PROCEEDINGS OF SCIENCE

Cosmic rays and the diffuse gamma-ray emission

Fiorenza Donato[*†]
Dipartimento di Fisica, Torino University and INFN Sezione di Torino
via P. Giuria 1, 10125 Torino, Italy E-mail: donato@to.infn.it

The diffuse γ-ray emission originated in the Galaxy is the main contributor to the photons observed by the *Fermi*-Large Area Telescope. It is a foreground or a background for the determination and the understanding of point sources and of diffuse processes. The diffuse galactic γ-ray emission is produced by the interactions of cosmic ray nuclei on the interstellar gas and of electrons on the interstellar radiation field. We discuss the impact that the charged cosmic rays (CRs) have on the determination of the gamma-ray diffuse galactic emission. We review the implications deriving from present data and outline some future prospects for data and models.

7th Fermi Symposium 2017
15-20 October 2017
Garmisch-Partenkirchen, Germany

[*]Speaker.

[†]The author warmly thanks the Organizers for the invitation to deliver the talk summarized in this paper. The Symposium has been an outstanding scientific experience, in a very warm and collaborative environment. We will never forget the first day, blessed by the exciting announcement of the observation of the first event of gravitational waves associated to an amazing plethora of electromagnetic counterparts.

1. Introduction

A large contribution to the knowledge and understanding of the Galaxy is given by the observation of the most energetic particles, the cosmic rays (CRs). These relativistic particles, reaching the Earth from the outer space, are either primary nuclei, arriving directly from their sources, or secondary products of the spallation processes (i.e. fragmentation by nuclear destruction) taking place during the propagation from the sources through the interstellar medium (ISM). They include nuclei from hydrogen to very high atomic number, usually in different isotopic compositions, in addition to electrons and antimatter (positrons and antiprotons measured up to now). The last years have seen a remarkable progress in the data collected by ballon or satellite borne experiments. In particular, Pamela and AMS-02 have marked a breakthrough in the understanding of primary fluxes such as proton and helium, the ration boron-to-carbon (B/C) and the cosmic antimatter component, specifically positrons and antiprotons.

The other component is the electromagnetic one, and notably the γ-rays, which is measured with unprecedented precision by the *Fermi* Large Area Telescope (LAT) from 100 MeV up to TeV energies. At the LAT energies the γ-ray sky is dominated by the diffuse emission of the Milky Way [1]. This emission pervades the Galaxy becoming more and more relevant towards the galactic plane. At all latitudes it is a background or a foreground for the detection of point sources or the identification of other diffuse components.

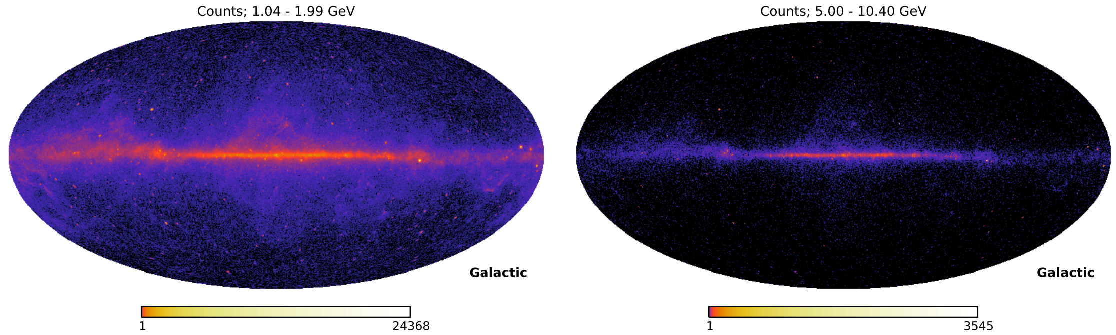

Figure 1: The γ-ray sky as measured by the *Fermi*-LAT in its first eight years of operation. The left (right) panel refers to the energy ranges of 1-1.99 (5-10.4) GeV.

In Fig. 1 we plot the γ-ray sky as measured by the *Fermi*-LAT in its first eight years of operation, for the two energy bins of [1-1.99] GeV and [5-10.4] GeV. The sky is composed of diffuse components and point sources, and the number of photons measured in each pixel decreases with increasing latitude. The Galactic diffuse emission, which will be discussed int he next Section, dominates the sky at latitudes.

