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Memorie della

Galactic gamma-ray diffuse emission

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Abstract. The Galactic γ-ray diffuse emission is currently observed in the GeV-TeV energy range with unprecedented accuracy by the Fermi satellite. Understanding this component is crucial as it provides a background to many different signals, such as extragalactic sources or annihilating dark matter. It is timely to reinvestigate how it is calculated and to assess the various uncertainties that are likely to affect the accuracy of the predictions.

Key words. gamma rays: diffuse background – cosmic rays – methods: analytical – gamma rays: ISM

1. Introduction

This work focuses only on the so-called hadronic component of the γ-ray diffuse emission, *i.e.*, the component due to the decays of π^0 particles produced by cosmic rays interacting on interstellar gas. It is well known (Stecker, 1977) that the hadronic component is dominant in the range of interest for the Fermi satellite. Understanding and estimating precisely the Galactic diffuse emission is of utmost importance for many γ-ray studies including extended sources detection, extragalactic component, or dark matter detection.

Of course, the galactic γ-ray diffuse emission has been studied before, the most commonly known model being GALPROP (Strong & Moskalenko, 1998; Strong et al., 2010; Strong, 2011). However a full discussion over the modelling uncertainties due to each ingredients of this emission was still to be done. One of the major interest of the present work and of Delahaye et al. (2011a) is that, thanks to our semi-analytical description of cosmic ray propagation, we were able to generate a full γ-ray sky map in less than a minute with a regular personal computer. This allowed us to fully explore the parameter space. Moreover, we use a model consistent with all other cosmic ray data (secondary to primary ratios, antiprotons and electrons) and we have updated all the various ingredients. The other originality of this work comes from the gas maps (Pohl et al., 2008) we use which take into account the dynamics of the Galaxy and up-to-date observational data.

In what follows, we will detail the main ingredients necessary to estimate this diffuse emission focusing on those which give the largest uncertainties. Then we will address

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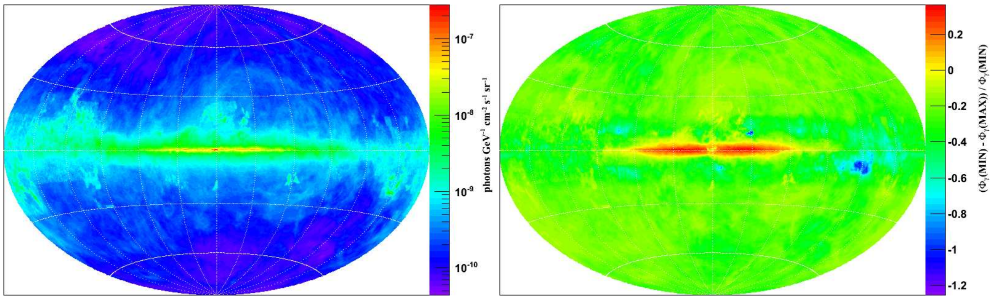

Fig. 1. ***Left panel***: Our reference map of the diffuse γ-ray emission of the Milky Way at 30 GeV obtained according to the method outlined in Delahaye et al. (2011a). The dominant hadronic component alone is considered. The cosmic ray proton and helium fluxes at the Earth's position are taken from Shikaze et al. (2007). These fluxes were *retropropagated* throughout the DH with the MED model of Donato et al. (2001). The distribution of primary CR sources in the Galactic disk was borrowed from Lorimer (2004). The differential photon production cross sections of CR protons and helium nuclei impinging on the ISM were parametrized according to Huang et al. (2007). This map is based on the HI and CO 3D Galactic distribution of Pohl et al. (2008). The X_{CO} factor was set equal to 2.3×10^{20} molecules cm^{-2} (K.km.s^{-1})$^{-1}$ everywhere in the Galaxy. ***Right panel***: This sky map features the differences between the MIN and MAX models relative to the MIN model. For each pixel we plotted the ratio (map1 − map2)/map1 where map1 (map2) has been derived exactly like the γ-ray reference map of the left panel with the sole difference of using the MIN (MAX) propagation parameters instead of the MED model.

more precisely the issue of the local γ-ray emissivity from pionic origin in the light of Fermi results (Abdo et al., 2009).

