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Electromagnetic cascades propagating from low-redshift blazars

M. Orellana[1,2], L.J. Pellizza[2,3], G.E. Romero[2,3], M. Tueros[2,3], M.C. Medina[2,3] & S. Pedrosa[2,4]

[1] *Sede Andina de la Universidad Nacional de Río Negro*
[2] *Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET)*
[3] *Instituto Argentino de Radioastronomía (IAR)*
[4] *Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA)*

Contact/ MO: morellana@unrn.edu.ar

Resumen / Se ha establecido que la radiación extragaláctica de fondo atenua los fotones de muy alta energía emitidos por blazares a través del proceso de creación de pares. Los pares son desviados por el campo magnético extragaláctico (EGMF) y se enfrían por dispersión Compton Inversa con los fotones del fondo cósmico de microondas mientras desarrollan cascadas electromagnéticas. El EGMF también puede extraer energía de los pares en forma de radiación sincrotrón. El espectro originalmente emitido, la extensión de la fuente y el tiempo de arribo de los fotones resultantes se ven modificados por tales procesos. Para estudiar este problema hemos considerado que la emisión originada por los blazares sigue una ley de potencias con un corte exponencial, y seguimos la trayectoria tridimensional de cada partícula y fotón de la cascada. En este trabajo describimos los resultados obtenidos a partir de las simulaciones considerando la propagación a lo largo de distancias del orden de unos 100 Mpc. Se pone el énfasis en la construcción de la distribución espectral final resultado de la conservación de la energía, que por tanto combina la información de los diferentes canales de pérdidas. La forma de la distribución espectral cambia al variar el valor del campo magnético asumido.

Abstract / It has been established that the Extragalactic Background Light attenuates the very high-energy photons emitted by blazars through pair production. The pairs are deflected by the Extragalactic Magnetic Field (EGMF) and cooled down by Inverse Compton scattering with the Cosmic Microwave Background (CMB) photons while they develop an electromagnetic cascade. The EGMF may also take out energy from the pairs in the form of synchrotron radiation. The originally emitted spectrum, the source extent and the arriving time of the photons are modified by such cascades. In order to study this problem we assume the blazar original emission to follow a power-law with exponential cutoff, and track the three-dimensional trajectories of each particle and photon in the cascade. In this work we describe the results of numerical simulations regarding the γ-ray propagation through ~ 100 Mpc scales, making focus on the construction of the outcoming spectrum which results from the energy conservation and thus combines the information from the different channels of energy losses. Different spectra arise when varying the EGMF strength.

Keywords / gamma rays: diffuse background — (galaxies:) BL Lacertae objects: general — radiative transfer

1. Interaction distances

Diffuse radiation fields permeate the Universe at all wavelengths. The diffuse light spanning the UV to far-IR wavelengths, known as the Extragalactic Background Light (EBL), is the result of the radiation by all the stars which have ever existed in the observable Universe, and the dust absorption and reradiation.

The EBL is a source of the very high-energy (VHE) gamma-ray opacity that results in $e^{\pm}$ pair creation. This is a largely studied problem (e.g Gould & Schreder, 1967), and one of present relevance evolving along with the growth of the high and VHE observational capabilities (Biteau, 2013, and references therein) . Over a wide energy range the pairs produced by the γ absorption interact with the Cosmic Microwave Background (CMB), as it is denser than the EBL and there is no threshold energy for the Inverse Compton (IC) scattering.

Several models have been proposed for the EBL spectra Franceschini et al. (2008); Finke et al. (2010); Gilmore et al. (2012) among others. The Fermi satellite has confirmed (Ackermann et al., 2012) the EBL imprint in connection with blazars, i.e. active galactic nuclei that expels relativistic jets of magnetized plasma in our direction.The EBL has a complex time evolution therefore the interaction distances of the γ-ray are redshift dependent. For testing purposes of our code we study a closeby blazar as the primary photon source, and approximate the EBL density for its spectrum at $z \ll 1$.

