Photon propagation and the very high energy $\gamma$-ray spectra of blazars: how transparent is the Universe?

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ABSTRACT
Recent findings by $\gamma$-ray Cherenkov telescopes suggest a higher transparency of the Universe to very high energy (VHE) photons than expected from current models of the extragalactic background light. It has been shown that such transparency can be naturally explained by the DARMA scenario, in which the photon mixes with a new, very light, axion-like particle predicted by many extensions of the Standard Model of elementary particles. We discuss the implications of DARMA for observations of blazar VHE $\gamma$-ray spectra, and show that it successfully accounts for the observed correlation between spectral slope and redshift when the same intrinsic emission spectrum is adopted for faraway sources and for nearby ones. DARMA also predicts the observed blazar spectral index to become asymptotically independent of redshift for faraway sources. Our prediction can be tested with the satellite-borne Fermi/LAT (Large Area Telescope) detector as well as with the ground-based Cherenkov telescopes HESS, MAGIC, CANGAROO III, VERITAS and the Extensive Air Shower arrays ARGO-YBJ and Milagro.

Key words: elementary particles – magnetic fields – BL Lacertae objects: general – diffuse radiation.

1 INTRODUCTION
An impressive amount of information about the Universe at $\gamma$-ray energies larger than 100 GeV – namely in the very high energy (VHE) $\gamma$-ray band – has been collected over the last few years by the Imaging Atmospheric Cherenkov Telescopes (IACTs) such as HESS, MAGIC, CANGAROO III and VERITAS. These IACTs have detected gamma-ray sources over an extremely wide interval of distances, ranging from the parsec scale for Galactic objects up to the Gpc scale for the farthest blazar 3C 279 at redshift $z = 0.536$ (Albert et al. 2008).

These observations allow us both to infer the intrinsic properties of the sources and to probe the nature of photon propagation through cosmic distances. The latter fact becomes particularly important in connection with the VHE $\gamma$-ray observations, since hard photons travelling through cosmological distances interact with soft background photons permeating the Universe, producing $e^+e^-$ pairs through the standard $\gamma\gamma \rightarrow e^+e^-$ process and thereby disappearing. Denoting by $E$ and $\epsilon$ the energy of the hard (incident) and of the soft (background) photons, respectively, and by $\varphi$ the scattering angle, the corresponding cross-section is (Heitler 1960)

$$\sigma_{\gamma\gamma}(E, \epsilon, \varphi) = 1.25 \times 10^{-25}(1 - \beta^2) \times \left[ 2\beta (\beta^2 - 2) + (3 - \beta^2) \ln \frac{1 + \beta}{1 - \beta} \right] \text{cm}^2,$$

which depends on $E$, $\epsilon$ and $\varphi$ through the dimensionless parameter

$$\beta(E, \epsilon, \varphi) \equiv \left[ 1 - 2m_e^2/E \epsilon(1 - \cos \varphi) \right]^{1/2}.$$  

This process is kinematically allowed for $\epsilon$ above the energy threshold $\epsilon_{\text{thr}}(E, \varphi) \equiv 2m_e^2/E(1 - \cos \varphi)$, i.e. for $\beta > 0$. $\sigma_{\gamma\gamma}$ reaches its maximum, $\sigma_{\gamma\gamma}^{\text{max}} \approx 1.70 \times 10^{-25}$ cm$^2$, for $\beta \approx 0.70$. Assuming head-on collisions, $\sigma_{\gamma\gamma}^{\text{max}}$ is attained when the background photon energy is $\epsilon_{\gamma}^{\text{thr}}(E) \approx (0.5 \text{ TeV}/E)$ eV. This shows that in the energy interval of 100 GeV < $E$ < 100 TeV, explored by the IACTs, the resulting opacity is dominated by the interaction with infrared/optical/ultraviolet diffuse background photons – usually called extragalactic background light (EBL) – with 0.005 eV < $\epsilon$ < 5 eV (corresponding to the wavelength range 0.25 $\mu$m < $\lambda$ < 250 $\mu$m).

