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C. Reylé, P. Di Matteo, F. Herpin, É. Lagadec, A. Lançon, Z. Meliani, F. Royer (eds)

CONSTRAINING THE EBL WITH THE 3FHL FERMI DATA

B. Biasuzzi[1], J. Biteau[1], O. Hervet[2] and D.A. Williams[2]

Abstract. The Extragalactic Background Light (EBL) is the light emitted by stars and accreting objects through the whole history of the Universe. Its spectrum is hard to measure directly due to both the presence of bright foreground emissions and magnitude limitations in galaxy surveys. Nevertheless, constraints on the EBL can be inferred by studying the absorption features in blazar spectra. By collecting a sample of 300 blazar spectra measured by *Fermi*-LAT in the energy range between 10 GeV and 2 TeV, we aim to determine the EBL scaling factor in a source-model-independent scenario. Furthermore, we want to investigate the feasibility of carring out a study on the EBL evolution as a function of redshift by using the newest 3FHL data.

Keywords: Extragalactic Background Light, Active Galactic Nuclei, Gamma-rays

1 Introduction

The Universe is permeated by a diffuse background radiation field that extends over the whole electromagnetic spectrum. The second brightest component - after the cosmic microwave radiation (CMB) - is the extragalactic background light (EBL), which is formed by the sum of the light from stars and active galactic nuclei (AGNs), emitted during all cosmic epochs. The EBL spectrum is characterized by two peaks: the first, the COB (Cosmic Optical Background, 0.1-8 μm) due to the direct light emitted by stars in the UV and optical band, and the second, the CIB (Cosmic Infrared Background, 8-1000 μm), formed by the fraction of light reprocessed and remitted in the IR band by dust and the interstellar medium.

The EBL density and its evolution as a function of redshift depend on the galaxy formation history. So, a full understanding of the EBL would provide fundamental contributions in several astrophysical fields. Unfortunately, the EBL spectrum is hard to measure directly because of the presence of strong foreground emissions, such as the zodiacal light and the diffuse light coming from the Galactic plane. Moreover, direct measurements can constrain the local background, but do not provide any information about its evolution with the cosmic epochs. Many EBL models try to reconstruct the EBL density and its evolution through different techniques: (i) models of Stecker & Scully (2006), Franceschini et al. (2008), Domínguez et al. (2011), and Franceschini & Rodighiero (2017), starting from the present galaxy luminosity functions, reconstruct the emission back in time by assuming a dependence on z (where, in turn, such a dependence is inferred by fitting the model prediction to the observed galaxy counts); (ii) models of Dwek & Arendt (1998), Razzaque et al. (2009), and Finke et al. (2010) simulate the galaxy and star formation process from the beginning of the Universe, taking into account the z-dependence of the star formation rate and models of population synthesis; and (iii) the model of Gilmore et al. (2012) follows a similar approach as in the case (i), but that uses the results provided by e.g. the *Wilkinson Microwave Anisotropy Probe* (Hinshaw et al. 2009) as initial conditions.

Another fruitful way to derive some constraints on the EBL and its evolution is through the observation of distant γ-ray sources such as AGNs. In particular the sub-class of blazars (AGNs whose relativistic jets point toward the observer) is particularly adapted for this purpose because (i) the γ-ray emission is amplified by relativistic boosting; and (ii) their presence over a large redshift range enables the study of the EBL evolution.

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[1] Institut de Physique Nucléaire, IN2P3/CNRS, Université Paris-Sud, Univ. Paris/Saclay, 15 rue Georges Clémenceau, 91406 Orsay, Cedex, France

[2] Santa Cruz Institute for Particle Physics and Department of Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA

Along their path, γ-rays emitted by blazars can interact with the photons of the EBL, generating electron-positron pairs. Such an interaction results in an observable flux decrease at very high energies in blazar spectra that depends on the EBL optical depth.

The aim of this work is to find a model-independent method to obtain the normalization factor of the EBL. A brief reminder on the EBL optical depth is introduced in Section 2. In Sections 3 and 4, we present the data sample and the analysis method, respectively. Finally, preliminary results are discussed in Section 5.