The intergalactic medium is also a magnetic, turbulent place. Observational evidence for the presence of the Extragalactic Magnetic Field (EGMF or Intergalactic, IGMF in some references) constraints its strength to be $\geq 10^{-17}$ G (Neronov & Vovk, 2010). This field deflects the pairs from their initial directions thus a 3D treatment of the electromagnetic cascade is mandatory. In this work we assume a coherence length $\lambda_{\rm B} \sim 1$ Mpc as the characteristic distance over which the magnetic field direction changes. We follow the topology proposed

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by Elyiv et al. (2009). Figure 1 shows a comparison between the mean free paths for $e^{\pm}$ and their giroradius for extreme values of the EGMF. If the EGMF were stronger the cascade may result in an extended isotropic emission or halo Ando & Kusenko (2010).

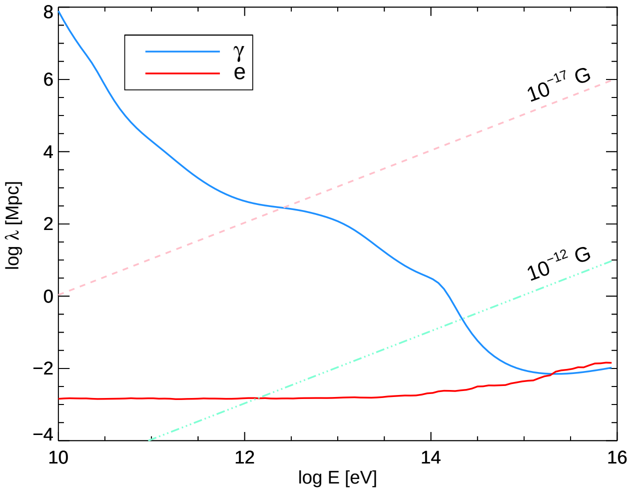

Fig. 1: Typical distances for the cascade development: the mean free paths and giroradii. The EBL model (Gilmore et al., 2012) corresponding to $z = 0.025$ was considered. Two values of the EGMF are shown for illustration purposes.

Our numerical simulations regarding the γ-ray propagation through ~ 100 Mpc scales were run with the code presented in Pellizza et al. (2010); Orellana et al. (2013) for solving the trajectory equations of the particles through Markov Chain Monte Carlo and molecular dynamic techniques. These methods are combined as to avoid simplifying assumptions by including the exact expressions of the involved cross sections. In addition, full temporal and spatial descriptions are achieved.

2. Simple jet model

Figure 2 shows results from monoenergetic injected photons of 100 TeV cascading from a source located at $d = 600$ Mpc, confined within a 6 degree jet-like cone. We recover all the photons at a distance greater than d crossing a plane perpendicular to the jet direction, i.e. on-axis. A detailed study of the angular and temporal properties will be presented in a forthcoming paper.

In order to consider a more realistic initial scenario, we have studied the reprocessing of VHE photons from a putative blazar located at 600 Mpc, similar to the blazar 1ES 0229+200. In recent years this blazar has become one of the primary sources used to put constraints on the EBL as it was detected by HESS, and has a weak Fermi detection. We assume the intrinsic spectrum to be a cut-off power-law with photon index $\Gamma = -1.5$ and $E_{\text{cut}} = 10$ TeV, similar to the study performed by Vovk et al. (2012). The injected and emerging spectral energy distributions are shown in Figure 3 for a case with same initial direction for all the photons. The cascade and absorbed SED match at energies above ~ 400 GeV.

