Determining the Spectrum of Cosmic Rays in Interstellar Space from the Diffuse Galactic Gamma-Ray Emissivity

C.D. Dermer¹, A.W. Strong², E. Orlando³, L. Tibaldo⁴, for the Fermi-LAT Collaboration.

1 Code 7653, Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375 USA
2 Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85748 Garching, Germany
3 W.W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
4 Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Charles.dermer@nrl.navy.mil, aws@mpe.mpg.de

Abstract: More than 90% of the Galactic gas-related γ-ray emissivity above 1 GeV is attributed to the decay of neutral pions formed in collisions between cosmic rays and interstellar matter, with lepton-induced processes becoming increasingly important below 1 GeV. Given the high-quality measurements of the γ-ray emissivity of local interstellar gas between ~ 50 MeV and ~ 40 GeV obtained with the Large Area Telescope on board the Fermi space observatory, it is timely to re-investigate this topic in detail, including the hadronic production mechanisms. The emissivity spectrum will allow the interstellar cosmic-ray spectrum to be determined reliably, providing a reference for origin and propagation studies as well as input to solar modulation models. A method for such an analysis and illustrative results are presented.

Keywords: cosmic rays, gamma rays, cross sections, solar modulation

1 Introduction

The major part of the ‘diffuse’ γ-ray emission of the Milky Way is of interstellar origin, with the contribution from a superposition of unresolved, low luminosity point sources estimated at only the 5-10% level in the Galactic plane, and with inverse-Compton contribution even less than that. Almost all of the gas-related interstellar emission is the result of hadronic cosmic rays colliding with the nuclei of interstellar gas (see e.g. [17, 6, 19, 20]), and cosmic-ray electrons and positrons making bremsstrahlung γ-rays. Besides making γ-rays a valuable tracer of the interstellar matter and radiation, the spectral energy distribution of the diffuse emission encodes the interstellar cosmic-ray spectrum.

Using data taken in the first six months of Fermi science operations, [1] measured the spectral energy distribution of gamma-ray emission associated with local neutral atomic hydrogen, HI, between 100 MeV and 10 GeV, finding that it is proportional to the HI column density and deriving an emissivity (emission rate per H atom) spectrum. Many measurements of the HI emissivity in the neighborhood of the solar system and the outer Galaxy were obtained using Fermi data. More recently, [4] presented a new emissivity spectrum of local atomic hydrogen between Galactic latitudes 10° < |b| < 70° for energies ~ 50 MeV to ~ 40 GeV with error bars mainly ~ 15%.

It is therefore an optimal time to use the emissivity to deduce the interstellar cosmic ray proton spectrum with improved accuracy.

A review of near-threshold hadronic γ-ray production has been given in [2], and more details will appear in [22]. Here we examine the total γ-ray production cross section in proton-proton collisions, remarking on the accuracy of different models in the low-energy, < 10 GeV, range. Some calculations are made for different production cross sections, illustrating the method. See [5] for an update on the local emissivity and an alternative approach to interpretation. For a recent analysis of PAMELA data including solar modulation modelling and relation to the present work, see [13].

2 γ-ray production cross section in proton collisions

The production threshold of π0 (mπ = 0.135 GeV) in collisions of energetic protons with protons at rest is 2mπ + (mπ^2/2m_p) = 0.280 GeV. Above this energy, the single π^0 cross section rises rapidly, reaching a value of ~ 4 mb above T_p ~ 1 GeV, before declining to less than ~ 1 mb at T_p ~ 5 GeV [6]. Because of the rapidly declining cosmic-ray spectrum, most of the γ rays are made from protons with T_p ~ 5 GeV [6], and a large fraction of these γ rays are made through resonance production. Almost all π^0 production below T_p ~ 1 GeV is through the Δ(1238) isobar, and heavier isobars and resonances contribute at the per cent level to T_p ~ 30 GeV.

Fig. 1 shows data for inclusive π^0 production [18, 7], single π^0 production, and resonance production [12] in p + p collisions. Because of different isospin decay channels, only a fraction of the resonance cross section results in a π^0. The low- and high-energy dashed curves in the left panel of Fig. 1 represent, respectively, the Δ(1238) resonance and scaling contributions to the total inclusive π^0 cross section in the model of [6]. The Δ(1238) resonance and N^0 (1600) resonance complex, and the diffractive and non-diffractive (scaling) contributions in the model of [11] are shown separately by the dotted curves. Model improvements, particularly at T_p ~ 10 GeV, are required to accurately infer the interstellar cosmic-ray spectrum and its uncertainty.
3 Determining the interstellar cosmic-ray spectrum

Using the newly-measured emissivity spectrum [3], we can proceed to explore interstellar CR spectra that are compatible with it. The analysis is performed by first computing the matrices connecting model CR spectra to the observed gamma-ray emissivities, in energy bands, and then scanning the parameter space of the models. The method is Bayesian, allowing a complete scan of the parameters, computing posterior probability distributions, mean values and error bars, while correctly accounting for the correlations among the parameters.

