Cosmic rays, gamma rays and synchrotron radiation 
from the Galaxy

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Abstract. Galactic cosmic rays (CR), interstellar gamma-ray emission and synchrotron 
radiation are related topics. CR electrons propagate in the Galaxy and interact with 
the interstellar medium, producing inverse-Compton emission measured in gamma rays and 
synchrotron emission measured in radio. I present an overview of the latest results with 
Fermi/LAT on the gamma-ray diffuse emission induced by CR nuclei and electrons. Then I 
focus on the recent complementary studies of the synchrotron emission in the light of the latest 
gamma-ray results. Relevant observables include spectral indices and their variations, using 
surveys over a wide range of radio frequencies. This paper emphasizes the importance of using 
the parallel study of gamma rays and synchrotron radiation in order to constrain the low-energy 
interstellar CR electron spectrum, models of propagation of CRs, and magnetic fields.

1. Introduction
The diffuse Galactic gamma-ray emission is produced by Cosmic rays (CR) particles interacting 
with the interstellar medium (ISM). The major contributors to the emission are neutral pion 
decay from interactions of nuclei with gas, inverse-Compton (IC) and bremsstrahlung radiation 
from CR electron interactions with gas, the interstellar radiation field (ISRF) and the cosmic 
microwaves background. Hence, observations of the diffuse gamma-ray emission is used to 
investigate CR origin and their propagation in the Galaxy, and also to study the ISM. In fact, 
prediction of the diffuse emission requires a good knowledge of the gas and the radiation fields 
as well as the CR spectra throughout the entire Galaxy. Direct measurements of CRs by balloon 
experiments and satellites constrain models of propagation and local CRs. The CR electrons 
and positrons responsible for gamma rays produce also synchrotron radiation by gyrating in 
the Galactic magnetic field (B-field), which is detectable in radio and microwave bands. This 
emission depends not only on CR electron intensity and distribution in the Galaxy, but also 
on the B-field. Hence, observations of total and polarized synchrotron emission can be used to 
constrain both regular and random components of the Galactic B-field. Fortunately, primary 
electron and secondary positrons and electrons sampled in gamma rays bracket those seen in 
radio and microwave band.

The parallel study of radio and gamma-ray emission has been largely studied since the 1980’s, 
e.g. in [1], [2], [3] and [4]. This approach is much more promising than studying these data 
separately, since the CR electrons are traced by both emissions and some degeneracy is removed. 
Moreover, CR electrons can also be constrained by direct observations, but these are affected by 
solar modulation at lower energies. A numerical model of CR propagation and interactions in
Figure 1. Fermi-LAT emissivity gradient for the 2nd (black) and 3rd (red) Galactic quadrants ([13], [16], [17]) compared with predictions by GALPROP (lines): varying the height of the propagation halo from 1 kpc to 20 kpc (left) and fixing the density of CR sources to constant for $R > 10^{-15}$ kpc (right). The solid line is for a halo height of 4 kpc.

...the Galaxy is required in order to exploit all the different data. GALPROP\(^1\)([5], [6], [7], [8], [9]) is an up-to-date code, which uses the latest CR and ISM data as input to predict gamma rays and synchrotron emission. In fact, the GALPROP code is able to describe the diffuse gamma rays detected by EGRET, and COMPTEL and to model the synchrotron emission [4]. It is used in the Fermi-LAT collaboration for interpreting the physics of the Galactic emission and more recently it has been improved to model synchrotron emission and observables such as spectral indices and radio surveys over a wide range of frequencies ([10], [11]).

I present an overview of the latest results with Fermi-LAT on the gamma-ray diffuse emission induced by CR nuclei and electrons. Then I focus on the recent complementary studies of the synchrotron emission in the light of the latest gamma-ray results and CR electron measurements. This paper reviews the recent results achieved on interpreting both emissions using the GALPROP code and underlines the importance of using the parallel study of gamma rays detected by Fermi-LAT and synchrotron radiation for understanding CRs and the ISM.

2. Recent studies

2.1. Diffuse gamma-ray emission

An early result from Fermi-LAT [12] was the observation of the diffuse gamma-ray emission from the Galaxy. This study was carry out at intermediate Galactic latitudes, where the diffuse emission comes mainly from local CR interactions with the ISM, and hence, uncertainties associated with CRs, gas distribution and ISRF are minimized. The Fermi gamma-ray spectrum showed that the so-called ‘GeV excess’ above the expected emission found by EGRET was an instrumental effect. The Fermi spectrum was found to be softer than the one measured by EGRET, with lower intensities for energies $>$1 GeV. The data were consistent with the expected spectrum based on CR spectra as measured locally. In particular, the spectrum was well described by pion decay, IC and bremsstrahlung, plus the contribution from point sources and an isotropic component, which included the extragalactic background. This result was confirmed in [13], where the local HI gamma-ray emissivity was derived for for a mid-latitude region in the 3rd Galactic quadrant and again found to be in good agreement with the expected spectrum based on locally measured CRs, within 10%. The model, obtained with the GALPROP code, included diffusive reacceleration with a 4 kpc halo height and it used the locally-measured CR proton and Helium spectra, and the electron spectrum as measured by Fermi [14] and [15].

