An alternative solution to the $\gamma$-ray Gradient problem

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The Fermi-LAT collaboration recently confirmed EGRET finding of a discrepancy between the observed longitudinal profile of $\gamma$-ray diffuse emission from the Galaxy and that computed with GALPROP assuming that cosmic rays are produced by Galactic supernova remnants. The accurate Fermi-LAT measurements make this anomaly hardly explainable in terms of conventional diffusion schemes. Here we use DRAGON numerical diffusion code to implement a physically motivated scenario in which the diffusion coefficient is spatially correlated to the source density. We show that under those conditions we are able to reproduce the observed flat emissivity profile in the outer Galaxy with no need to change the source term, the diffusion halo height, or the CO-H$_2$ conversion factor (X$_{CO}$) with respect to their preferred values/distributions. We also show that our models are compatible with gamma-ray longitudinal profiles measured by Fermi-LAT, and still provide a satisfactory fit of all observed secondary-to-primary ratios, such as B/C and antiprotons/protons.

1. Introduction

It has been known since the EGRET era that, if one computes the cosmic ray (CR) Galactocentric radial distribution adopting a source function deduced from pulsar or supernova remnant (SNR) catalogues, the result appears much steeper than the profile inferred from the $\gamma$-ray diffuse emission along the Galactic plane: the latter appears flatter, with a high contribution from large Galactic radii. This discrepancy is known as the $\gamma$-ray gradient problem. A sharp rise of the conversion factor between CO emissivity and H$_2$ density (the so called X$_{CO}$) with the Galactocentric radius was invoked at the time to fix the problem [Strong et al. 2004], a larger gas density at large radii compensates for the decreasing CR population and is able to explain the $\gamma$-ray flux detected at high Galactic longitudes.

Fermi-LAT confirmed the existence of such a problem [Ackermann et al. 2011]. Moreover, the high spatial resolution of the LAT permitted to disentangle the emission coming from the interaction of CRs with the molecular gas (whose modelling is strongly affected by the uncertainty on the X$_{CO}$) from the emission originated by the interaction of the Galactic CRs with the atomic gas (whose density is better known from its 21 cm radio emission). An analysis based on $\gamma$-ray maps of the third Galactic quadrant [Ackermann et al. 2011] pointed out that the $\gamma$-ray emissivity from neutral gas (tracing the actual CR density) is indeed flatter than the predicted one confirming the gradient problem independently of the X$_{CO}$. This result led the authors of [Ackermann et al. 2011] to look for alternative explanations of the problem, e.g. invoking a thick CR diffusion halo or a source term that becomes flatter at large radii. Both solutions, however, do not appear completely satisfactory: a thick halo is disfavoured both from $^{10}$Be/$^{9}$Be and synchrotron data; a smooth source distribution is in contrast with SNR catalogues.

Here we consider a different interpretation based on relaxing the approximation of isotropic and spatially uniform diffusion.

2. Inhomogeneous and anisotropic diffusion

Nearly all CR diffusion models presented in the literature adopt an isotropic and spatially uniform diffusion coefficient throughout all the Galaxy. This is the case, for example, of GALPROP numerical package on which the predictions of [Ackermann et al. 2011] are based. It is reasonable, however, to expect that CR diffusion is not isotropic in the Galaxy. This could be the consequence either of Galactic winds [Gebauer and de Boer 2009] or just of the anisotropy of the regular component of the Galactic magnetic field which is oriented almost azimuthally along the Galactic plane. The former possibility was suggested as a possible solution of the $\gamma$-ray gradient problem originated by EGRET observations [Breitschwerdt et al. 2002]. Here we consider the latter option and extend also to the recent Fermi-LAT data the arguments we developed in [Evoli et al. 2008] to interpret earlier EGRET measurements.
Our approach is based on the consideration that, for geometrical reasons, CRs should escape from the Galaxy almost perpendicularly to the Galactic plane: their density, therefore, should be determined by the perpendicular component of the diffusion coefficient $D_{\perp}$. We know – both from quasi linear diffusion theory and from more realistic numerical simulations [DeMarco et al. 2007] – that $D_{\perp}$ should increase with increasing strength of the Galactic magnetic field turbulent component; from a physical point of view, such behaviour can be understood in terms of magnetic field line random walk becoming stronger when the turbulence strength increases. As a consequence, the regions where CR injection is more intense should also be those characterized by a stronger MHD turbulence and hence a faster CR escape along the $z$ axis: this should smooth the CR gradient, and hence the $\gamma$-ray profile, in a rather natural way.

In the next section we will show this effect by means of dedicated numerical computations.

### 3. Our method and results

Figure 1: Two different CR proton distribution maps in arbitrary units computed with DRAGON at 10 GeV are shown as functions of the Galactic cylindrical coordinates $R$ and $z$.

- **Panel a)** The proton distribution is computed with no radial dependence of diffusion coefficient.
- **Panel b)** Here the diffusion coefficient is correlated to the source term: $D \propto Q^\tau$, with $\tau = 0.8$. The model shows a significant flattening in the CR profile along $R$. The normalization is fixed at $R_{Sun} = 8.5$ kpc in both cases; notice how the maximum proton density is reduced by a factor $\approx 2$ in the second panel.

Figure 2: Two gamma-ray longitudinal profiles along the Galactic plane computed with DRAGON and GammaSky and compared to preliminary Fermi-LAT data extracted from the talk by A.W.Strong at the Workshop on Indirect Dark Matter Searches, DESY, Hamburg, June 2011 (http://www.mpe.mpg.de/~aws/talks/). Data are integrated over the latitude interval $-5^\circ < b < +5^\circ$ and in energy between 1104 and 1442 MeV. Red line: IC. Green line: Bremsstrahlung. Blue line: $\pi^0$ decay. Purple line: contribution from unresolved sources. Grey line: $\pi^0 +$ IC + Bremsstrahlung. Black line: total. **Panel a)** The profile is computed with no radial dependence of diffusion coefficient. **Panel b)** Here the diffusion coefficient follows the source term: $D \propto Q^\tau$, with $\tau = 0.8$.

In this section we use DRAGON numerical diffusion package\(^1\) to solve the diffusion equation in the presence of a diffusion coefficient spatially correlated to the CR source term $Q(r, z)$. We perform our analysis using a Plain Diffusion (PD) setup with no convection and no reacceleration in order to better highlight the effects of inhomogeneous diffusion; similar results may be obtained with different choices of the diffusion parameters, and a more detailed study on the effects of another setup will be performed in a forthcoming paper. The CR propagation model adopted here is basically the same as the PD model described in [Di Bernardo et al. 2011]; the astrophysical parameters (in particular the source term, gas distribution and $X_{CO}$) are also the same used in that analysis. Only the normalization of the proton injection spec-

\(^1\)The DRAGON code for cosmic-ray transport and diffuse emission production is available online at http://www.desy.de/~maccione/DRAGON/
The emissivity is the number of $\gamma$ photons emitted by each gas atom per unit time and unit energy.
to the source density: regions in which star, hence SNR, formation is stronger are expected to present a stronger turbulence level and therefore a larger value of the perpendicular diffusion coefficient. This effect favours CR escape from most active regions helping to smooth their density through the Galaxy hence also the γ-ray gradient. We used DRAGON package to implement this scenario and to check that CR data are still reproduced under those conditions. In spite of being purely phenomenological (as a self-consistent theory/computation of non-linear CR - MHD turbulence interaction in the Galaxy is far from being developed) our approach provides a remarkably good description of the spectrum and longitude distribution of the diffuse γ-ray emission measured by the Fermi-LAT collaboration.

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