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IL NUOVO CIMENTO Vol. 34 C, N. 3 Maggio-Giugno 2011
DOI 10.1393/ncc/i2011-10874-1

Colloquia: Scineghe2010

Spectral candles to measure the Extragalactic Background Light

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(ricevuto il 25 Febbraio 2011; pubblicato online il 12 Maggio 2011)

Summary. — Extragalactic Background Light (EBL) is the integrated light from all stars that have ever formed, and spans in a range of Infrared (IR) to Ultraviolet (UV). The interaction of very-high-energy (VHE: $E > 100\,\mathrm{GeV}$) γ-rays emitted by Active Galactic Nuclei (AGN) at cosmological distances with the EBL results in electron-positron pair production that leads to an energy-dependent attenuation of the observed VHE flux. Here we introduce a method based on the attenuation to measure the EBL photon number density. We then apply this method on simultaneous blazar data—PKS 2155-304—to determine the optical density at $z = 0.12$ and compare it with the optical densities predicted by popular EBL models.

PACS 98.70.Vc – Background radiations.
PACS 98.54.Cm – Active and peculiar galaxies and related systems (including BL Lacertae objects, blazars, Seyfert galaxies, Markarian galaxies, and active galactic nuclei).

1. – Introduction

The Extragalactic Background Light (EBL) reflects the time integrated history of cosmological star formation. Its shape must reflect the two humps that characterize the spectral energy distributions (SEDs) of galaxies: one arising from starlight and peaking at $\lambda \sim 1\,\mu\mathrm{m}$ (optical background), and one arising from warm dust emission and peaking at $\lambda \sim 100\,\mu\mathrm{m}$ (IR background). However, direct measurements of the EBL are hampered by the dominance of foreground emission (interplanetary dust and galactic emission), hence the level of EBL emission is uncertain by a factor of several orders of magnitude.

One approach to evaluate the EBL emission level has been modeling the integrated light that arises from an evolving population of galactic stellar populations. However,

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uncertainties in the assumed galaxy formation and evolution scenarios, stellar initial mass function, and star-formation rate have led to significant discrepancy among models. Another, more phenomenological approach deduces upper limits on the level of EBL attenuation making basic assumptions on the intrinsic VHE ($E_\gamma > 0.1\,\mathrm{TeV}$) γ-ray shape of AGN spectra (*i.e.*, before the VHE photons are affected, on their way to the Earth, by $\gamma\gamma$ interaction with the intervening EBL photons). The only unquestionable constraints on the EBL are model-independent lower limits based on galaxy counts.

2. – EBL absorption

The cross-section for the reaction $\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-$ is

$$\sigma_{\gamma\gamma}(E,\epsilon) = \frac{3}{16}\,\sigma_\mathrm{T}\,(1-\beta^2)\;\times\;\left[2\,\beta\,(\beta^2-2) + (3-\beta^4)\ln\frac{1+\beta}{1-\beta}\right],$$

where σ_T is the Thompson cross-section and $\beta \equiv \sqrt{1-(m_e c^2)^2/E\epsilon}$.

Purely for analytical demonstration purposes, let us assume, following Stecker *et al.* (1992), that $n(\epsilon) \propto \epsilon^{-2.55}$ is the local number density of EBL photons having energy equal to ϵ (no redshift evolution — as befits the relatively low redshifts currently accessible to IACTs), z_e is the source redshift, and the cosmology is flat no-Λ ($\Omega_0 = 1$). The optical depth due to pair-creation attenuation between the source and the Earth,

$$\tau_{\gamma\gamma}(E,z_e) = \frac{c}{H_0}\int_0^{z_e}\sqrt{1+z}\;\mathrm{d}z\;\int_0^2\frac{x}{2}\mathrm{d}x\;\times\;\int_{\frac{2(m_e c^2)^2}{Ex(1+z)^2}}^{\infty} n(\epsilon)\;\sigma_{\gamma\gamma}\big(2xE\epsilon(1+z)^2\big)\mathrm{d}\epsilon,$$

where $x \equiv (1-\cos\theta)$ with θ the angle between the photons, and H_0 the Hubble constant, turns out to be $\tau_{\gamma\gamma}(E,z) \propto E^{1.55} z_s^{\eta}$ with $\eta \sim 1.5$.