2 EBL optical depth

Along the path from the source to the observer, γ-rays can interact with EBL photons generating electron-positron pairs. This interaction results in a flux decrease in the high energy spectrum of blazars, that is strictly related to the EBL optical depth, $\tau(E_o, z_0)$. The latter, in turn, is given by integrating over (i) the source distance; (ii) the energy of the EBL photons field; and (iii) the angle θ between the EBL and γ-ray photons:

$$\tau(E_0, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_1^{-1} d\cos(\theta) \frac{1-\cos(\theta)}{2} \sigma_{\gamma\gamma}[\beta(E_0, z, \epsilon, \cos(\theta))] \tag{2.1}$$

where $\partial L / \partial z$ is the distance element in a flat ΛCDM cosmology, $n(\epsilon, z)$ is the numerical density of the EBL photon field, and $\sigma_{\gamma\gamma}$ is the pair production cross-section, given by the Bethe-Heitler formula (see Stecker et al. 1992):

$$\sigma_{\gamma\gamma}(\beta) = \frac{3\sigma_T}{16}(1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \tag{2.2}$$

where β is:

$$\beta = \sqrt{1 - \frac{2(m_e c^2)^2}{E_0 \epsilon} \frac{1}{1+z} \frac{1}{1-\cos(\theta)}} \, . \tag{2.3}$$

As an approximation, the evolution of the EBL spectrum with redshift can be parametrized as the product between the local EBL density at $z = 0$ and an evolution term, $evol(z)$, by following Madau & Phinney (1996):

$$d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) = d\epsilon_0 \frac{\partial n}{\partial \epsilon_0}(\epsilon_0, 0) \times evol(z) \, , \tag{2.4}$$

where the evolution term represents the sources contribution to the EBL photon field during the cosmic epoch.

3 Data

In this work we analyzed - by following the method described in Section 4 - the spectra of 300 blazars, taken from the preliminary release (rev. v11) of the Third Catalogue of Hard *Fermi*-LAT Sources (3FHL, The *Fermi*-LAT Collaboration 2017). Such a catalogue collects the data of 7 years of *Fermi*-LAT observations and counts 1556 objects detected between 10 GeV and 2 TeV. The improved sensitivity and angular resolution (by a factor 3 and 2, respectively with respect to the previous catalogue 1FHL, Ackermann et al. 2013), and the newest event-level analysis, Pass 8 (Atwood et al. 2013), yielded a better event reconstruction and classification together with an increased energy coverage.

We selected 300 blazar spectra with known redshift and TS > 25, including both BL Lac and Flat Spectrum Radio Quasars. The sample has been divided into three different redshift bins: 109 sources for $z \leq 0.2$, 100 for $0.2 < z \leq 0.5$, and 91 for $0.5 < z < 2.0$. Spectra contain typically from 3 to 5 significant points (most of them contains only 3 points). Upper limits have been excluded from the analysis because approximations are needed to include them in the fitting procedure.

4 Analysis method

As remarked above, the interaction between EBL photons and γ-rays, causes a flux decrease in the high energy spectrum of distant sources. Hence, the observed spectrum is attenuated according to:

$$\Phi_{obs} = e^{-\tau(E,z)} \, \Phi_{intr} \tag{4.1}$$

where Φ_{obs} and Φ_{intr} are the observed and intrinsic spectrum, respectively. The previous equation can be rewritten by multiplying the optical depth by the so-called scaling factor, α:

$$\Phi_{obs} = e^{-\alpha\,\tau(E,z)}\,\Phi_{intr} \tag{4.2}$$

that basically quantifies the agreement between the γ-ray observations and the EBL models providing $\tau(E, z, n)$. This approach has been adopted by many authors, and was e.g. applied on the *Fermi*-LAT data in Ackermann et al. (2012). In this work, we followed the same strategy, and we retrieved the scaling factor α for three different redshift bins, by combining a large number of blazar spectra. To model the intrinsic spectrum, the following functions have been taken into account: (i) power law, $\Phi_{PWL}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$; (ii) exponential cutoff power law, $\Phi_{EPWL}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-E/E_{cut}}$; and (iii) log parabola, $\Phi_{LP}(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma - b\ln(E/E_0)}$; where Φ_0 is the flux normalization, $E_0 = \sqrt{E_{min}\,E_{max}}$ (with E_{min} and E_{max} the minimum and maximum spectrum energy, respectively) is the reference energy, Γ is the photon index at the reference energy, b is the curvature parameter, and E_{cut} is the energy corresponding to the cutoff.