The EBL is produced during the star formation history of the Universe, including a possible early generation of stars formed before galaxies were assembled. Based on the synthetic models of the evolving stellar populations in galaxies as well as on deep galaxy

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1 Natural Lorentz–Heaviside units with $\hbar = c = K_B = 1$ are employed throughout.
from equation (2) it follows that \( \Phi_1 \) entails a larger probability for a beam photon to be absorbed. It

2 We are adopting a standard Λ cold dark matter cosmological model with \( \Omega_M \approx 0.7 \) and \( \Omega_M \approx 0.3 \). Distances are expressed in terms of the redshift \( z \), and we will henceforth write \( E(z) = E(0)(1 + z) \) and \( \epsilon(z) = \epsilon(0)(1 + z) \), with \( E_0 \) and \( \epsilon_0 \) referring to the present cosmic epoch (\( z = 0 \)).

Table 1. Blazars with known redshift and VHE \( \gamma \)-ray flux and spectrum.

| Source         | \( z \)   | \( \Gamma_{\text{obs}} \) | \( \Phi_{\text{obs}}(>0.2\,\text{TeV}) \) |
|----------------|----------|--------------------------|----------------------------------|
| Mrk 421        | 0.031    | 2.33 ± 0.08              | (1.0 ± 0.1) \times 10^{-10}     |
| Mrk 501        | 0.034    | 2.28 ± 0.05              | (1.7 ± 0.1) \times 10^{-11}     |
| IES 2344+514   | 0.044    | 2.95 ± 0.12              | (1.2 ± 0.1) \times 10^{-11}     |
| Mrk 180        | 0.045    | 3.30 ± 0.70              | (8.5 ± 0.4) \times 10^{-12}     |
| IES 1959+650   | 0.047    | 2.72 ± 0.14              | (3.0 ± 0.4) \times 10^{-11}     |
| BL Lacertae    | 0.069    | 3.60 ± 0.50              | (3.3 ± 0.3) \times 10^{-12}     |
| PKS 0548–322   | 0.069    | 2.80 ± 0.30              | (3.3 ± 0.7) \times 10^{-12}     |
| PKS 2005–489   | 0.071    | 4.00 ± 0.40              | (3.3 ± 0.5) \times 10^{-12}     |
| RGB J0152+017  | 0.080    | 2.95 ± 0.36              | (4.4 ± 1.2) \times 10^{-12}     |
| PKS 2155–304   | 0.116    | 3.37 ± 0.07              | (2.9 ± 0.2) \times 10^{-11}     |
| IES 1426+428   | 0.129    | 3.55 ± 0.46              | (2.5 ± 0.4) \times 10^{-11}     |
| IES 0229+200   | 0.139    | 2.50 ± 0.19              | (4.5 ± 0.7) \times 10^{-12}     |
| H2356–309      | 0.165    | 3.09 ± 0.24              | (2.5 ± 0.7) \times 10^{-12}     |
| IES 1218+304   | 0.182    | 3.00 ± 0.40              | (1.0 ± 0.3) \times 10^{-11}     |
| IES 1101–232   | 0.186    | 2.94 ± 0.20              | (4.4 ± 0.7) \times 10^{-12}     |
| IES 0347–121   | 0.188    | 3.10 ± 0.23              | (3.9 ± 0.7) \times 10^{-12}     |
| IES 1011+496   | 0.212    | 4.00 ± 0.50              | (6.4 ± 0.3) \times 10^{-12}     |
| PG 1553+113    | >0.25    | 4.20 ± 0.30              | (5.2 ± 0.9) \times 10^{-12}     |
| 3C 279         | 0.536    | 4.1 ± 0.7               | (2.9 ± 0.5) \times 10^{-11}     |

Figure 1. The observed spectral indices of all known VHE blazars are shown as filled circles (with error bars). Superposed is the predicted behaviour of the observed spectral index within two different scenarios. In one scenario (light grey area) \( \Gamma_{\text{obs}} \) is computed in the framework of standard physics, whereas in the DARMA scenario (dark grey area) \( \Gamma_{\text{obs}} \) is evaluated in the framework of the proposed photon–ALP oscillation mechanism. Both scenarios use the same SDS model for the EBL.

