The γ-ray sky points to radial gradients in cosmic-ray transport

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The standard approach to cosmic-ray (CR) propagation in the Galaxy is based on the assumption that local transport properties can be extrapolated to the whole CR confining volume. Such models tend to underestimate the γ-ray flux above few GeV measured by the Fermi Large Area Telescope towards the inner Galactic plane. We consider here for the first time a phenomenological scenario allowing for both the rigidity scaling of the diffusion coefficient and convective effects to be position-dependent. We show that within this approach we can reproduce the observed γ-ray spectra at both low and mid Galactic latitudes – including the Galactic center – without spoiling any local CR observable.

Introduction.

Since 2008 the Fermi Large Area Telescope (Fermi-LAT) has been surveying the γ-ray sky between about few hundred MeV and few hundred GeV with unprecedented sensitivity and resolution. The bulk of the photons detected by the Fermi-LAT is believed to be associated with diffuse emission from the Milky Way, originated by Galactic cosmic rays (CRs) interacting with the gas and the interstellar radiation field (ISRF) via production and decay of π0s, inverse Compton (IC), and bremsstrahlung. There is a striking consistency between general features in the diffuse γ-ray maps and the diffuse γ-ray flux models: the predictions mainly rely, on the side concerning emitting targets, on (indirectly) measured gas column densities and ISRF models, while, on the side of incident particles, on propagation models tuned to reproduce locally measured fluxes. When addressing at a quantitative level the quality of such match between predictions and data, most analyses have mainly developed optimized models looping over uncertainties on the emitting targets. In particular, in ref. 1 the authors – besides allowing for a radially-dependent rescaling of the ISRF and a remodulation of the atomic hydrogen column densities (depending on the assumed opacity of the 21 cm line) – adopt a tuning of the poorly known conversion factor between the observed CO emissivities and the molecular hydrogen column densities, usually dubbed XCO. In ref. 1 it is shown that such approach is sufficient to generate models in agreement with the data within about 15% in most regions of the sky; a remarkable exception is the fact that this procedure tends to systematically underestimate the measured flux above few GeV in the Galactic plane region, most notably towards the inner Galaxy. Fig. 1 shows the spectrum for the γ-ray flux measured by the Fermi-LAT in the energy range between 300 MeV and 100 GeV and a large angular window encompassing the inner Galactic plane (5 years of data, within the event class ULTRACLEAN according to Fermi tools v9r3p5). The yellow band corresponds to the point sources (PS) modelled using the 2-years Fermi-LAT Point Source Catalogue via a dedicated Monte Carlo (MC) code. The brown line is the contribution of the extragalactic background (EGB) obtained by a full-sky fit of the data for |b| > 20°. The double dot-dashed line and gray triangles are, respectively, the prediction and residuals for the Fermi benchmark model, labelled 8SZ4R20F150C5 (FB hereafter), selected for fig. 17 in ref. 1, and reproduced here using the GALPROP WebRun 2 3: while the model is optimized at low energy, it gives a poorer description of the data at high energy, a feature that is generic for all models proposed in that analysis.

FIG. 1. Upper panel. Comparison between the γ-ray flux computed with the CR propagation model proposed in this Letter (KRAγ total flux: solid black line; individual components shown) and the Fermi-LAT data (purple dots, including both statistic and systematic errors) in the Galactic disk. For comparison, we also show the total flux for the FB model defined in ref. 1 (double dot-dashed gray line). Lower panel. Residuals computed for the KRAγ and FB models.
The selected angular window is interesting because the diffuse emission from the inner Galactic plane is potentially a precious source of information for CR transport modelling. Being the region with largest gas column densities, it is the brightest zone of the sky and, unlike other regions where the interplay among components allows more modelling freedom, its flux is predominantly shaped by only one contribution, namely the $\pi^0$ decays, especially when looking at intermediate energies. The $\pi^0$ emissivity slope is the same as the incident proton slope, hence the inner Galactic plane allows an indirect measurement of the CR proton spectral index towards the center of the Galaxy, far away from the region where direct measurements are available. This aspect is seldom emphasized, since the standard approach consists in solving the propagation equation for CR species [4] under the assumption that diffusive properties of CRs are the same in the whole propagation volume. This implies reducing the spatial diffusion tensor to a single constant diffusion coefficient $D(\rho) = D_0(\rho/\rho_0)^\delta$, whose scaling $\delta$ on rigidity $\rho$ and normalization $D_0$ are constrained by local CR data (a range between about $\delta = 0.1$ and about $\delta = 0.85$ is allowed [5,7]). Such hypothesis freezes the proton spectral index $\gamma_p$ and therefore the $\pi^0$ spectral index $\gamma_{\pi^0}$ to be very close to the local one everywhere in the CR propagation region. For this reason, in fig. I and in the following, the $\gamma$-ray flux is multiplied by $E_{\gamma}^{-\delta}$, since $\gamma_p = 2.820 \pm 0.003$ (stat) $\pm 0.005$ (sys) is the proton index measured by the PAMELA experiment in the range 30–120 GeV [8]. The FB model gives a slightly rising curve since it assumes $\gamma_p = 2.72$.

