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The interstellar environment in the outer Galaxy as seen in γ-rays by *Fermi*

L. Tibaldo(1)(2)(*), I. A. Grenier(2) and T. Mizuno(3)
on behalf of the Fermi-LAT Collaboration

(1) *INFN, Sezione di Padova and Dipartimento di Fisica "G. Galilei"*
Università di Padova - 35131 Padova, Italy
(2) *Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique*
CEA Saclay, 91191 Gif sur Yvette, France
(3) *Department of Physical Sciences, Hiroshima University - Higashi-Hiroshima*
Hiroshima 739-8526, Japan

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Summary. — Gamma-ray emission produced by interactions between cosmic rays (CRs) and interstellar gas traces the product of their densities throughout the Milky Way. The outer Galaxy is a privileged target of investigation to separate interstellar structures seen along the line of sight. Recent observations by the *Fermi* Large Area Telescope (LAT) shed light on open questions of the EGRET era about the distribution of CR densities and the census of the interstellar medium. The gradient of γ-ray emissivities measured in the outer Galaxy is significantly flatter than predictions from widely used CR propagation models, given the rapid decline of putative CR sources beyond the solar circle. Large propagation volumes, with halo heights up to 20 kpc, or a flat CR source distribution are required to match the data. Other viable possibilities include non-uniform CR diffusion properties or more gas than accounted for by the radio/mm-wave data. γ-ray data constrain the evolution of the $X_{\mathrm{CO}} = N(\mathrm{H}_2)/W_{\mathrm{CO}}$ ratio within a few kpc from the Sun. There is a significant increase by a factor 2 from nearby clouds in the Gould Belt to the local spur. No further significant variations are measured from the local spur to the Perseus spiral arm. At the level of statistical accuracy provided by the LAT data, the most important source of uncertainty, often overlooked so far, is due to the optical depth correction applied to derive the column densities of H I. Reliable determinations of the amount of atomic gas in the plane are key to better probe the properties of CRs in the Galaxy.

PACS `95.85.Pw` – γ-ray.
PACS `98.38.Am` – Physical properties (abundances, electron density, magnetic fields, scintillation, scattering, kinematics, dynamics, turbulence, etc.).
PACS `98.70.Sa` – Cosmic rays (including sources, origin, acceleration, and interactions).

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TABLE I. – *Regions seen toward the outer Galaxy and their approximate Galactocentric distances.*

	Second quadrant $100^\circ < l < 145^\circ$	Third quadrant $210^\circ < l < 250^\circ$
Gould Belt	8.5–8.8 kpc	–
Local arm	8.8–10 kpc	8.5–10 kpc
interarm region	–	10–12.5 kpc
Perseus arm	10–14 kpc	12.5–16
outer region	> 14 kpc	> 16 kpc

1. – Introduction

Interstellar γ-ray emission is produced by interactions of high-energy cosmic rays (CRs) with the gas in the interstellar medium (ISM) and the soft interstellar radiation fields. Its observations carry information about CR properties in distant locations and it provides a tracer of the total interstellar gas densities to be compared with radio/mm-wave data: the 21 cm line of atomic hydrogen, H I, and the 2.6 mm line of CO, used as a surrogate tracer of molecular mass.

Open issues in the understanding of the interstellar γ-ray emission concern the identification and spatial distribution of CR sources and the census of the ISM, notably the $X_{\mathrm{CO}} = N(\mathrm{H}_2)/W_{\mathrm{CO}}$ conversion factor. The outer Galaxy is a privileged observational target since the Doppler shift of radio/mm-wave lines due to the Galactic rotation unambiguously locates the emitting clouds. There are two longitude windows with a steep velocity gradient leading to a good kinematic separation [1].

We reported analyses of recent measurements by the Large Area Telescope (LAT) on board the *Fermi γ-ray Space Telescope* [2] for the second [3] and third [4] Galactic quadrants. The component separation based on likelihood fitting allowed us to extract the emissivities per H atom, $q_{\mathrm{H\,I}}$, and per W_{CO} unit, q_{CO}, in several regions along the lines of sight as described in table I. We refer the interested reader to the aforementioned papers for details about the analysis and we briefly discuss here the implications of the results for the distribution of CRs in the Galaxy and the calibration of the X_{CO} ratio.

2. – The spatial distribution of CR densities

Provided that the H I column densities are accurately measured from radio data, the emissivity $q_{\mathrm{H\,I}}$, *i.e.* the γ-ray emission rate per hydrogen atom, directly relates to the average CR densities in each of the regions considered. The $q_{\mathrm{H\,I}}$ profile (integrated above 200 MeV) as a function of Galactocentric distance R is shown in fig. 1 (left panel).

CR densities appear to be uniform within 20% for comparable Galactocentric distances in the two regions studied. There is a small decrease from nearby complexes in the Gould Belt(1) to the Perseus spiral arm, but no further significant gradient is observed beyond $R \simeq 11$ kpc.

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(1) Our measurement of the local emissivity is compatible with expectations based on CR spectra as they are measured near the Earth [3, 5].