A range of possible values for the scaling factor α is defined, and for equally spaced α values a fit to the data is performed in order to find the best spectral parameters describing each source. Then, the maximum likelihood value of α determines the best scaling factor according to the data. Since the emission processes of blazars are still not very well understood, it is difficult to disentangle if the spectrum curvature is due to internal emission mechanisms or to EBL absorption. So, a check on the spectral models is performed: for the best α value, a spectral model is switched into a more complex one if the latter is preferred at least at the 2σ level. A further condition to be satisfied in the fitting procedure - so that each spectral model is fully constrained - is that the degrees of freedom must be ≥ 1 (i.e., only sources whose spectrum contains strictly more than 3 significant points can be modelled with a log parabola or exponential cutoff power law). The check on the spectral models and determination of α is an iterative process, and it stops when the model-set converges.

The adopted EBL model is that of Franceschini et al. (2008), hereafter FR08. The scaling factor α has been obtained both for the full model and for an evolution template. In the latter case, we assumed that the EBL evolution term (see Equation 4.3) can be parametrized as in Raue & Mazin (2008):

$$evol(z) = (1+z)^{3-f_{evol}}\ . \tag{4.3}$$

The value of f_{evol} is set to 1.7. Such a value was demonstrated by Biteau & Williams (2015) to well reproduce the FR08 and Gilmore et al. (2012) EBL models up to $z \sim 0.6$ at least. Above this redshift, the parametrization is used, at this stage, as a toy model to study the sensitivity of our approach to the evolution of the EBL.

Finally, to test the robustness of the model selection, we run the whole procedure starting from different sets of intrinsic spectral models: (i) power law; and (ii) log parabola. Developing a model-independent approach is crucial to avoid biased results deriving from incorrect assumptions on the intrinsic spectrum (i.e., all absorption is due to the EBL in case of power law models, or most of absorption is due to internal mechanisms in case of log parabola models).

5 Results

For each redshift bin, we derived the scaling factor α (i) by assuming both the full FR08 EBL model (Figure 1), and a template evolution (Figure 2); and (i) by starting both from different initial spectral models (i.e., power law, and log parabola). Results presented in Ackermann et al. (2012) are shown for comparison, and were obtained by using the full FR08 EBL model. Their sample includes 150 blazars taken from the second *Fermi* Large Area Telescope source catalog (2FGL, Nolan et al. 2012), analyzed with the event-level analysis Pass 7. All intrinsic spectra have been modelled with a log parabola function, whose best-fit parameters were obtained by fitting the unabsorbed part of the spectrum (< 10 GeV). The uncertainties on the α-values obtained in our work are significantly reduced thanks both to the twice larger size of the source sample, and to the larger statistics and better performance in analyzing 3FHL data. We note nonetheless that more freedom is allowed in our parametrization of the intrinsic models, with both the model and parameters of each spectrum being fit jointly with the EBL normalization.