2. Ingredients and sources of uncertainties

When dealing with γ-rays, one needs to describe the whole interstellar medium. As we are here interested in the hadronic emission only, we can put aside the leptonic cosmic rays, the Galactic magnetic fields and the interstellar radiation field that we would need to describe the Bremsstrahlung and the inverse Compton components. Even though, the number of ingredients we need to model is quite important.

First, one needs to know the cosmic ray fluxes everywhere in the Galaxy, which requires:

- Cosmic ray source distribution
- Propagation model
- Cosmic ray fluxes measured at the Earth,

then a gas distribution model which requires:

- 3-D maps of HII, HI and CO
- X_{CO} conversion factor and its variation in the Galaxy
- Metallicity

and finally the γ-ray production cross sections.

Each of these ingredients has been updated and described in details in Delahaye et al. (2011a). We will focus here on those that cause the largest uncertainties, namely propagation parameters, gas maps and source distribution.

As one can see from the right panel of Fig. 1, varying the propagation parameters, within the limits set by secondary to primary cosmic ray ratios (Maurin et al., 2001; Putze et al., 2010), leads to variations of the estimated γ-ray flux up to +40% in the region of the Galactic center and -120% in the direction of far away, off-plane, molecular clouds. These uncertainties affect the intensity but also the morphology of the emission. In particular, the latter strongly depends on the size L of the cosmic ray diffusion halo whenever the line of sight crosses molecular clouds located far apart ($\sim$ 800 pc) from the Galactic plane. As shown in the left panel of Fig. 2, the cosmic ray density inside these clouds is quite sensitive to L. Hence the morphology of the γ-ray diffuse emission could provide valuable informations on that parameter.

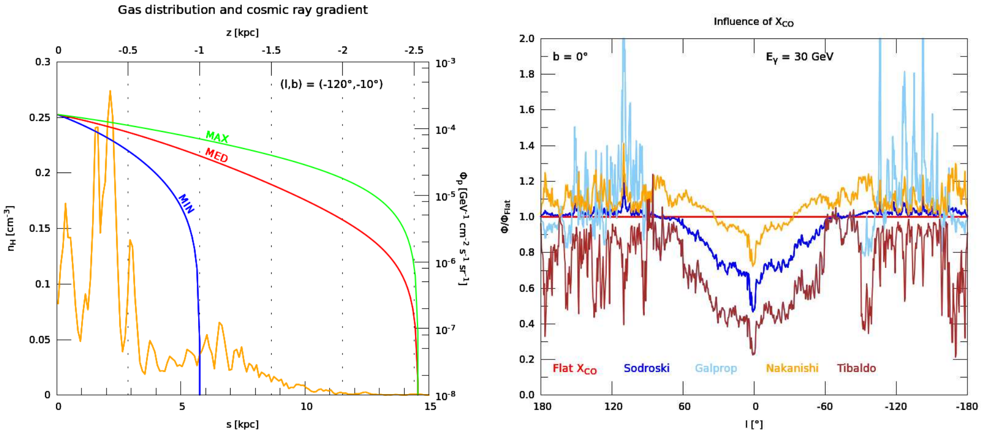

Fig. 2. ***Left panel***: The gas density (orange with units on the left y-axis) and the CR proton flux $\Phi_p(\mathbf{x})$ (units on the right y-axis) are plotted along the line of sight in the direction specified by the Galactic longitude and latitude $(l, b) = (-120°, -10°)$, which corresponds to the blue spot of the right panel of Fig. 1. The three models of Donato et al. (2001) have been considered for the calculation of the proton flux. They lead to the blue (MIN), red (MED) and green (MAX) curves. As an illustration, the CR proton total energy $E_p = m_p + T$ has been set equal to 30 GeV. The relative distribution of primary nuclei along the line of sight is not expected to change much with energy. ***Right panel***: The variations in the γ-ray flux at 30 GeV and $b = 0°$ are displayed relative to our reference model of Fig. 1 for which the constant value of 2.3×10^{20} molecules cm^{-2} (K.km.s^{-1})$^{-1}$ has been assumed for $X_{\rm CO}$. Each coloured line corresponds to a X_{CO} model available in the literature with references detailed in Delahaye et al. (2011a). The three (cyan) peaks, whose maxima have not been displayed for clarity, reach a value of 3.0, 2.3, and 2.3 respectively from left to right.