The present analysis goes beyond standard approaches by allowing for spatial gradients in diffusion, using as a guideline the Fermi-LAT $\gamma$-ray data. In the CR transport equation, the diffusion term describes at macroscopic level the effective interplay between CRs and the magnetohydrodynamics turbulence, see, e.g., ref. [9]. In the framework of quasi-linear theory (QLT), $\delta$ is related to the turbulence spectrum (e.g. $\delta = 1/3$ for Kolmogorov-like turbulence and $\delta = 1/2$ for Kraichnan-like one); QLT however assumes that the turbulent component of the magnetic field is subdominant compared to the regular one, an hypothesis that does not seem to be supported by recent models [10,11]. Studies based on non-linear theory approaches, on the other hand, find more involved environmental dependencies, resulting in different scalings in different regions of the Galaxy, and deviations from a single power law in rigidity [12,13]. An additional element to take into account is the possibility that CRs themselves generate the turbulent spectrum responsible for their propagation [14], introducing local self-adjustments in propagation. Given these arguments, in the following we will consider models with variable $\delta$ and show how they naturally improve the description of $\gamma$-ray data.

**Analysis.** We decide to follow a data-driven approach. In order to quantify the change of the $\gamma$-ray slope along the Galactic disk and the resulting discrepancy between the FB model and the actual data, we show in table I the power-law index obtained by fitting the Fermi-LAT $\gamma$-ray data in the energy window $E_{\gamma} = [5-50]$ GeV, and in the second row of table II the $\chi^2$ of the FB model. The observed power-law index ranges from $E_{\gamma}^{-2.47}$ to $E_{\gamma}^{-2.60}$, thus resulting in a $\gamma$-ray flux much harder than the prediction of the FB model. The quality of the fit for the FB model is worse in the innermost windows (e.g. $|l| < 10^\circ$ and $20^\circ < |l| < 30^\circ$), with $|b| < 5^\circ$), it slightly ameliorates going towards outer longitudinal values ($50^\circ < |l| < 60^\circ$, with $|b| < 5^\circ$) but remains poor considering in average the whole Galactic disk ($|l| < 80^\circ$, with $|b| < 5^\circ$). In order to have a deeper understanding of the discrepancy, it is important to trace, for each line of sight (l.o.s.), which portion of the Galaxy the emission comes from. For this

\[
\begin{array}{cccc}
\text{sky window} & \Phi \sim E_{\gamma}^{-\alpha} & \text{sky window} & \Phi \sim E_{\gamma}^{-\alpha} \\
(|l| < 5^\circ) & & (|l| < 5^\circ) & \\
0^\circ < |l| < 10^\circ & \alpha = 2.55 & 40^\circ < |l| < 50^\circ & \alpha = 2.57 \\
10^\circ < |l| < 20^\circ & \alpha = 2.49 & 50^\circ < |l| < 60^\circ & \alpha = 2.56 \\
20^\circ < |l| < 30^\circ & \alpha = 2.47 & 60^\circ < |l| < 70^\circ & \alpha = 2.60 \\
30^\circ < |l| < 40^\circ & \alpha = 2.57 & 70^\circ < |l| < 80^\circ & \alpha = 2.52 \\
\end{array}
\]