2. The γ-ray diffuse emission

Gamma rays originating from the interaction of CRs with interstellar gas and interstellar radiation fields (ISRFs) in our Galaxy are the main contributors to the photons observed by the LAT above 100 MeV, and constitute the diffuse Galactic emission (DGE). The DGE contributes five times more photons than point sources at energies above 50 MeV. Half of the Galactic diffuse photons are produced in the inner 6° across the Galactic plane [1].

Modeling the DGE is a complex task, whose results come equipped with high systematic uncertainties. The morphological structure and the spectrum of the Galactic emission are due to a sum of different contributions, driven by a variety of different physical parameters. The interaction of CRs with the interstellar H_I and H_2 gas is responsible for the production of γ rays through non-thermal bremsstrahlung and π^0 production and their subsequent decay, while the interaction of Galactic electrons with the ISRFs produces γ rays through inverse Compton (IC) scattering. To properly compute these contributions, models for CR sources, energy spectra for injection in the ISM, and diffusion in our Galaxy, as well as good knowledge of the interstellar gas distribution and the structure of radiation fields are required. The computation of the different components is additionally hampered, for instance, by the presence of large-scale structures correlated to Galactic Loop I or the *Fermi* Bubbles, or by well-known degeneracies among CR propagation parameters.

Shortly, the emission of γ-rays is predicted from the following classes of sources:

- the Galactic gas (H_I, H_2, dark neutral gas)
- the Galactic Inverse Compton (IC) photon population
- an isotropic (mostly extragalactic) background
- point sources
- extended sources (included Fermi Bubbles and Loop I)
- the Sun and the Moon
- the residual Earth Limb (negligible for E> 200 MeV)

Models for the γ-ray emission have been built by the *Fermi*-LAT Collaboration based on the *template* method, which employs the spatial correlation between γ-ray data and a combination of IC ad gas maps [1]. The intensity associated with each template is determined from a fit to γ-ray data. For a given map pixel and energy bin, the number of photons is computed for all the components listed above [1] (see their Eq. 2). The models contain a number of free parameters - namely the emissivity for the different gas components, the normalizations for the IC map, for the isotropic background, the limb and for the extended sources, as well as the number of photons emitted from each point source. These parameters are fitted to the *Fermi*-LAT γ-ray data at various galactocentric distances, and lead to the determination of the GDE. As well as the detailed knowledge of the gas maps for the hadronic γ-ray emission, it is crucial the determination of the ISRFs. Very recently, [2] have presented a new model for the ISRFs of the Milky Way, derived from modelling COBE, IRAS and Planck maps of the all-sky emission in their relevant bands. Comparisons with the frequently used model GALPROP (also employed in the *Fermi*-LAT model [1]) show that the radiation fields calculated by GALPROP systematically differ from those predicted by [2].

3. The charged cosmic ray galactic component

The model discussed in [1] relies on the emissivity, a quantity that effectively includes the information on the CRs and their cross sections on the ISM atoms. The γ-ray emissivity is fitted to the data once templates are provided for the gas distribution. Indeed, a procedure inspired to more fundamental principles would rely on the determination of the CR fluxes in every point of the Galaxy. The nuclear CR component should then be convolved with the inelastic cross sections (into π^0 or for bremsstrahlung) off the gas elements and the ISRF. Indeed, a thorough determination of the CR spectra in the whole Galaxy is a very challenging task. Charged particles are bent in the galactic magnetic fields, so there is no obvious way of tracking them back to their sources. The energy spectrum which is observed at Earth is folded with the source one through an energy dependent diffusion coefficient which shapes the effects of the galactic magnetic field in an effective way, and which can be deduced only phenomenologically, and from data taken at the Earth. These peculiarities are at variance with γ rays, which point directly to the sources.
The most realistic CR propagation models are the diffusion ones, which account for spatial dependence of sources, CR densities and ISM density distribution. The Galaxy is usually shaped as a thin gaseous disk where all the astrophysical sources are located, embedded in a thick diffusive magnetic halo. Diffusive models, besides being more realistic and closer to a physical interpretation for each component, have proven to be successful in reproducing the nuclear, antiproton and radioactive isotopes data. They also allow to treat contributions from dark matter (or other exotic) sources located in the diffusive halo.
The relevant transport equation for a charged particle wandering through the magnetic inhomogeneities of the galactic magnetic field writes in terms of the differential density $N(E,\vec{r})$ as a function of the total energy E and the position $\vec{r}$ in the Galaxy. Assuming steady-state ($\partial N/\partial t = 0$), the transport equation for a given nucleus can be written in a compact form as

$$(-\vec{\nabla}\cdot(K\vec{\nabla}) + \vec{\nabla}\cdot\vec{V}_C + \Gamma_{\rm rad} + \Gamma_{\rm inel})N + \frac{\partial}{\partial E}\left(bN - c\frac{\partial N}{\partial E}\right) = \mathscr{S} \ . \tag{3.1}$$