This calculation, although it refers to an idealized case, highlights an important property of the VHE flux attenuation by the $\gamma_\mathrm{VHE}\gamma_\mathrm{EBL} \to \mathrm{e}^+\mathrm{e}^-$ interaction: $\tau_{\gamma\gamma}$ depends both on the distance traveled by the VHE photon (hence on z) and on the photon's (measured) energy E. So the spectrum measured at Earth is distorted with respect to the emitted spectrum. In detail, the expected VHE γ-ray flux at Earth will be: $F(E) = (\mathrm{d}I/\mathrm{d}E)\,e^{-\tau_{\gamma\gamma}(E)}$ (differential) and $F(>E) = \int_E^\infty(\mathrm{d}I/\mathrm{d}E')\,e^{-\tau_{\gamma\gamma}(E')}\mathrm{d}E'$ (integral).

3. – Proposed method

Here we describe a new method to *measure* the EBL that we have recently proposed [1]. It stems from the consideration that neither the EBL nor the intrinsic VHE γ-ray spectra of background sources are separately known—only their combination is. Hence, as spectral beacons to measure the EBL at different z, one should choose a class of intrinsically bright sources whose spectra can be described by one well-known emission model. We choose BL Lac objects, *i.e.* AGNs whose relativistic jets point directly toward the observer so their luminosities are boosted by a large factor and dominate the source flux with their Synchrotron-Self-Compton (SSC) emission: and within BL Lacs, we specifically propose to use the sub-class of high-frequency–peaked BL Lacs (HBLs) because their Compton peaks fall within the typical operation range of Cherenkov telescopes—unlike for other types of BL Lacs. For a given source, our method

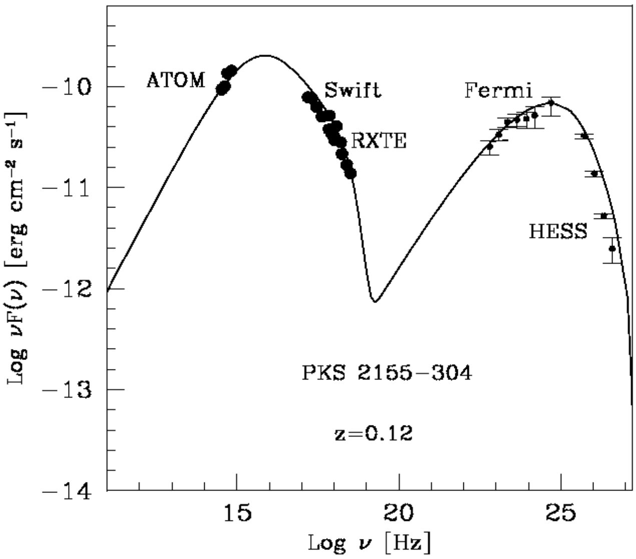

Fig. 1. – Data (from [2]) and best-fit SSC model (solid curve) of the SED of PKS 2155-304. The best-fit SSC parameters are: $n_\mathrm{e} = 150\,\mathrm{cm}^{-3}$, $\gamma_\mathrm{br} = 2.9 \times 10^4$, $\gamma_\mathrm{max} = 8 \times 10^5$, $\alpha_1 = 1.8$, $\alpha_2 = 3.8$, $R = 3.87 \times 10^{16}\,\mathrm{cm}$, $\delta = 29.2$, $B = 0.056\,\mathrm{G}$.

involves using a simultaneous broad-band SED that samples the optical ($E_\gamma \sim$ eV), X-ray ($E_\gamma \sim$ keV), high energy (HE: $E_\gamma > 0.1\,\mathrm{GeV}$) and VHE ($E_\gamma > 0.1\,\mathrm{TeV}$) γ-ray bands. Simultaneous data are crucial here, considering the strong and rapid variability displayed by most HBLs. A given observed SED will be best fitted, from optical through HE γ-rays, with an SSC model. (Under reasonable circumstances, only VHE photons are affected by EBL attenuation.) Extrapolating such best-fitting SED model into the VHE regime, we shall assume the latter to represent the source's intrinsic VHE γ-ray emission. Contrasting measured *vs.* intrinsic emission leads to a determination of the Universe's $\gamma\gamma$ opacity to VHE photons.

4. – Application

To show the potential of our method, we apply this procedure to the simultaneous SED data set of the southern HBL source PKS 2155-304 [2], located at a redshift $z = 0.12$. The data and resulting best-fit SSC model (from optical through HE γ-rays) are shown in fig. 1. The extrapolation of the model into the VHE γ-ray range clearly lies below the observational H.E.S.S. data, progressively so with increasing energy. We attribute this effect to EBL attenuation, $F_\mathrm{obs}(E;\, z) = F_\mathrm{em}(E;\, z)\, e^{-\tau_{\gamma\gamma}(E;\, z)}$. The corresponding values of $\tau_{\gamma\gamma}(E;\, z)$ for $E = 0.23$, 0.44, 0.88, 1.70 TeV and a source redshift $z = 0.12$ are, respectively, $\tau_{\gamma\gamma} = 0.12$, 0.48, 0.80, and 0.87. These values are compared with predicted values by some of the popular EBL models [3-8] in fig. 2.

