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# Diffuse gamma emission of the Galaxy from cosmic rays

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**Abstract**

The diffuse γ-rays and neutrino emissions of the Galaxy may provide a unique tool to probe galactic cosmic rays (CR) and their interaction with the interstellar medium. At the same time, if not well understood, such emissions may be annoying backgrounds for dark matter searches. Therefore, it is crucial to model them as better as possible. We do that by combining simulations of the CR propagation with recent models of the gas distribution. Respect to previous works, we perform a treatment of CR diffusion which accounts for a more realistic spatial dependence of the diffusion coefficients. Although our analysis is focused on the energy range above the TeV, we can reliably extrapolate our predictions at lower energies and compare them with EGRET measurements finding a good agreement. Then, we compare our predictions with MILAGRO and TIBET observations in several regions of the sky, including Cygnus and the Galactic Centre. Finally, we briefly discuss the implication of our finding for neutrino astronomy.


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## 1. Introduction

Several orbital observatories (see Ref. [1] for a review), especially EGRET [2,3], found that, at least up to 10 GeV, the Galaxy is pervaded by a γ-ray diffuse radiation. While a minor component of that emission is likely to be originated by unresolved point-like sources, the dominant contribution is expected to come from the interaction of galactic cosmic rays (CR) with the interstellar medium (ISM). The γ-ray high energy range will be soon probed by GLAST [4] (up to 300 GeV) and by air shower arrays (ASA) (e.g. MILAGRO [5,6] and TIBET [7]) (above the TeV). Above the GeV, the main γ-ray emission processes are expected to be the decay of $\pi^0$ produced by the scattering of CR nuclei onto the diffuse gas (hadronic emission) and the Inverse Compton (IC) emission of relativistic electron colliding onto the interstellar radiation field (leptonic emission). It is unknown, however, what are the relative contributions of those two processes and how they change with the energy and the position in the sky (the so-called *hadronic–leptonic degeneracy*). Several numerical simulations have been performed in order to interpret EGRET data as well as forthcoming measurements at high energy (see e.g. Refs. [8,9]). Generally, they predict the hadronic emission to be dominant, in the proximity of the Galactic Plane (GP), between 0.1 GeV and few TeV, while between 1 and 100 TeV a comparable, or even larger IC contribution may be allowed.

The 1–100 TeV energy range, on which we focus here, is also interesting from the point of view of neutrino astrophysics. In that energy window neutrino telescopes (NTs) can look for up-going muon neutrino and reconstruct their arrival direction with an angular resolution better than 1°. Since hadronic scattering gives rise to γ-rays and neutrinos in a known ratio, the possible measurement of the neutrino emission from the GP may allow to resolve the hadronic–leptonic degeneracy.

In this contribution we discuss the main results of a recent work where we modelled the γ-ray and neutrino

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diffuse emission of the Galaxy due to hadronic scattering [10]. We improve previous analyses under several aspects: the distribution of CR sources, the way we treated CR diffusion by accounting for spatial variations of the diffusion coefficients, the distribution of the atomic and molecular hydrogen.

## 2. The spatial structure of the ISM

In order to assess the problem of the propagation of CRs and their interaction with the ISM we need the knowledge of three basic physical inputs, namely: the distribution of SuperNova Remnants (SNR) which we assume to trace that of CR sources; the properties of the Galactic Magnetic Field (GMF) in which the propagation occurs; the distribution of the diffuse gas providing the target for the production of $\gamma$-rays and neutrinos through hadronic interactions. In the following we assume cylindrical symmetry and adopt the Sun galactocentric distance $r_\odot = 8.5\,\mathrm{kpc}$.

Several methods to determine the SNR distribution in the Galaxy are discussed in the literature (see e.g. that based on the surface brightness–distance relation [11]). Here we adopt an SNR distribution inferred from observations of pulsars and progenitor stars as done in Ref. [12]. Such an approach is less plagued by systematics and its results agree with those inferred from the distribution of radioactive nuclides like of $^{26}$Al. A similar approach was followed in Ref. [13], where the contribution of type I-a SNR (dominating in the inner 1 kpc) was, however, disregarded.