The first bracket in the l.h.s. accounts for: i) spatial diffusion $K(\vec{r},E)$, ii) convection with speed $\vec{V}_C(\vec{r})$, iii) the (possible, for some isotopes with half lifetime τ_0) radioactive decay rate $\Gamma_{\rm rad}(E) = 1/(\gamma\tau_0)$ (γ here is the Lorentz factor), iv) the destruction rate $\Gamma_{inel}(\vec{r},E) = \sum_{ISM} n_{\rm ISM}(\vec{r}) v \sigma_{\rm inel}(E)$ due to collisions with the ISM. In this last expression $n_{\rm ISM}(\vec{r})$ is the density of the ISM in the various locations of the Galaxy and in its different H and He components, and $\sigma_{\rm inel}(E)$ is the destruction (inelastic) cross section for a given nucleus. The coefficients b and c are respectively first and second order gains/losses in energy. The source term $\mathscr{S}$ includes primary sources of CRs (e.g. supernovae), secondary sources due to the fragmentation of heavier nuclei, and secondary decay-induced sources. The quasi-linear theory leads to a rigidity power law for the diffusion coefficient, which is usually assumed to have the form:

$$K(E) = K_0 \beta^\eta R^\delta \tag{3.2}$$

(β is the Lorentz factor). K_0 is linked to the level of the hydromagnetic turbulence and δ to the density spectrum of these irregularities at different wavelength. η is usually set to 1, while a different value parameterizes very low energy deviations. The lack of information on the magnetic field irregularities prevents us from a precise determination of the diffusion coefficient, which is instead possible only from interpretation of CR data. The most important observable at these regards is the ratio B/C of the boron to carbon fluxes. It is considered a kind of standard candle in the CR phenomenology, being the ratio of an almost secondary species to an almost primary one. Semi-analytical models are treated *e.g.* in [3]. Fully numerical solution is the one adopted by the GALPROP code [4] (and references therein). Comparable results for the propagation of stable primary and secondary nuclei have been obtained in [5]. Recently, the PICARD code has been presented as well in [6]. For a full treatment of galactic CRs physics we refer to [7].

In addition to propagation uncertainties, the secondary fluxes, produced by the spallation of CR protons and helium nuclei on the ISM, are affected by nuclear uncertainties. Now, one of the best measured secondary spectrum is the antiproton one. The prediction of this flux is determined with an uncertainty coming from propagation and comparable to the B/C one, and another uncertainty due to the production cross sections. The reactions at stake require the $pp, pHe, Hep, HeHe$ inclusive cross sections into $\bar{p}$+X. The only reaction measured with a good coverage of the phase space is the pp one [8].

We have recently determined the characteristics that a high energy experiment should have in order to measure the $pp \to \bar{p} + X$ cross section, and similarly the other ones, with an accuracy so good not to exceed the errors on the AMS-02 antiproton data [9]. In Fig. 2 we give our results as functions of the kinematical variables in both the LAB and CM reference frames. It shows the parameter space that has to be covered in order to guarantee the AMS-02 precision level on the $\bar{p}$ source term, if the $p + p \to \bar{p} + X$ cross section is determined with 3% uncertainty within the blue shaded regions and by 30% outside the contours. The plot is done for the LAB (left panel, a) and CM (right panel, b) reference frame variables. For the LAB frame we show the contours as functions of η and T, for selected values of $T_{\bar{p}}$ from 1.1 (the lowest energy) below 30% uncertainty in the CR $\bar{p}$ flux to 300 GeV. As expected the contour size decreases when $T_{\bar{p}}$ approaches to 1 GeV, because there the AMS-02 uncertainty on the antiproton flux reaches 30%. A similar explanation holds for large $T_{\bar{p}}$. Antiprotons of increasing energy require the coverage of increasing η values. For example, the $\sigma_{\rm inv}(p + p \to \bar{p} + X)$ at $T_{\bar{p}}$=2 GeV is known at 3% level if data were taken with proton beams between 10 and 200 GeV and pseudorapidity from 1.8 to 4. If the whole AMS-02 energy range had to be covered with high precision, one should collect $p + p \to \bar{p} + X$ cross section data with proton beams from 10 GeV to 6 TeV, and η increasing from 2 to nearly 8. We address to [9] for all the details.