![FIG. 2. Relative contribution (upper panel), and power-law spectral index of the $\pi^0$ emission (lower panel, with scaling $\sim E_{\gamma}^{-\alpha}$) for three reference l.o.s. as a function of the radial distance from the Galactic center. The FB (KRA) model corresponds to thinner (thicker) lines. We average in latitude over the interval $|b| < 5^\circ$.](image)

**TABLE I. Energy slope of Fermi-LAT $\gamma$-ray data on the Galactic disk. The power-law index has been obtained by fitting the data in the energy window $E_{\gamma} = [5-50]$ GeV. We average in latitude over the interval $|b| < 5^\circ$.**
reason, in fig. 3 we plot the relative contribution to the total $\pi^0$ emission for three reference l.o.s. as a function of the Galactocentric distance, $R$. At large values of the Galactic longitude $l$ (where the FB model gives a better fit) the emission is dominated by the local environment; instead, the closer to the center we look, the wider the relevant region gets, with the central rings contributing as much as 20% for the Galactic center window (where the fit is worse and the data turn out to be significantly harder). In the lower panel of fig. 3 we show the power-law spectral index of the $\pi^0$ component as a function of $R$; for the FB model, as expected, we find a constant value equal to the measured local proton spectral index. Driven by these results, we argue that the FB model should be corrected in such a way to get a significantly harder propagated proton index for smaller values of $R$.

**Method.** We propose a propagation model based on the following three ingredients: 1) Bearing in mind the motivations outlined in the introduction, we drop the oversimplified assumption of constant diffusion, and we consider the possibility that the slope of the diffusion coefficient $\delta$ is a function of $R$. 2) We allow for position-dependent convective effects; the presence of a significant convective wind in the inner region of the Galaxy is motivated by the X-ray observations of the ROSAT satellite [15], and may affect cosmic-ray propagation [16]. 3) We allow for a larger value of $X_{\text{CO}}$ in the outer part of the Galaxy; this hypothesis stems from the existence of a gradient in metallicity across the Milky Way [17]. The metallicity follows the star density, and is higher towards the Galactic center, while it decreases going outwards; since lower metallicities imply less dust shielding [18], it is reasonable to expect larger values of $X_{\text{CO}}$ for increasing $R$.

For this purpose, we exploit the numerical packages **DRAGON** [19, 20] and **GammaSky** (a dedicated code recently used in [21–23] to simulate diffuse $\gamma$-ray maps). As a starting point, we consider the Kraichnan diffusion model defined in ref. [25] (labeled KRA therein). As a first step, we modify $\delta$ introducing a functional dependence on $R$; as simplest and a posteriori sufficient guess, we consider $\delta(R) = AR + B$ with local normalization $\delta(R_C) = 0.5$, and − to avoid unrealistically large values − saturate it to $\delta(R > 11 \text{ kpc}) = \delta(R = 11 \text{ kpc})$. The free parameter $A$ is fixed by fitting the $\gamma$-ray data in the energy range $E_\gamma = [5 - 50]$ GeV; to this purpose, we divide the Galactic disk $|b| < 5^\circ$, $|l| < 80^\circ$ in eight longitudinal windows of 10 degrees each. The energy spectra we obtain from this procedure correctly reproduce the measured slope in all the analyzed sky windows but overshoot the data at low energies, in particular for small values of $l$. To tame this problem, in the inner region with $R < R_w$, we allow for a strong convective wind with uniform gradient in the $z$-direction. We extract $R_w$ and the intensity of the convective gradient by fitting the low-energy data with $E_\gamma < 1$ GeV. Concerning the molecular hydrogen, we assume − in units of $10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ − $X_{\text{CO}} = 1.9$ at $R < 7.5$ kpc, and $X_{\text{CO}} = 5$ at $R > 7.5$, in order to correctly match the normalization of the observed flux for $|l| > 50^\circ$. The last step of our method consists in verifying a posteriori that the corrections described above do not spoil the local observables (protons, helium, B/C, antiprotons, and leptons). In particular, we find that a small tuning in the value of the normalization of the diffusion coefficient $D_0$ and in the source spectral index $\gamma$ are needed. All in all, we report the following best-fit values for the parameters described above: $A = 0.035$ kpc$^{-1}$, $R_w = 6.5$ kpc, $dV/dz = 100$ km s$^{-1}$kpc$^{-1}$, $D_0 = 2.24 \times 10^{28}$ cm$^2$s$^{-1}$,