From the two plots, one can conclude that the model selection has a very similar effect both for the full and the evolution template of the FR08 EBL model: the major discrepancy occurs at low redshift, and then disappears at higher redshift. This could be due to a lack of statistics in the absorbed part of the spectrum at

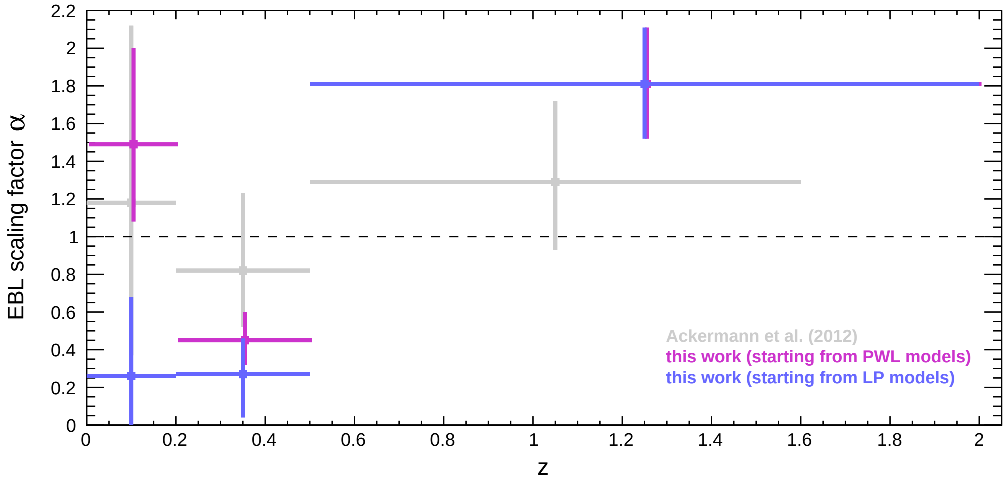

Fig. 1. EBL scaling factor as a function of redshift for the FR08 EBL model. Points were obtained for two different sets of initial spectral models: power law models (blue), and log parabola models (magenta). Results of Ackermann et al. (2012) are shown for comparison (grey).

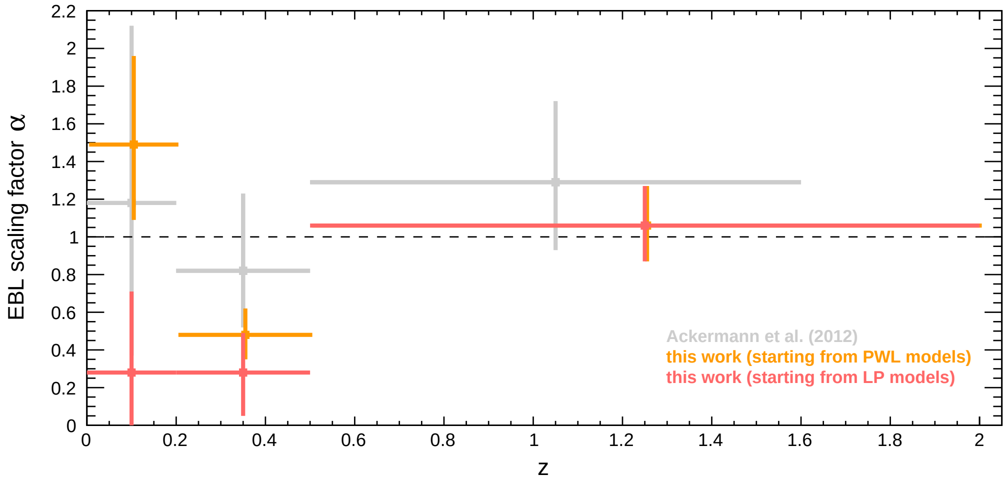

Fig. 2. Same as Figure 1, but for the evolution template of FR08 EBL model (see Equations 2.4 and 4.3), and with $f_{evol}(z) = 1.7$.

low redshift that makes the constraining power on the EBL poorer. This can lead to slightly different sets of spectral models, where the presence of few log parabola models can drive the fit to an unlikely absorption-free scenario.

What we can conclude from the inspection of the 3FHL data is that the effects of the model selection are still too large to allow us to investigate the impact of the parameter evolution. The lack of robustness at low redshifts is probably related to the fact that the intrinsic spectra are poorly constrained. To robustly evaluate the reliability of this model-independent approach, we need to broaden the investigated spectral region to lower energies, for example taking into account the spectral points contained in the third *Fermi* Large Area Telescope source catalog (3FGL, Acero et al. 2015).

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