In addition to the antiproton one, an extensive laboratory campaign aimed at measuring the missing production and destruction cross sections is envisaged for a huge number of nuclei, isotopes, antinuclei and positrons, in the perspective of a reliable interpretation of the direct measurements of galactic CRs. A precise determination of the various CR spectra contribute to test and finally to shape a Galaxy model which is fundamental to the prediction of the γ-ray DGE. A thorough analysis can be found in [**?**], where the γ-ray production cross sections and several other ones are derived with the Fluka Monte Carlo Code.

4. Gamma-rays and charged cosmic rays consistency

The γ-ray emission rate per hydrogen atom or emissivity provides a unique indirect probe of

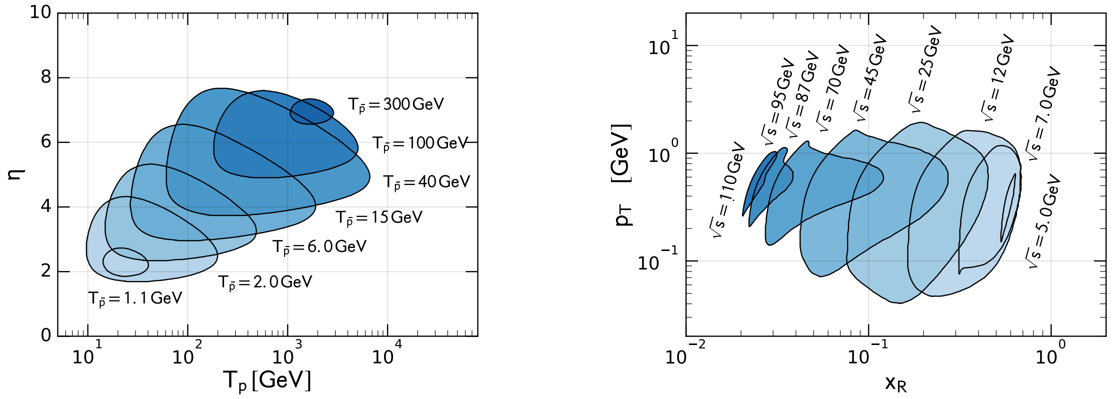

Figure 2: Parameter space of the pp to $\bar{p}$ cross section necessary to determine the antiproton source term with the accuracy reached by recent AMS-02 measurements. Here we require that the cross section has to be known by 3% within the blue shaded regions and by 30% outside the contours. The left (right) panel displays the result for the LAB (CM) reference frame variables.

the CR fluxes which are the sources of the photons produced by the scatterings off the nuclei of the ISM and off the ISRFs. A way to probe the correctness of the γ-ray emissivity obtained from *Fermi*-LAT data is to derive the local CR fluxes and compare it directly with data. This procedure has been performed in [11] on a subset of 4 years of *Fermi*-LAT data restricted to absolute latitudes $10^\circ < |b| < 70^\circ$. The γ-ray data has been fitted including atomic, molecular, and ionized hydrogen column density templates, as well as a dust optical depth map. The extracted emissivities have been compared to those calculated from the γ-ray production cross sections and CR spectra - mainly p, He and e^- - measured at the Earth. The result for the p and He CR fluxes is shown in Fig. 3 along with the Pamela and AMS-02 data. It is clear from this figure that the consistency with the CR fluxes is good unless, as expected, for the lowest energy part of the spectrum affected by solar modulation. As noted in [11], the accuracy of γ-ray production cross sections was a significant limitation in deriving the CR spectra from the emissivities (see also the previous Section of this paper).

5. Conclusions

The diffuse γ-ray emission originated in our Galaxy contributes most of the photons observed by the *Fermi*-LAT. Its prediction is clou to any precise understanding of the *Fermi*-LAT data, concerning both point sources and diffuse contributions. In particular, it is one of the main systematic uncertainties when extracting possible signals (or fixing upper limits) for dark matter annihilating into γ-ray photons in the halo of the Galaxy [12] (and referencies therein).