| $\chi^2$ values (25 data points) | 0° < |l| < 80° | 0° < |l| < 10° | 20° < |l| < 30° | 50° < |l| < 60° | 0° < |l| < 180° |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|
| $\chi^2$ KRA$_\gamma$          | 11.30          | 3.79           | 12.27          | 11.50          | 6.94           |
| $\chi^2$ FB model              | 53.00          | 74.83          | 70.04          | 24.85          | 17.60          |

**TABLE II.** Results of the $\chi^2$ analysis for the fit of the Fermi-LAT $\gamma$-ray data.

![3. The same as in fig. 3 but considering the window |l| < 10°, |b| < 5°.](image-url)
FIG. 4. The same as in fig. 1 but considering the strip $|l|<180^\circ$, $10^\circ < |b| < 20^\circ$. The azure band represents the contribution of the Fermi bubbles according to ref. [24].

\[ \gamma = 2.35. \] We label this model KRA$\gamma$.

Results. We show in fig. 1, 3, and 4 the $\gamma$-ray spectra for our KRA$\gamma$ model in three relevant sky windows: the Galactic disk, a small window focused on the Galactic center, and the mid-latitude strip with $|l|<180^\circ$, $10^\circ < |b| < 20^\circ$. In fig. 5 we show the longitudinal profile. In table I we list the $\chi^2$ for our optimized model, showing a remarkable improvement with respect to the FB model.

There are in principle alternative scenarios leading to tilted $\gamma$-ray fluxes, see e.g. [1, 26, 27]. However: 1) Following ref. [28], we find that a population of unresolved pulsars, consistent with the observed counterpart, gives an insufficient extra contribution to the total $\gamma$-ray flux. 2) Running a dedicated MC code, we find that fluctuations in the proton spectrum due to the stochasticity of the sources never exceed, even in the inner Galactic region, the few percent level. 3) We test the possibility of an enhanced IC emission; we find that a rescaling of the ISRF by one order of magnitude, together with a factor of 10 decrease in the $X_{CO}$, may solve the discrepancy. However, we discard this hypothesis since in this case the bulk of the $\gamma$-ray flux would have leptonic origin, in contrast with the observed correlation with the gas distribution as shown in fig. 5. We refer to a companion paper (in preparation) for a more detailed discussion.

Conclusions. We addressed the problem of modelling the $\gamma$-ray emissivity in the Galaxy from a new perspective. The aim was learning how the properties of CR diffusion change through the Galaxy. Our strategy consisted in developing a CR propagation model relaxing the assumption of homogeneous diffusion: we allowed $\delta$ to vary with the Galactocentric radius $R$. The main motivation is the discrepancy between the observed and predicted $\gamma$-ray slope: in particular, the models discussed in [1] underestimate the high-energy data in the Galactic plane region. Being the $\pi^0$ emission dominant at low latitudes, the $\gamma$-ray spectral index is determined by the proton spectrum; since the latter is well constrained by recent data, we assumed this tension to be a hint of a different diffusion regime taking place in the inner region of the Galaxy. We adopted a minimal set of assumptions (linear variation of $\delta$, high convective regime for small $R$) and we found that our model reproduces the $\gamma$-ray data in many relevant windows of the sky within the systematic uncertainty. We achieved this result without relying on ad hoc tunings of astrophysical ingredients such as the gas distribution, the $X_{CO}$ conversion factor, the source distribution or the interstellar radiation field, and keeping a good agreement with locally measured CR spectra. Remarkably, in the Galactic center window our residuals do not exceed the 10% level (see fig. 3), which is comparable with the alleged Dark Matter signal reported in [29-31]. A more detailed analysis with focus on this region will be presented in a forthcoming work.

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