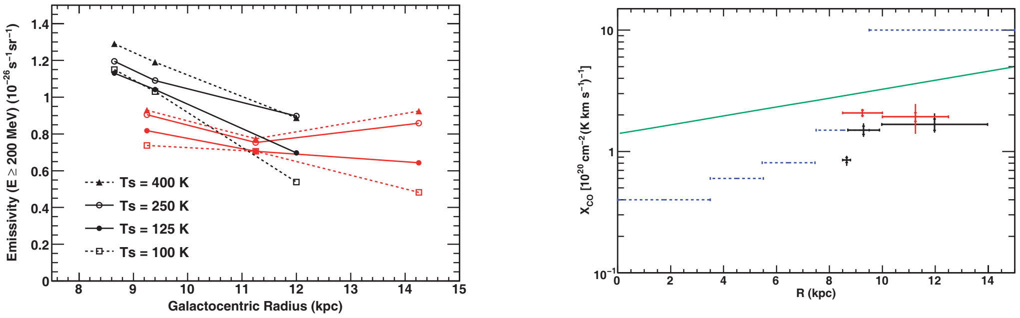

Fig. 1. – (Colour on-line) Left: $q_{\text{H I}}$ (integrated above 200 MeV) as a function of Galactocentric radius R for different H I spin temperatures, as measured in the second (black) and third (red or gray) quadrants. Statistical errors are comparable with marker sizes. Right: X_{CO} as a function of R. The error bars include the uncertainties due to the H I optical depth correction. The (blue) step function represents the model by Strong *et al.* [6], the (green) line that by Nakanishi and Sofue [7].

We assessed the uncertainties due to the optical depth correction applied to the H I line intensities to derive $N(\text{H I})$. In fig. 1 (left panel) we have explored a range of possible spin temperatures (T_S), showing that the uncertainties in the H I mass, often overlooked in the past, dominate the errors in the emissivity determination.

3. – The calibration of molecular masses

If subject to the same CR flux, the emissivity of a H_2 molecule is two times that of a hydrogen atom. We can therefore calibrate X_{CO} as $q_{\text{CO}}/2\,q_{\text{H I}}$. Our results, constraining X_{CO} over a few kpc from the solar system, are shown in fig. 1 (right panel).

There is a significant increase by a factor ~ 2 from the nearby clouds of Cepheus and Cassiopeia in the Gould Belt to the local arm, whereas no further significant variations are observed up to $R \sim 14$ kpc. The increase by one order of magnitude in the outer Galaxy proposed by Strong *et al.* [6] is not confirmed. The γ-ray estimates are also systematically lower than predictions by Nakanishi and Sofue [7] from virial masses.

4. – The cosmic-ray gradient problem

The comparison between the measured γ-ray emissivities and expectations from CR propagation models has implications for the origin and propagation of cosmic rays in the Galaxy. We adopted the widely-used GALPROP propagation code [8]. A conventional model analogous to [6, 9] (solid line in fig. 2, left panel) predicts a gradient steeper than inferred from the LAT measurements.

To alleviate the discrepancy one can increase the CR propagation halo or the radial scale of the CR source distribution. In fig. 2 (left panel) we varied the halo height(^{2}), showing that halo heights from 10 kpc to 20 kpc are preferred if the CR source profile is

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(^{2}) And correspondingly the diffusion parameters to stay consistent with CR isotopic abundances measured at the Earth.

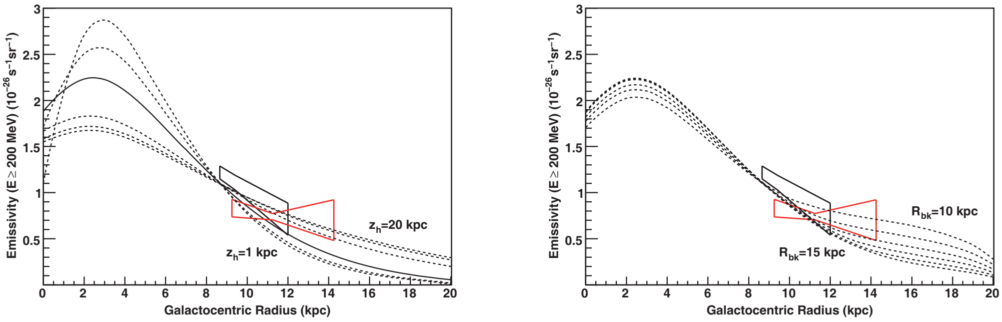

Fig. 2. – (Colour on-line) $q_{\mathrm{H\,I}}$ as a function of galactic radius R: bow-ties represent our estimates for the second (black) and third (red or gray) quadrants. The curves give the predictions by some GALPROP models, on the left varying the height of the propagation halo from 1 kpc to 20 kpc (the solid line corresponds to 4 kpc, a value often assumed in past studies [9]), on the right setting the density of CR sources to a constant for $R > R_{\mathrm{bk}} = 10$–15 kpc.

that derived from pulsar and supernova remnant observations. In fig. 2 (right panel) we assume a halo height of 4 kpc and we set the CR source density profile to a uniform value beyond a given break radius. We found that γ-ray data point to a flat source distribution beyond $R \sim 10$ kpc.

The solutions are not unique: alternative CR propagation models can be considered, with, *e.g.*, a non-uniform diffusion coefficient [10]. On the other hand, $q_{\mathrm{H\,I}}$ might be overestimated due to large amounts of dark gas in the outer disc of the Milky Way not accounted for by radio/mm-wave data [11].

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