Data on CRs - leptons, light nuclei and antiprotons - have been collected with very high precision and extended energy range, first by Pamela and now by AMS-02. They are requiring a step forward in the phenomenological models of transport of charged particles, as well as in the distribution of sources in the Galaxy. Also, new measurements about a number of cross sections are necessary for a better understanding of the secondary nuclei and the γ rays of hadronic origin.

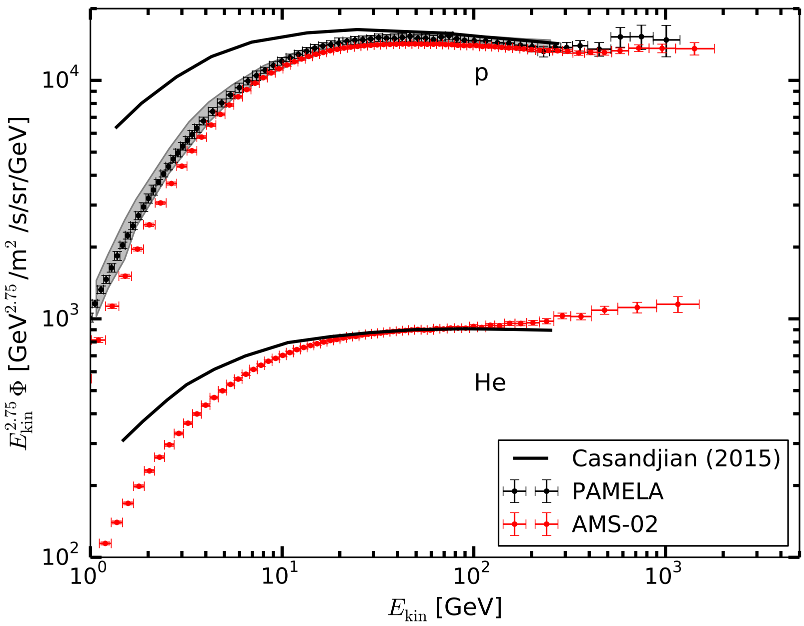

Figure 3: The proton and helium CR fluxes as derived in [11] (solid lines) along with the data from Pamela and AMS-02.

Together with more precise gas maps, all these ingredients contribute to photons of the galactic diffuse emission.

We believe that one major step forward in the exploitation of the invaluable *Fermi*-LAT data reservoir is a better understanding and shaping of the galactic diffuse emission.

References

[1] Acero, F. et al., the Fermi Collaboration, *Development of the model of galactic interstellar emission for standard point-source analysis of Fermi Large Area Telescope data ApJSS* **223** (2016) 26.

[2] Popescu, C. C. et al., *A radiation transfer model for the Milky-Way: I. Radiation fields and application to High Energy Astrophysics MNRAS* **470** (2017) 2538.

[3] Maurin, D., Donato, F., Salati, P., Taillet, R., *Cosmic Rays below Z=30 in a diffusion model: new constraints on propagation parameters*, *ApJ* **555** (2001) 585.

[4] Porter, T.A., Jóhannesson and Moskalenko, I.V. *High-energy gamma rays from the milky way: three-dimensional spatial models for the cosmic-ray and radiation field densities in the interstellar medium ApJ* **846** (2017) 67.

[5] Evoli, C. et al., *Cosmic-ray propagation with DRAGON2: I. numerical solver and astrophysical ingredients JCAP* **2** (2017) 015.

[6] Kissmann, R. *PICARD: A novel code for the Galactic Cosmic Ray propagation problem*, *Astropart. Phys.* **55** (2014) 37.

[7] Castellina, A. and Donato, F., *Astrophysics of Galactic charged cosmic rays*, *Planets, Stars and Stellar Systems* **5** (2012) Springer.

[8] Di Mauro, M., F. Donato, A. Goudelis, P.D. Serpico, *New evaluation of the antiproton production cross section for cosmic ray studies Phys. Rev.* **D90** (2014) 085017.

[9] Donato, F., Korsmeier, M. and Di Mauro, M., *Prescriptions on antiproton cross section data for precise theoretical antiproton flux predictions* , *PRD* **96** (2017) 043007.

[10] Casandjian, J.-M., *Local HI emissivity measured with Fermi-LAT and implications for cosmic-ray spectra ApJ* **806** (2015) 240.

[11] Zechlin, H.-S., Manconi, S., Donato, F. *Constraining Galactic dark matter with gamma-ray pixel counts statistics Phys. Rev.* **D** subm. (2017), [arxiv:1710:01506].