\(^1\) http://galprop.stanford.edu
CR sources were assumed to follow supernova remnants as traced by pulsars. Model parameters are described in [9] and references therein. Another important result came with a detailed Fermi-LAT study of the 2nd Galactic quadrant [16], which was then confirmed with a reanalysis of the 3rd quadrant [13]. These studies showed an increase in the H$_2$-to-CO factor with Galactocentric radius and larger intensities in the outer Galaxy with respect to previous models (Fig.1). There are various possible explanations: larger halo size, flatter distribution of CR sources in the outer Galaxy, larger amount of gas or diffusion parameters different from those derived from local CR isotopic abundances used by GALPROP. A preliminary study of other regions of the sky was presented in [19], where the spectrum of the inner Galaxy, longitude and latitude profiles were shown. The model reproduced the Fermi data over the sky within 20%; the inner Galaxy revealed an excess at GeV energies that was plausibly explained by unresolved sources. It was shown that latitude profiles improved with a larger halo height of about 10 kpc, consistent with the previous works mentioned above. IC emission, which traces ISRF and CR electrons, dominates at high latitudes. While the diffuse gamma-ray emission above 100 MeV is traced mostly by CR nuclei, at lower energies IC plays a fundamental role. This contribution is also investigated in [19], where comparison of the expected emission with the INTEGRAL data was carried out for the inner Galaxy$^2$.

2.2. Diffuse synchrotron emission
Recent studies of the Galactic synchrotron emission in the light of the latest Fermi gamma-ray results, CR electron measurements were published in [10] and [11]$^3$. The first result of the analysis [11] was that the local interstellar electron spectrum turns over below a few GeV, with an ambient index around 2. Below a few GeV the local interstellar electron spectrum cannot be directly measured, since CR electrons with energy lower than a few GeV are affected by solar modulation. Hence, synchrotron radiation (from tens of MHz to tens of GHz) was exploited [11] to probe interstellar electrons from 0.5 to 20 GeV for the typical B-field of a few $\mu$G. In fact, they reviewed data which showed that the spectral index of the brightness temperature of the synchrotron emission increases steadily from about 2.5 to 3.0 over the frequency range from tens of MHz to tens of GHz, constraining the local interstellar spectral index to turn over from 2 to 3 at few GeV, independent of propagation models. They noted that the low-energy turnover in the directly measured electrons, normally attributed mainly to solar modulation, may instead reflect the local interstellar spectrum. Then they tested propagation models, generated with GALPROP, based on CR and gamma-ray data, against the synchrotron data [11], in order to constrain the injected CR electron spectrum, before propagation effects. These models were consistent with CR nuclei secondary-to-primary ratios and gamma rays, and only the electron injection spectrum and the B-field were varied. In order to avoid absorption effects at low frequencies, and free-free emission at higher frequencies, the analysis was restricted to regions out of the Galactic plane. Considering a plain diffusion model, with a halo height of 4 kpc, they found that the best fit to synchrotron data was obtained using a low-energy primary electron injection index below 1.6, with the best value 1.3$^4$ as shown in Fig.2. It was noted [11] that secondary leptons, originating via interactions of CR nuclei, produced one third of the observed low-frequency synchrotron intensity. They [11] also found that the standard diffusive reacceleration models used to describe gamma-ray data were not consistent with the observed synchrotron spectrum, since the total intensity from primary and secondary leptons exceeded the measured synchrotron emission at low frequencies. This was due to the secondary leptons,

\footnote{Another recent study on the Fermi Galactic gamma-ray diffuse emission and the Bubbles is [18].}
\footnote{Other recent studies on the Galactic synchrotron emission are [21], [22], [23], [24], [25], [26], which will not be discussed here.}
\footnote{Similar results were obtained in the Galactic plane [20] using the CR electron distribution that fit the gamma rays, but using the Hammurabi code[21]}

$^2$
which have a large peak due to reacceleration making them equal to primary electrons around 1 GeV in such models. Reacceleration models were not excluded in [11], but it showed that they pose a challenge to be addressed in future. In addition, the B-field was investigated. The approach was to use the models for the regular component of the B-field derived from rotational measurements, i.e. in [25], combining these with a random field, which was then determined. They [11] obtained a random field with double exponential in \((R, z)\), with scale lengths of 30 kpc in \(R\) and 4 kpc in \(z\) and the local B-field of 7.5 \(\mu\)G. This value was based on a local regular field of 2 \(\mu\)G.

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