

Observations of Diffuse Gamma-Ray Emission from Giant Molecular Clouds by *Fermi*/LAT

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Abstract. Orion A and B are two of the brightest giant molecular clouds in diffuse MeV–GeV gamma rays. These energetic photons are considered to be produced by hadronic and electromagnetic interactions between Galactic cosmic rays and the two clouds. We present a preliminary analysis of GeV gamma-ray observations of the clouds by the Large Area Telescope (LAT) onboard the *Fermi Gamma-ray Space Telescope (Fermi)*. The spectral shape of the clouds are well reproduced by the latest gamma-ray emissivity model and the Galactic cosmic-ray spectrum. The total molecular masses in Orion A and B regions are estimated as $\sim 100 \times 10^3 M_\odot$ and $\sim 40 \times 10^3 M_\odot$, respectively. The gamma-ray intensity map and that of CO in the regions of the clouds correlates in general though the slopes of two regions are found to be different by a factor of 1.3.

Keywords: diffuse gamma-ray emission, cosmic-ray flux, molecular cloud

I. INTRODUCTION

Diffuse emission of > 100 MeV gamma rays in the Galaxy is mainly induced by hadronic interactions between cosmic rays (CRs) and interstellar matter (ISM), via the productions of π^0 particles and their subsequent decay. This emission can be used to study the structure of ISM and the Galactic distribution of cosmic rays, because its emissivity can be written as the product of the CR flux and ISM density.

Orion A and B are typical giant molecular clouds (GMCs) located about 400 – 500 pc away from the Sun, and their total mass is estimated to be of the order of $10^5 M_\odot$ [1]. Diffuse gamma-ray emission from these clouds has been studied with preceding gamma-ray detectors such as COS-B and EGRET [2][3], because their fluxes are strong enough to be distinguished from the other diffuse emission components (H I gas, H II gas, inverse Compton, extragalactic emission and instrumental background), and they are located around ($\ell \simeq 210^\circ, b \simeq -15^\circ$), which is far from the Galactic plane and the Galactic center. Also, no bright point sources of gamma rays are known in the Orion A and B regions.

However, those previous detectors was not able to study the spatial distribution of gamma-ray intensity and the shape of energy spectrum in detail, due to their limited sensitivity and angular resolutions. The Large Area Telescope (LAT) onboard the *Fermi Gamma-ray Space Telescope (Fermi)* enables us to study the

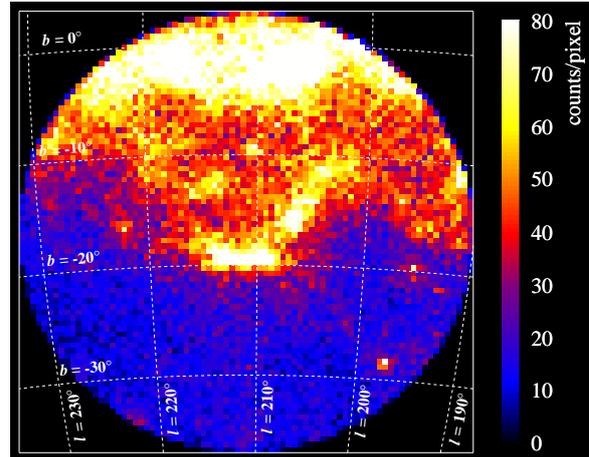


Fig. 1. Gamma-ray count map of the Orion region binned in $0.5^\circ \times 0.5^\circ$ pixels with Hammer-Aitoff projection. The coordinate center and the radius of the region-of-interest are $(\ell, b) = (211^\circ, -17^\circ)$ and 20° respectively. Orion A and B correspond to the bright extended regions around $(\sim 212^\circ, \sim -19^\circ)$ and $(\sim 206^\circ, \sim -16^\circ)$ respectively.

diffuse gamma-ray emission with large field of view (2.4 sr), large effective area ($\sim 8000 \text{ cm}^2$), broad energy band (20 MeV – 300 GeV) and high angular resolution (0.6° at 1 GeV) [4]. We present the results from the first 7 months of observations of the Orion region by *Fermi*/LAT.