2 VHE \( \gamma \)-RAY ABSORPTION BY THE EBL: THE CONVENTIONAL VIEW

A full-fledged prediction of how a broadband (100 GeV \( < E_0 < 100 \) TeV) SED of blazars is affected by the EBL would be beyond the scope of this Letter. We will, instead, examine modifications of the blazar spectra due to the physical processes possibly taking place in the intergalactic space and discuss them with respect to the current IACT data. Such data cover the 0.2 TeV \( < E_0 < 2 \) TeV energy range, hence the corresponding relevant EBL range is 0.25 eV \( < \epsilon_0 < 2.5 \) eV. Within this range, we find it convenient to adopt the following analytic parametrization of the EBL spectral number density at the present cosmic epoch (SDS):

\[
n_{\gamma}(\epsilon_0, 0) \approx 10^{-3} \alpha \frac{\epsilon_0}{eV}^{-2.55} \text{ cm}^{-2} \text{eV}^{-1},
\]

where \( \alpha \) is a suitable constant. Indeed, in the range of 0.25 eV \( < \epsilon_0 < 2.5 \) eV, equation (4) does reproduce the basic behaviour of the SED reported in the most recent phenomenological model of the EBL (Franceschini et al. 2008) for 0.5 \( < \alpha < 3.3 \). 3 We remark that in the band 0.25 eV \( < \epsilon_0 < 2.5 \) eV, the assumed SDS parametrization also encompasses both the lowest EBL level predicted by Primack
et al. (2005) and the higher EBL level predicted by the ‘baseline model’ of Stecker et al. (2006).\footnote{In this Letter, we disregard the ‘fast evolution model’ of Stecker et al. (2006), which predicts an even higher EBL level and would require $\tau_{\gamma}$ > 3.} From the definition of $\tau_{\gamma}(E_0, z)$ (see e.g. Fazio & Stecker 1970), we finally obtain

$$\tau_{\gamma}(E_0, z) \simeq 0.50 \alpha \left( \frac{E_0}{500 \text{ GeV}} \right)^{1.55} \left[ (1 + z)^{3.4} - 1 \right],$$

where evolutionary effects arising from the galaxy evolution (Raue & Mazin 2008) have been included on top of those produced by the cosmic expansion. We have checked that for $1.2 < \alpha < 3$, $0.2 \text{ eV} < \epsilon_0 < 2.5 \text{ eV}$ and $0.05 < z < 0.5$, equation (5) is approximately consistent with the analytic fit, provided by Stecker & Scully (2006), of $\tau_{\gamma}(E_0, z)$ as predicted by the ‘baseline model’ of Stecker et al. (2006).

Since for the nearby blazars ($z < 0.03$) the EBL photon absorption is expected to be negligible, we assume that for such sources observations do yield $\Phi_{\text{em}}$. We find, on average, $\Gamma_{\text{em}} \simeq 2.4$.\footnote{Several interpretations for the scattering of the data in Fig. 1 for $z < 0.2$ are possible: e.g. different sources can be observed in different emission states, and so they may exhibit slightly different slopes (Persic & De Angelis 2008).} Various emission models for blazars have been developed and are briefly summarized in Appendix A. In the widely used synchrotron-self-Compton (SSC) emission model (e.g. Ghisellini et al. 1998), $\Gamma_{\text{em}} \simeq 2.4$ suggests a Compton peak at around or below 100 GeV. The predicted observed spectral index $\Gamma_{\text{obs}}$ then follows from equations (3) and (5); it is represented as the light-grey area in Fig. 1.

Fig. 1 shows that the actually observed spectral index increases more slowly than $\Gamma_{\text{obs}}$ for redshifts $z > 0.2$. Moreover, the observed values cannot be explained for $z > 0.3$ by the EBL model of SDS even for $\alpha$ as low as 0.5. Because the optical depth is a monotonically increasing function of $z$, we interpret the conflict between $\Gamma_{\text{em}}$ and $\Gamma_{\text{obs}}$ – apparent in Fig. 1 – as calling for a departure from the conventional view and we proceed to explore its consequences.

A possible way out relies upon a systematic hardening of the emission spectrum with increasing $z$. That is $\Gamma_{\text{em}}$ – which is currently supposed to be independent of $z$ – has to decrease as $z$ increases, so as to offset the growth of $\tau_{\gamma}(E_0, z)$. This situation is very difficult to achieve within the SSC emission model: even assuming that we selectively observe increasingly flaring sources at higher redshifts, the radiating electrons will be emitting more and more in the Klein–Nishina regime. Therefore – unlike the synchrotron peak which will appreciably shift to higher energies – the Compton peak will hardly shift, thereby ensuring that $\Gamma_{\text{em}}$ is indeed virtually independent of $z$ (Persic & De Angelis 2008).