Concerning the GMF we adopt the following analytical distribution which is based on Faraday Rotation Measurements (RMs) of polarised radio sources [14,15]:

$$B_{\rm reg}(r,z) = B_0 \exp\left\{-\frac{r-r_\odot}{r_{\rm B}}\right\}\frac{1}{2\cosh(z/z_r)} \quad (1)$$

where $B_0 \equiv B^{\rm disk}_{\rm reg}(r_\odot, 0) \simeq 2\,\mu\mathrm{G}$ is the strength at the Sun circle. The parameters $r_{\rm B}$ and $z_r$ are poorly known. However, we found that our final results are practically independent of their choice. In the following we adopted $r_{\rm B} = 8.5\,\mathrm{kpc}$ and $z_r = 1.5\,\mathrm{kpc}$.

More uncertain are the properties of the turbulent component of the GMF. Here we assume that it strength follows the behaviour:

$$B_{\rm ran}(r,z) = \sigma(r) B_{\rm reg}(r,0)\frac{1}{2\cosh(z/z_t)} \quad (2)$$

where $\sigma(r)$ parametrizes the turbulence strength and $z_t = 3\,\mathrm{kpc}$. From polarimetric measurements and RMs is known GMF are chaotic on all scales below $\sim$100 pc. The power spectrum of the those fluctuations is also poorly known. Similarly to what done in previous works we adopt here a Kolmogorov ($B^2(k) \propto k^{-5/3}$) spectrum. In Ref. [10] we also considered a Kraichnan ($B^2(k) \propto k^{-3/2}$) power spectrum.

Concerning the gas distribution we adopt a model which is based on a suitable combination of different analyses which have been separately performed for the disk and the galactic bulge. For the $H_2$ and HI distributions in the bulge we use a detailed 3D model recently developed by Ferriere et al. [16] on the basis of several observations. For the molecular hydrogen in the disk we use the well-known Bronfman's et al. model [17]. For the HI distribution in the disk, we adopt Wolfire et al. [18] 2D model. Similarly to what done in Ref. [13] we adopt here a radially dependent value of the CO–$H_2$ conversion factor ($X_{\rm CO}$). We assume $X_{\rm CO} = 0.5 \times 10^{20}\,\mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s}$ for $r < 2\,\mathrm{kpc}$ and $1.2 \times 10^{20}$ (in the same units) for $r \geqslant 2\,\mathrm{kpc}$.

## 3. CR diffusion

The ISM is a turbulent magneto-hydro-dynamic (MHD) environment. Since the Larmor radius of high energy nuclei is smaller than $L_{\max}$, the propagation of those particles takes place in the spatial diffusion regime. The diffusion equation describing such a propagation is (see e.g. Ref. [19])

$$-\nabla_i (D_{ij}(r,z)\nabla_j N(E,r,z)) = Q(E,r,z) \quad (3)$$

where $N(E,r,z)$ is the differential CR density averaged over a scale larger than $L_{\max}$, $Q(E,r,z)$ is the CR source term and $D_{ij}(E,r,z)$ are the spatial components of the diffusion tensor. In the energy range considered in our work energy loss/gain can be safely neglected. Since we assume cylindrical symmetry the only physically relevant components of the diffusion coefficients are $D_\perp$ and $D_{\rm A}$, respectively, the diffusion coefficient in the direction perpendicular to $\mathbf{B}_{\rm reg}$ and the antisymmetric (Hall) coefficient. We adopted expressions for those coefficients as derived by Monte Carlo simulations of charged particle propagation in turbulent magnetic fields [20]. With respect to other works, where a uniform value of the diffusion coefficient all over the magnetic halo was assumed and no distinction was done between perpendicular and parallel diffusion (see e.g. Ref. [9]), our approach is more realistic. We know, in fact, that the turbulence strength has to be spatially dependent and that the role of the regular GMF (which breaks isotropy) is likely to be not negligible at high energies. We found that although the role of Hall diffusion is negligible up to several PeV's, a realistic spatial dependence of $D_\perp$ gives rise to non-negligible effects.

## 4. Mapping the $\gamma$-ray and $\nu$ emission

Assuming that the primary CR spectrum is a power-law and that the differential cross-section follows a scaling behaviour (well justified at the energies considered in this paper), the $\gamma$-ray (muon neutrino) emissivity due to hadronic scattering can be written as

$$\frac{\mathrm{d}n_{\gamma(\nu)}(E;b,l)}{\mathrm{d}E} \simeq f_N \sigma_{\rm pp} Y_{\gamma(\nu)}(\alpha)\int \mathrm{d}s\, I_{\rm p}(E_{\rm p};r,z) n_{\rm H}(r,z). \quad (4)$$