II. OBSERVATION AND DATA

The LAT has finished its Launch and Early Operations phase in the first 2 months after the launch on 11 June 2008. From early August 2008, it has started nominal science operations in an all-sky survey mode.

For this study we accumulated 7 months of data from 4 August 2008 to 17 Mar 2009 (239557413 – 259000000 in MET¹), and extracted *DIFFUSE*² class events within a 20° radius around the Galactic coordinates of $(\ell = 211^\circ, b = -17^\circ)$. The energy band was limited to 200 MeV – 20 GeV in order to reduce the systematic uncertainties at lower energies and of in recognition of limited statistics at higher energies. We applied a zenith cut of $< 100^\circ$ to reduce the contamination from Earth albedo gamma rays. Fig. 1 is a photon count map in the region obtained in this way. It reveals clear count excesses at the positions of Orion A and B.

¹Mission Elapsed Time (MET): Zero is set at 00:00 UTC on 1 January 2001.

²The tightest cut for gamma/CR separation [4].

III. ANALYSIS AND RESULTS

A. Event Extraction from Orion A and B

Gamma-ray emission in the region of interest consists of the following major components.

- (A) π^0 gamma and CR electron bremsstrahlung from GMC (H_2 region).
- (B) π^0 gamma and CR electron bremsstrahlung from H I and H II gas.
- (C) Inverse Compton (IC) scattering of CR electrons off interstellar radiation fields.
- (D) Extragalactic diffuse emission and unresolved weak point sources.
- (E) Instrumental residual background from misclassified interactions of cosmic rays in the LAT.

The component (A), which is our target, needs to be extracted from the total gamma-ray emission. We subtracted (B) to (E) from the photon data using the process described below.

The main component of the ISM is H I gas. Its distribution in the Galaxy has been studied with the 21 cm line emission of atomic hydrogen. We converted H I spectra obtained by the LAB survey [5] into H I column densities with under the assumption of a uniform spin temperature of 125 K, and estimated the component (B) using Science Tools³ and GALPROP⁴ [6]. We also calculated the H II and IC components using GALPROP. Since their contributions are small and almost flat in the Orion region, uncertainties of their estimates are negligible in our analysis. The bremsstrahlung contribution to (B) is subject to relatively large (several tens of percent) uncertainty. However its effect is also small, and does not affect our analysis results, because its contribution is important only in the energy range below 100 MeV. In calculating the π^0 -gamma emissivity, we used a recent model of the gamma-ray inclusive cross section in p - p interactions [7]. We multiplied 1.20 to the π^0 gamma components calculated by GALPROP to take into account contributions from heavier nuclei interactions [8], [9], [10].

We subtracted (B) and (C) from the total photon data, and estimated (D) and (E) from the residual in the off-source regions that are more than 3° away from the clouds themselves and bright point sources, assuming that these two components distribute uniformly over the regions. Finally the gamma-ray intensity map consisting of (A) and point sources was obtained and rebinned into $1^\circ \times 1^\circ$ pixels as shown in fig. 2a. We defined boundaries of Orion A and B regions with solid lines in the same figure. Note that the boundary definitions are rougher than that of radio observations (e.g. [1]) due to our limited angular resolution.

³Standard analysis tools for *Fermi*/LAT data. Version v9r11 and response function P6_V3_DIFFUSE were used through the analysis.

⁴C++ program which calculates diffuse gamma-ray emission and cosmic-ray propagation in the Galaxy based on observational and theoretical studies. We used a configuration file 54_78Xvarh7O.

The largest uncertainty in this extraction process comes from the estimation of the gamma-ray intensity of H I gas; because the H I data and the local CR flux have $\sim 10\%$ uncertainties. In addition, the flux of CRs outside the solar system is not directly measured. Our model prediction calculated with GALPROP is subject to these systematic errors, and thus its normalization must be adjusted to reproduce the observed gamma-ray flux in all the Galaxy. Calculation of this normalization factor has been done by several methods, and each of them is found to be consistent with our GALPROP model within $\pm 10\%$ (1.15 – 1.28). We thus use the scaling factor of 1.20 unchanged.