Other possibilities have been suggested based on the modifications of the emission mechanism. One involves strong relativistic shocks, which can give rise to the values of $\Gamma_{\text{em}}$ considerably smaller than previously thought (Stecker, Baring & Summerlin 2007; Stecker & Scully 2008). Another rests upon photon absorption inside the blazar, which has been shown to lead to a substantial change of $\Gamma_{\text{em}}$ (Aharonyan, Khangulyan & Costamante 2008a). A further option could be the underlying emission mechanism of the more luminous sources (e.g. flat-spectrum radio quasars) being hadronic, with the muon (and cascade) synchrotron component peaking in the sub-TeV region and the (neutral- and charged-)pion cascades crossing the 0.2–2 TeV band with a very hard ($\Gamma \sim 1.9$) spectrum, as shown in the very case of 3C 279 (Böttcher, Reimer & Marscher 2008).

While successful at substantially reducing $\Gamma_{\text{em}}$ in individual sources, these attempts fail to provide a systematic correlation of $\Gamma_{\text{em}}$ versus $z$, needed to overcome the above difficulty.

### 3 VHE $\gamma$-RAY ABSORPTION BY THE EBL: THE DARMA VIEW

In the framework of the same basic emission mechanism being at work in blazars and flat-spectrum quasars both at low and at high redshift, we propose a different solution, referred to as the DARMA scenario (De Angelis, Roncadelli & Mansutti 2007). Implicit in all the previous considerations is the hypothesis that photons propagate in the standard way throughout cosmic distances. We instead suppose that, in the presence of cosmic magnetic fields, photons can oscillate into a new, very light, spin-zero particle – named as the axion-like particle (ALP) – and vice versa. Once ALPs are produced close enough to the source, they travel unimpeded throughout the Universe and can convert back to photons before reaching the Earth. Since ALPs do not undergo EBL absorption, they act as if the observed photons had an effective optical depth smaller than $\tau_{\gamma}(E_0, z)$. Equation (3) entails that $\Gamma_{\text{obs}}$ gets reduced by the same amount as far as the $z$-dependence is concerned, thereby avoiding the conflict shown in Fig. 1. Now the dependence of $\Gamma_{\text{obs}}$ on $z$ is in agreement with the observations, since the photon–ALP oscillation reduces photon absorption even for the standard emission spectra. In order to guarantee consistency with the observations of nearby blazars, we take $\Gamma_{\text{em}} \simeq 2.4$ for all the sources represented in Fig. 1.

The key ingredient of the DARMA scenario – namely the existence of ALPs – is not an ad hoc assumption invented to solve the problem in question.\footnote{Other aspects concerning the relevance of ALPs for gamma-ray astrophysics have been addressed in Hooper & Serpico (2007), Hochmuth & Sigl (2007), De Angelis, Mansutti & Roncadelli (2008b), Simet, Hooper & Serpico (2008), Chelouche & Guendelman (2008) and Chelouche et al. (2008).} Instead, very light ALPs turn out to be a generic prediction of many extensions of the Standard Model of elementary particle physics and have attracted considerable interest over the past few years. Besides in four-dimensional models (Masso & Toldra 1995, 1997; Coriano & Irges 2007; Coriano, Irges & Morelli 2007), they naturally arise in the context of the compactified Kaluza–Klein theories (Chang, Tazawa & Yamaguchi 2000; Dienes, Dudas & Gherghetta 2000) as well as in the superstring theories (Svrcek & Witten 2006; Turok 1996). Moreover, it has been argued that an ALP with mass $m \sim 10^{-33}$ eV is a good candidate for the quintessential dark energy (Carroll 1998) which might trigger the present accelerated cosmic expansion.

Below, we first review the motivation and the properties of ALPs which are of direct relevance for this discussion. Next, we outline the computation of the predicted observed spectral indices $\Gamma_{\text{obs}}$. Details on the derivation, as well as on the dependence of $\Gamma_{\text{obs}}$ on the adopted EBL model, will be reported elsewhere.