To illustrate the method, the measured emissivities have been fitted with γ-ray spectra calculated for a broken power law in momentum for protons and Helium, with the free parameters being break momentum, spectral index below and above the break, and the overall normalization. The range of break momentum scanned is 1–20 GeV, since this is found necessary to fit the emissivity spectrum. The CR He/p ratio is fixed to the value measured by PAMELA at 100 GeV/nuc [3], and the He and p spectra are assumed to have the same shape (since they cannot be distinguished in gamma rays). Note that CR spectra are expressed as particle density per momentum. The use of a sharp break in the CR spectrum is over-simplified but serves to illustrate the method; more physically plausible spectra (e.g., smooth breaks) are also being investigated, but they do not lead to essentially different conclusions.

The first set of hadronic cross sections used is from [6]. The p-p cross sections are scaled for p-He, He-p and He-He interactions using the function given in [15]. The second set is from [10] below 20 GeV, (QGSJET) above 20 GeV. For [11] the p-p cross sections are scaled for p-He, He-p and He-He interactions using [15]. For [10] the p-p, p-He, He-p cross-section are provided, so only He-He is scaled from p-p. The He fraction in the interstellar medium is taken as 0.1 by number.

The electron (plus positron) spectrum producing bremsstrahlung is based on Fermi-LAT measurements above 10 GeV [2], with a break below 3 GeV as indicated by synchrotron data [21]. The synchrotron data shown there require a flattening of the interstellar electron spectrum by about 1 unit in the spectral index below a few GeV, so this is used as a constraint; the actual low-energy index is determined by the fit to the emissivities.

The resulting cosmic-ray proton and electron spectra and the corresponding emissivities are shown in Fig 2. The fit to the measured emissivities is good, as can be expected with the freedom allowed. The proton spectrum, having been determined from gamma rays (and gas tracers) alone with no input from direct CR measurements except for the He/p ratio, is close to that measured directly at high energies. The solar modulation is clearly seen in the deviation of the interstellar spectrum from the direct measurements below 10 GeV. Bremsstrahlung gives an essential contribution below ≈ 1 GeV, and is an important component in the analysis.

In this particular example, the interstellar proton spectrum steepens by about 1/2 unit in the momentum index above a few GeV, compatible with expectations from the cosmic-ray B/C ratio, which shows a similar break due to propagation. A power-law injection in momentum modified by propagation would then be a plausible scenario. The spectrum shown for [6] cross sections has momentum index 2.5 (2.8) below (above) 6.5 GeV, with a scaling factor 1.4 relative to PAMELA at 100 GeV; for the [11] cross sections, the values are 2.4 (2.9) and 1.3, with the same break energy. The formal significance of the break is...
**Figure 2**: Spectra derived from model fitting. Yellow band shows model range. Model ranges are 1 standard deviation on the parameterized synthetic spectra. Top: Measured and derived cosmic-ray proton spectra. Data are AMS01 (asterisks) and PAMELA (diamonds). Middle: Measured and derived cosmic-ray electron spectra. Data are AMS01 (asterisks), PAMELA (diamonds), and *Fermi*-LAT (squares). Bottom: *Fermi*-LAT emissivity data (vertical bars) and model, with red and green curves showing the hadronic and leptonic bremsstrahlung contributions; the yellow band shows the total. Emissivities from Casandjian [4], and cross sections from [6] (left column), [11, 10] (right column).

**PRELIMINARY**
The sensitivity of the results to the cross sections is significant but not overwhelming, though uncertainties in the production cross sections must be included in the error budget to derive firm conclusions. In both of these illustrative cases, the high-energy proton index is compatible with PAMELA (2.82) [3]. The scaling factor excess may have various origins, including uncertainties in the cross sections and the gas tracers, and/or hidden systematic errors in the direct measurements themselves. A difference between the interstellar spectrum and the direct measurements cannot be ruled out at this stage either.

This preliminary result illustrates how it is possible to constrain the interstellar CR spectra with the *Fermi*-LAT emissivity data. In a forthcoming paper [22], all the uncertainties will be addressed, including those in emissivities (gas, instrumental response, etc.) and cross sections. The evidence for a break and more exact constraints on the spectrum will be presented there.

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2. Code available from http://sourceforge.net/projects/ppfrag
3. available at http://adsabs.harvard.edu/abs/1971NASSP.249.....S