B. Energy Spectra and Mass Estimation

Fig. 3 shows the spectral energy distributions of Orion A and B regions derived from fig. 2a. They can be well fitted by a sum of the π^0 gamma and electron bremsstrahlung models. The normalizations of both components are set free. In this fitting we calculated the proton and alpha-particle fluxes at the Galactic location of $R = 8.8$ kpc and $Z = -0.14$ kpc using GALPROP 54_78Xvarh7O, which are 8% less than those of the location of the Earth ($R = 8.5$ kpc and $Z = 0$ kpc). The CR flux at the Earth predicted by GALPROP are consistent within 5% with observed data [12], [13].

We are now able to calculate the total masses of the two cloud regions upon assumptions of the CR fluxes and the π^0 emission model. “Mass” includes H_2 , He and metal but H I. We obtained

$$M_A = (95.3 \pm 9.3_{\text{stat}} \pm 7.6_{\text{sys,HI}} \pm 10\%_{\text{sys,LAT}}) \times 10^3 \times M_\odot \times (d/400 \text{ pc})^2, \quad (1)$$

and

$$M_B = (40.2 \pm 6.5_{\text{stat}} \pm 4.0_{\text{sys,HI}} \pm 10\%_{\text{sys,LAT}}) \times 10^3 \times M_\odot \times (d/400 \text{ pc})^2 \quad (2)$$

as the total masses inside the Orion A and B regions, respectively, where d is the distance between the Sun and the clouds. We adopted 400 pc as the typical distance according to recent parallax observations of the Orion Nebula [14], [15], [16], [17]. The ISM abundance was assumed to be $\text{H} : \text{He} = 1 : 0.1$ by number [18]. Systematic errors of the H I estimation and LAT response are shown in addition to the statistical errors.

C. Correlation with CO Map

Line emission from the $J=1-0$ rotational transition of carbon monoxide (CO) has been widely used to estimate the column density of H_2 gas [1], because H_2 the main element of molecular clouds, does not emit observable emission. Usually, H_2 column density $N(\text{H}_2)$ is estimated from velocity-integrated CO intensity W_{CO} by assuming that their ratio, $X_{\text{CO}} \equiv N(\text{H}_2)/W_{\text{CO}} \text{ cm}^{-2}(\text{K km s}^{-2})^{-1}$, has a roughly constant value, e.g. $(2.6 \pm 1.2) \times 10^{20}$ by [19] or $(1.8 \pm 0.3) \times 10^{20}$ by [11]. However, the value of X_{CO} is

