG — but at the price of a hard intrinsic spectrum so as to fit the HESS observations.

References
Aharonian, F., Akhperjanian, A. G., Aye, K.-M., et al. 2005, A&A, 437, 95
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, Nature, 440, 1018
Aharonian, F. A., Coppi, P. S., & H.J., V. 1994, ApJ, 423, L5
Aharonian, F. A., Timokhin, A. N., & Plyasheshnikov, A. V. 2002, A&A, 384, 834
Biller, S. D. 1995, Astroparticle Physics, 3, 385
Cheng, L. X. & Cheng, K. S. 1996, ApJ, 459, L79
Dai, Z. G., Zhang, B., Gou, L. J., Meszáros, P., & Waxman, E. 2002, ApJ, 580, L7
Dole, H., Lagache, G., Puget, J.-L., et al. 2006, A&A, 446
Fan, Y. Z., Dai, Z. G., & Wei, D. M. 2003, A&A, 13
Gould, R. J. & Schréder, G. 1966, Phys. Rev. Lett., 16, 252
Jones, F. C. 1967, Phys. Rev., 167, 1159
Kronberg, P. P. 1994, Reports of Progress in Physics, 57, 325
Lagache, G., Dole, H., & Puget, J.-L. 2003, MNRAS, 338, 555
Neronov, A. & Semikoz, D. V. 2006, ArXiv Astrophysics e-prints
Patiri, S. G., Betancort-Rijo, J. E., Prada, F., Klypin, A., & Gottlöber, S. 2006, MNRAS, 369, 335
Peiris, H. V., Komatsu, E., Verde, L., et al. 2003, ApJS, 148, 213
Plaga, R. 1995, Nature, 374, 430
Primack, J. 2002, in COSPAR, Plenary Meeting
Primack, J. R., Bullock, J. S., & Somerville, R. S. 2005, in AIP Conf. Proc. 745: High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian, H. J. Völk, & D. Horns, 23–33
Primack, J. R., Bullock, J. S., Somerville, R. S., & MacMinn, D. 1999, Astroparticle Physics, 11, 93
Protheroe, R. J. 1986, MNRAS, 221, 769
Protheroe, R. J. & Stanev, T. 1993, MNRAS, 264, 191
Stecker, F. W., de Jager, O. C., & Salamon, M. H. 1992, ApJ, 390, L49
Vallée, J. P. 2004, New A Rev., 48, 763
Widrow, L. M. 2002, Reviews of Modern Physics, 74, 775
Xu, C., Lonsdale, C. J., Shupe, D. L., O‘Linger, J., & Masci, F. 2001, ApJ, 562, 179
Zdziarski, A. A. 1988, ApJ, 335, 786

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