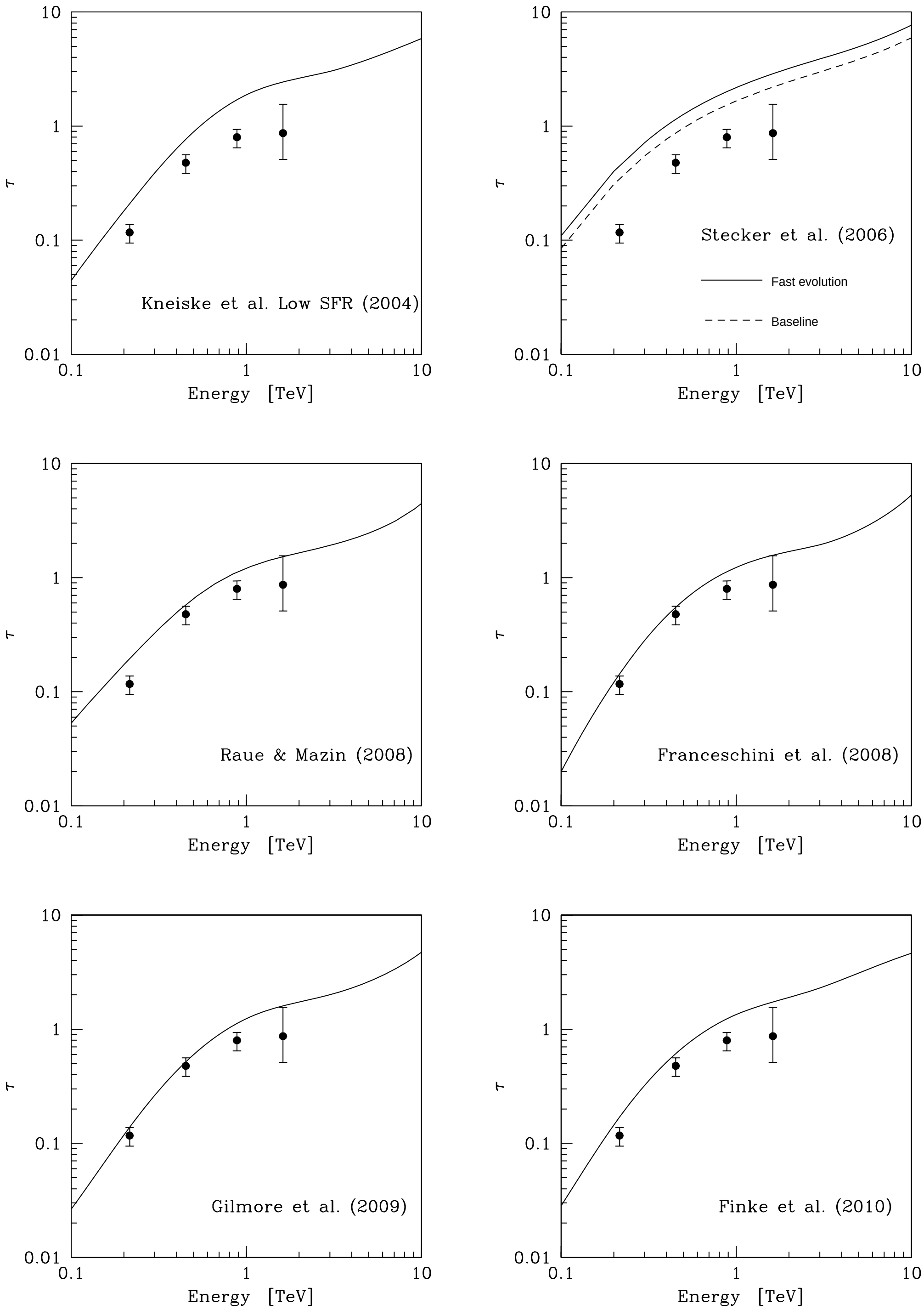

Fig. 2. – Measured values of $\tau_{\gamma\gamma}(E;\, z)$ for $E = 0.23, 0.44, 0.88, 1.70$ TeV derived from comparing, for simultaneous observations of the HBL blazar PKS 2155-304 ($z = 0.12$), the (EBL-affected) VHE γ-ray data with the eV-through-GeV best-fitting SSC model extrapolated into the TeV domain. The curves represent, for redshifts $z = 0.12$ optical depth $\tau_{\gamma\gamma}(E)$ according to recent EBL calculations: top left: [3], top right: [4], center left: [5], center right: [6], bottom left: [7], bottom right: [8].

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