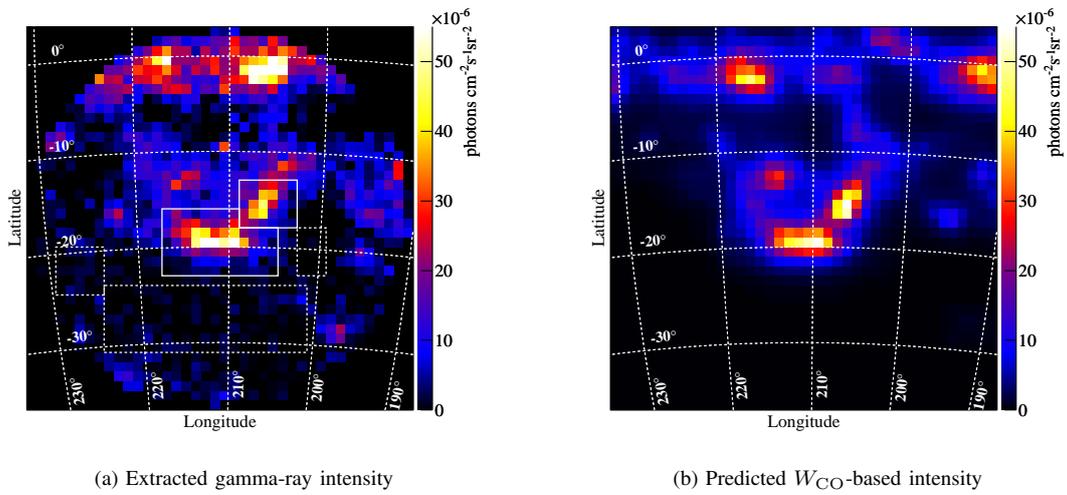


Fig. 2. (a) Same as fig. 1, but shown after subtracting the other diffuse components. The unit is integrated photon intensity between 200 MeV and 20 GeV. Solid lines show the definitions of the regions of Orion A (larger) and B (smaller). Dashed lines show the regions which are used to estimate the uniform component. (b) A simulated gamma-ray intensity map estimated from a constant $X_{CO} = 1.5 \times 10^{20}$, a W_{CO} map [11], the LAT response, the emissivity of π^0 gamma and electron bremsstrahlung, and the CR flux predicted by GALPROP. (These figures are still *PRELIMINARY*)

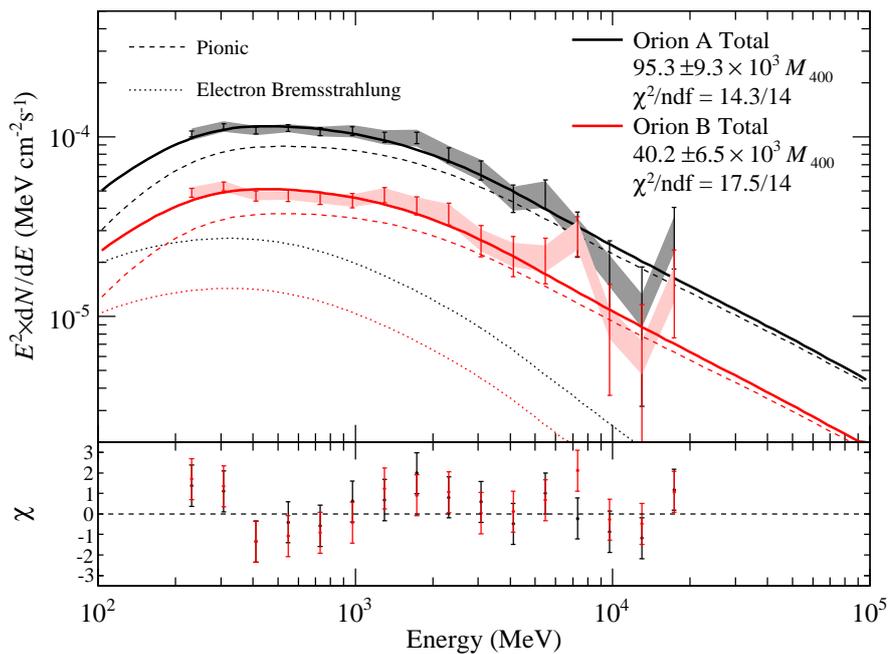


Fig. 3. *PRELIMINARY* energy spectra of Orion A (black) and B (red) fitted with modeled spectra of π^0 gamma (dashed) and electron bremsstrahlung (dotted). Statistical errors are shown with bars, and the systematic errors of the LAT response are shown with shaded area. Note that by chance the statistical and systematic errors are almost equal below 3 GeV.

rather uncertain, and its constancy is questionable due to the Galactic-location dependence of metallicity [20], [21] and possible existence of “dark gas” [22].

To study the X_{CO} factor in the Orion region, we calculated a gamma-ray intensity map which is predicted by W_{CO} , constant factor $X_{CO} = 1.5 \times 10^{20}$ [21], the emissivity models of electron bremsstrahlung and π^0 gamma, and the instrumental response of the LAT. The

predicted map is shown in fig. 2b.