On the basis of phenomenological as well as conceptual arguments, the Standard Model is currently viewed as the low-energy manifestation of some more fundamental and richer theory of all elementary–particle interactions including gravity. Therefore, the Lagrangian of the Standard Model is expected to be modified by small terms describing interactions among known and new particles. ALPs are spin-zero light bosons defined by the following
low-energy effective Lagrangian:
\[
\mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m^2 a^2 - \frac{1}{4 M} F^{\mu\nu} \tilde{F}_{\mu\nu} a, \tag{6}
\]
where \( F^{\mu\nu} \) is the electromagnetic field strength, \( \tilde{F}_{\mu\nu} \) is its dual, \( a \) denotes the ALP field, whereas \( m \) stands for the ALP mass. According to the above view, it is assumed that for the inverse two-photon coupling \( M \gg G_{\ast} F^{-1/2} \approx 250 \) GeV. On the other hand, it is supposed that \( m \ll G_{\ast} F^{-1/2} \approx 250 \) GeV and for definiteness we take \( m < 1 \) eV. As far as the generic ALPs are concerned, the parameters \( M \) and \( m \) are to be regarded as independent.

So, what really characterizes ALPs is the trilinear \( \gamma-\gamma-\alpha \) vertex described by the last term in \( \mathcal{L}_{\text{ALP}} \), whereby one ALP couples to two photons. Owing to this vertex, ALPs can be emitted by astrophysical objects of various kinds, and the present situation can be summarized as follows. The negative result of the CERN Axion Solar Telescope (CAST) experiment designed to detect ALPs emitted by the Sun yields the bound \( M > 0.86 \times 10^{10} \) GeV for \( m < 0.02 \) eV (Zioutas et al. 2005; Andriamonje et al. 2007). Moreover, the theoretical considerations concerning star cooling via ALP emission provide the generic bound \( M > 10^{11} \) GeV, which for \( m < 10^{-10} \) eV gets replaced by the stronger one \( M > 10^{13} \) GeV, even if with a large uncertainty (Raffelt 1990, 1996; Khlopov & Rubin 2004).

The same \( \gamma-\gamma-\alpha \) vertex produces an off-diagonal element in the mass matrix for the photon–ALP system in the presence of an external magnetic field \( B \). Therefore, the interaction eigenstates differ from the propagation eigenstates and photon–ALP oscillations show up (Sikivie 1984a,b; Maiani, Petronzio & Zavattini 1986; Raffelt & Stodolsky 1988). The situation is analogous to what happens in the case of massive neutrinos with different flavours, but while all neutrinos have equal spin – hence neutrino oscillations can freely occur – ALPs have instead spin zero, whereas the photon has spin one, and so the transformation can take place only if the spin mismatch is compensated for by an external magnetic field \( B \).

We imagine that a sizeable fraction of photons emitted by a blazar soon convert into ALPs. They propagate unaffected by the EBL and we suppose that before reaching the Earth, a substantial fraction of photons emitted by a blazar and so the transformation can take place only if the spin mismatch lies in the range of \( 0.3 \) nG and \( m \) and so the transformation can take place only if the spin mismatch lies in the range of \( 0.9 \) nG. This conclusion agrees with previous upper bounds (Blasi, Burles & Olinto 1999), so we assume that before reaching the Earth, a substantial fraction of photons emitted by a blazar and so the transformation can take place only if the spin mismatch lies in the range of \( 0.3 \) nG and \( m \) and so the transformation can take place only if the spin mismatch lies in the range of \( 0.9 \) nG. 

4 CONCLUSION

In conclusion, for a realistic EBL model (defined by equation 4 with \( 0.5 < \alpha < 3 \) and assuming the same nominal emission spectral slope \( \Gamma_{\text{em}} \approx 2.4 \) for all VHE blazars, the DARMA scenario naturally explains the IACT data and predicts that \( \Gamma_{\text{obs}} \) becomes asymptotically independent of \( z \) for faraway sources. Our prediction can be tested with the satellite-borne Fermi/LAT detector as well as with the ground-based Cherenkov telescopes HESS, MAGIC, CANGAROO III, VERITAS and the Extensive Air Shower arrays ARGO-YBJ and Milagro. We remark that the DARMA scenario could lose much of its motivation – and be eventually disproved – if the emission mechanisms of VHE blazars and quasars had a variation according to, e.g., luminosity. The most distant and luminous VHE \( \gamma \)-ray source that appears in Fig. 1 is 3C 279, a remarkable example of flat-spectrum radio galaxies: for these sources, the flaring and accompanying intermittency of source activity, not well understood at present, may point to emission mechanisms different from those that are commonly being used for blazars [i.e. the leptonic synchrotron–Compton (SC) models]. Such emission mechanisms may provide the hard spectra emitted by high-luminosity, high-\( z \) sources, which in Fig. 1 are required to counterbalance the spectral steepening imposed on TeV radiation by traversing the EBL over cosmological distances.

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