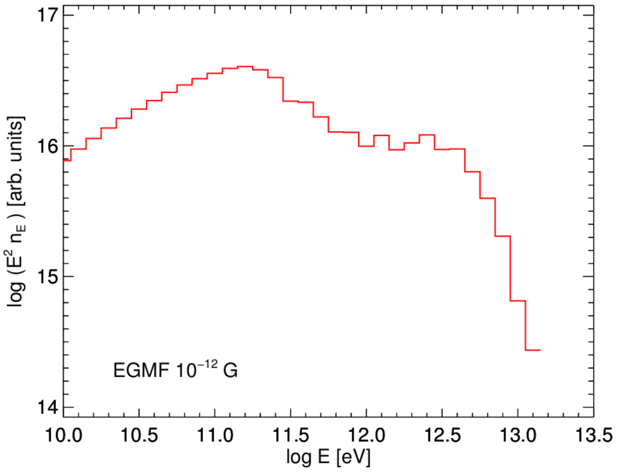

Fig. 2: Outcoming spectral energy distribution (SED) from a monoenergetic injection of 100 TeV photons, considering an aperture of the initial emission of 6 degrees. Energy binning of 0.1 dex was used.

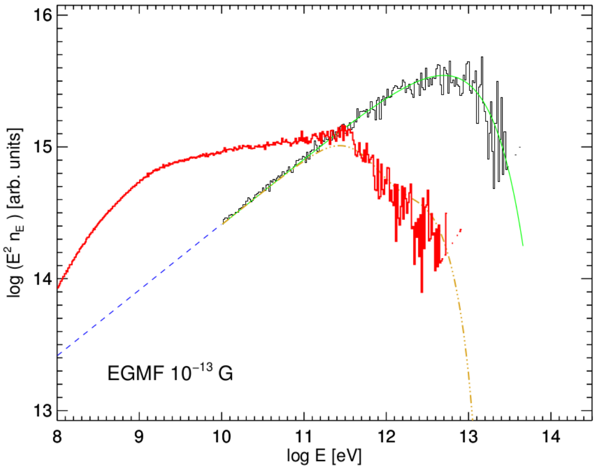

Fig. 3: Cascade processed spectrum. The theoretically injected correspond to a photon index $\Gamma = -1.5$ and 10 TeV cut-off. A large number of primaries ($\sim 10^4$) was tracked in the simultaion. The primary SED is shown in black and theoretical in green. The pure absorbed SED, with the same model as in Figure 1 is in dotted-line. The red continuous line was obtained after the simulation and a synthetic component at low energies was added, indicated by the blue dashed line.

In the simulation runs for Figure 3 the outcome as synchrotron emission was negligible. In Table 1 we show the total energy conservation.

The usual power-law injected spectra (negative photon index, i.e. $\Gamma < 0$) overproduces low-energy primary photons. At energies where $\tau(E) \ll 1$ we have added their contribution to the input and output spectra as a synthetic one. This is not a requirement, but helps to the program performance by avoiding the cpu time

Table 1: Total energy conservation for the example of Figure 3. All the energies are expressed in eV. Note the accuracy reached. Here the low-energy photons have $E < 100$ MeV.

Energy injected by primaries	1.401932×10^{16}
Energy injected by targets	1.396942×10^{9}
Energy lost via synchrotron	2.477848
Energy lost via leptons	6.221365×10^{15}
Energy via low-energy photons	1.162669×10^{14}
Energy via high-energy photons	7.681694×10^{15}

that would require to generate and follow them, and focus all the resources in the injection at higher energies where the number of photons is smaller. Even with this precaution the final SED is expected to be more noisy at the highest energies considered where the number of photons is smaller[⋆]. If a larger number of initial photons were considered, that noise is expected to be reduced.