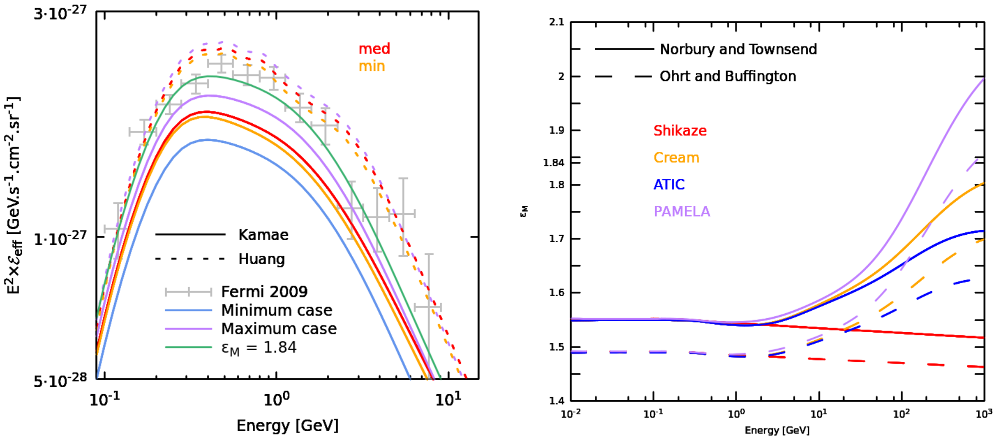

Fig. 3. ***Left panel***: Local γ-ray emissivity as measured by the Fermi experiment (grey points) and compared with various models. Dashed lines were obtained using the cross-sections of Huang et al. (2007) while the full ones correspond to the results by Kamae et al. (2006). The effect of propagation is shown thanks to the red and yellow curves (MED and MIN propagation parameters sets respectively). In the case of the cross section from Kamae et al. (2006) we have also displayed the highest and lowest emissivity we were able to get, varying all the other parameters. Finally, in green, is shown what one gets by using the nuclear enhancement factor ϵ_M set to be 1.84 as suggested by the Fermi collaboration. ***Right panel***: Nuclear enhancement factor ϵ_M as a function of energy for various cosmic ray fluxes at the Earth. As one can see, this coefficient is a function of the energy and should be considered as a constant parameter.

Another large source of uncertainty is the interstellar gas distribution. In this work, we have made use of the maps derived by Pohl et al. (2008) which rely on up-to-date observations and hydrodynamical simulation of the Galaxy which take into account its spiral structure. Replacing these maps by those used in GALPROP generates a 50% variation in the γ-ray flux and also impacts its morphology. Moreover, variations in the Galactic radial profile of the X_{CO} factor lead to uncertainties as large as 300% in the Milky Way plane, as featured in the right panel of Fig. 2.

Finally, the spatial distribution of cosmic ray sources has a non negligible impact on the morphology of the diffuse emission, mainly in the Galactic plane.

3. Local emissivity

Up to now, we have focused mainly on the morphology of the γ-ray diffuse emission, but its energy spectrum is very interesting too. Very recently, the Fermi collaboration published a measurement of the *local* γ-ray emissivity (Abdo et al., 2009). In spite of the difficulty to extract the local emissivity from its line-of-sight average, the Fermi collaboration succeeded in this task by selecting specific regions of the sky containing mostly nearby clouds.

The emissivity measured by Fermi may not be a priori as local as claimed. As shown by Delahaye et al. (2011b), it is actually mildly affected by cosmic ray propagation and gas metallicity. One can indeed see from the left panel of Fig. 3 that the uncertainties affecting the local emissivity are quite important and the data accuracy does not allow to lift them yet. The Fermi measurement, once extended at higher energies, could provide valuable informations on the cross section of the $p_{CR} + H_{ISM} \Rightarrow \pi^0$ process as well as on those implying heavier elements like helium. In that respect, we claim that the nuclear enhancement factor ϵ_M, for which Fermi derives a value of 1.84, is no longer a relevant quantity as it depends on the photon energy as shown in the right panel of Fig. 3

4. Conclusions

The modelling of the γ-ray diffuse emission suffers from uncertainties that are not easy to lift and forthcoming public study from the Fermi collaboration will be of great interest.

It is true that the model used in this study is quite simplistic (homogeneous propagation parameters) but gives surprisingly accurate results for all cosmic-ray species hence before trying to refine the model it is interesting to reduce its uncertainties as γ-ray study may allow. But also to exploit it as much as possible.

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