Fig. 4 correlates, pixel by pixel ($1^\circ \times 1^\circ$), the actual gamma-ray intensity (fig. 2a, x) with the W_{CO} -based prediction (fig. 2b, y) for the two cloud regions, and fitted the points with linear functions $y = p_0 + p_1 x$. If the gamma-ray intensity can be represented by the product of a constant CR flux and a constant X_{CO} , and the emissivity model and LAT detector response

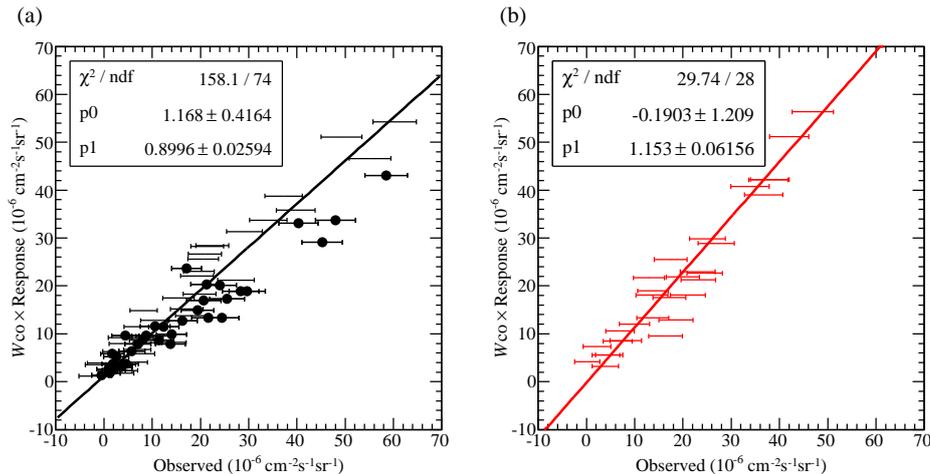


Fig. 4. Correlations between the measured gamma-ray intensity (x) and a model prediction by W_{CO} (y) assuming $X_{\text{CO}} = 1.5 \times 10^{20}$. Data points are fitted with a linear function $y = p_0 + p_1x$. (a) Orion A. Circles correspond to the data in pixels of $\ell > 212^\circ$. (b) Orion B. (This figure is still preliminary)

are perfect, the slope p_1 would be the same between the two clouds, and would be consistent with unity within the uncertainty of X_{CO} . However, as given in fig. 4, the best fit slopes for Orion A and B have been obtained as $0.90 \pm 0.03_{\text{stat}} \pm 0.08_{\text{sys,HI}} \pm 10\%_{\text{sys,LAT}}$ and $1.15 \pm 0.06_{\text{stat}} \pm 0.10_{\text{sys,HI}} \pm 10\%_{\text{sys,LAT}}$ respectively. They are different by a factor of 1.3 with more than 3σ significance. In addition, the dispersion of data points in Orion A is larger than that of Orion B. Therefore, the X_{CO} factor or the CR flux is suggested to be variable even within the Orion A cloud.

IV. DISCUSSION AND SUMMARY

We obtained the energy spectra of the Orion A and B with unprecedented photon statistics, especially in the energy range above 1 GeV. They are well fitted with the model calculated from CR fluxes and π^0 gamma emissivity. This means that diffuse gamma-ray emission in the clouds is mainly induced by hadronic interactions between Galactic CRs and the matter in the clouds.

The different slopes obtained in fig. 4 upon an assumption of constant CR fluxes and a constant X_{CO} factor in the region, while still preliminary, provide an interesting result. Although this could be due to contamination by unresolved point sources inside the clouds, there is no detected bright gamma-ray source [23] and no bright candidate source that can explain the difference (e.g. [24]).

There are two possible interpretations of the slopes. The first is that the X_{CO} factor is not constant inside the clouds, due to different chemical conditions inside the clouds. The second is that the CR flux is not constant inside the clouds. Each of these possibilities offers us a new view of molecular clouds and diffuse gamma-ray emission. More photon statistics and analyses of other molecular clouds will enable us to understand the result more deeply.

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