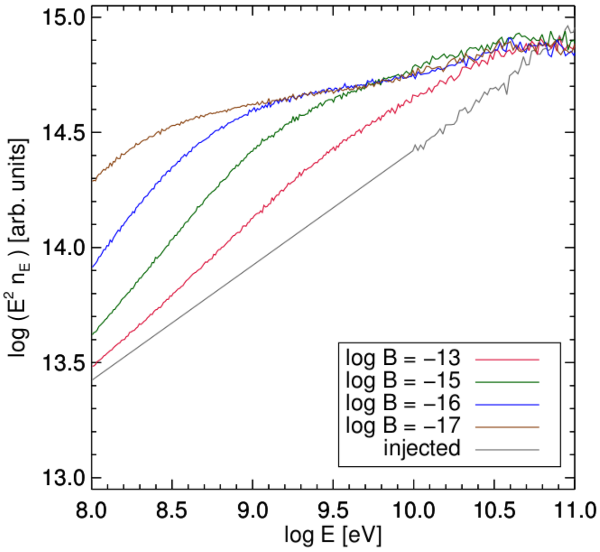

Fig. 4: Cascade from a power-law injection: detail at low energies. A 100 Mpc distance was considered in this case. Colour figures are provided in the electronic edition of the Bulletin.

The cooling of leptons through synchrotron radiation is responsible of the variation of the spectral distribution at GeV energies with the magnetic field strength. Results from other testing runs in Figure 4 illustrate this effect.

3. Conclusions

In order to construct the SED the outcomming photons are binned in energy, being also posible to consider their temporal or spatial distributions. Total energy conservation allows to plot in a consistent way the injected and cascade processed SEDs.

IC scattering in the Thomson regime make the VHE pairs to emit HE photons (i.e. photons with significantly lower energy). If we consider many decades in energy, as in the SEDs shown here, those HE photons cannot be disregarded (see also Aharonian et al., 1994). But, in terms of computing time, we have found a better performance when adding the HE photons as a synthetic component to the injected and the outcoming spectrum. Such procedure is admissible at energies where the opacity is $\tau \ll 1$. The trends of our analysis are consistent with Oikonomou et al. (2014) or Vovk et al. (2012), i.e. a similar variation of the overall SEDs with EGMF strength is found.

The properties of the extended emission around extragalactic gamma-ray sources could be used to reveal the presence of extremely weak magnetic fields in the intergalactic medium, as well as to study the jet configuration and blazar initial spectrum.

Future observations with ground-based Cherenkov telescopes, such as MAGIC Stereo, HESS 2 and CTA, will dramatically improve the measurements of blazar spectra below 100 GeV, allowing much better constraints on the EGMF and EBL. According to these expectations we are currently engaged in the tune of our code for the investigation of VHE radiation reprocessing. The code will allow the simulation of the spectrum of gamma-ray sources in arbitrary environments, using ab-initio computations, eliminating as many simplifying assumptions as possible. We plan to use this tool to simulate different astrophysical sources.

References

Ackermann M., et al., 2012, Science, 338, 1190
Aharonian F. A., Coppi P. S., Voelk H. J., 1994, ApJL, 423, L5
Ando S., Kusenko A., 2010, ApJL, 722, L39
Biteau J., 2013, in Cambresy L., Martins F., Nuss E., Palacios A., eds, SF2A-2013, Constraining gamma-ray propagation on cosmic distances. pp 303–312
Elyiv A., Neronov A., Semikoz D. V., 2009, PhysRevD, 80, 023010
Finke J. D., Razzaque S., Dermer C. D., 2010, ApJ, 712, 238
Franceschini A., Rodighiero G., Vaccari M., 2008, A&A, 487, 837
Gilmore R. C., et al., 2012, MNRAS, 422, 3189
Gould R. J., Schreder G. P., 1967, Phys.Rev., 155, 1408
Neronov A., Vovk I., 2010, Science, 328, 73
Oikonomou F., Murase K., Kotera K., 2014, A&A, 568, A110
Orellana M., Pellizza L., Romero G. E., 2013, Boletin de la Asociacion Argentina de Astronomia, 56, 333
Pellizza L. J., Orellana M., Romero G. E., 2010, International Journal of Modern Physics D, 19, 671
Vovk I., et al., 2012, ApJL, 747, L14

[⋆] The automatic bin size routine chooses a number of bins (initially, $\sqrt{2N}$). If this leads to a histogram in which $> 1/5$ of the central 50% of the bins are empty, it decreases the number of bins and tries again. See NASA IDL Astronomy User's Library.