Evidence of a Spectral Break in the Gamma-Ray Emission of the Disk Component of the Large Magellanic Cloud: A Hadronic Origin?

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Abstract

It has been suggested that the high-energy gamma-ray emission (>100 MeV) of nearby star-forming galaxies may be produced predominantly by cosmic rays colliding with the interstellar medium through neutral pion decay. The pion decay mechanism predicts a unique spectral signature in the gamma-ray spectrum, characterized by a fast-rising spectrum (in $E^2\phi(E)$ representation) and a spectral break below a few hundred MeV. Here, we report evidence of a spectral break, around 500 MeV in the disk emission of the Large Magellanic Cloud (LMC), that was found during an analysis of the gamma-ray data extending down to 60 MeV, observed by the Fermi-Large Area Telescope. The break is consistent with the pion decay model of gamma-ray emission, although leptonic models, such as electron bremsstrahlung emission, cannot be ruled out completely.

Key words: cosmic rays – galaxies: individual (LMC) – gamma rays: galaxies

1. Introduction

It is generally believed that Galactic cosmic rays are accelerated by supernova remnant (SNR) shocks (Ginzburg & Syrovatskii 1964). Cosmic-ray (CR) protons interact with the interstellar gas and produce neutral pions (schematically written as $p + p \rightarrow \pi^0 +$ other products), which in turn decay into gamma rays. Cosmic-ray electrons can also produce gamma rays via bremsstrahlung and inverse-Compton (IC) scattering emission (Strong et al. 2010; Chakraborty & Fields 2013; Foreman et al. 2015). Detailed calculation of the CR propagation in our Galaxy using the GALPROP code finds that $\pi^0$-decay gamma rays form the dominant component of the diffuse Galactic emission (DGE) above 100 MeV, while the bremsstrahlung and IC emissions contribute a subdominant, but non-negligible fraction (Strong et al. 2010). GeV gamma-ray emissions have also been detected from nearby star-forming galaxies (Abdo et al. 2010a; Ackermann et al. 2012; Tang et al. 2014; Griffin et al. 2016; Peng et al. 2016), and they are interpreted as arising dominantly from CR protons colliding with the interstellar gas (Pavlidou & Fields 2002; Torres 2004; Stecker 2007; Thompson et al. 2007; Persic & Rephaeli 2010; Lacki et al. 2011).

Although these theoretical arguments favor the pion decay model for the GeV gamma-ray emission in these galaxies, there is no direct evidence for such a pion decay mechanism. Recently, the Fermi-Large Area Telescope (hereafter LAT) detected a characteristic pion decay feature in the gamma-ray spectra of two supernova remnants, IC 443 and W44 (Ackermann et al. 2013). The pion decay spectrum in the usual $E^2\phi(E)$ representation rises steeply below several hundred MeV and then breaks to a softer spectrum. This characteristic spectral feature (often referred to as the “pion decay bump”) uniquely identifies pion decay gamma rays and thereby high-energy CR protons.

Motivated by this, we attempt to study the gamma-ray spectra of nearby star-forming galaxies and examine such unique pion decay bump spectral signatures. The LMC is the brightest external galaxy in gamma-ray emission, as it is very close to us (only 50 kpc). The LMC is near enough that individual star-forming regions can be resolved and thus their contribution can be removed so that one can obtain a relatively pure diffuse disk component. The high Galactic latitude of the LMC also leads to a low level of contamination, due to the Galactic diffuse gamma-ray emission. We analyze the Fermi-LAT data of the LMC and pay special attention to the gamma-ray spectrum extending to 60 MeV using 8 years of Fermi-LAT Pass 8 data. We find that the gamma-ray spectrum shows a rise in $E^2\phi(E)$ representation at low energies and breaks to a softer spectrum at about 500 MeV.

Our work differs from earlier works based on the Fermi-LAT observations of the LMC (Abdo et al. 2010b; Foreman et al. 2015; Ackermann et al. 2016), which focused on the gamma-ray emission above 200 MeV.

2. Data Analysis and Results

2.1. Data Selection

The LAT Pass 8 data between 2008 August 4 and 2016 August 4 are taken from the Fermi Science Support Center (hereafter FSSC). Events with energies between 60 MeV and 100 GeV are selected. These data are analyzed using the Fermi Science Tools package (v10r0p5) available from the FSSC. We select “FRONT+BACK” SOURCE class events and use instrument response functions P8R2_SOURCE_V6. Events with zenith angles >90° are excluded to reduce the contribution of Earth-limb gamma rays and events where the rocking angle of the satellite was larger than 52° are also excluded. Gamma rays in a box region of interest (ROI), $20^\circ \times 20^\circ$ centered at the position of R.A. = $80^\circ 894$, decl. = $-69^\circ 756$, are used in the spectrum analysis between 60 MeV and 100 GeV, in which energy dispersion correction

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https://fermi.gsfc.nasa.gov/ssc/
is considered. Binned maximum-likelihood analyses are performed in this work.\footnote{https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/binned\_likelihood\_tutorial.html}

2.2. Background Sources

With a large angular containment of the low-energy gamma-ray photons, all identified sources from the third LAT catalog (3FGL, Acero et al. 2015) within 20° from the center position are included. Four of them are excluded because they are located in the intensive LMC region (Ackermann et al. 2016), specifically 3FGL J0454.6–6825, 3FGL J0456.20–6924, 3FGL J0525.2–6614, and 3FGL J0535.3–6559. Another point source, 3FGL J0537.0–7113, is also at the edge of the LMC region and is thus excluded. These sources must be removed from the background sources so that the LMC sources can be distinguished significantly. A total of 72 point sources are included, with fixed positions as in the 3FGL.

For sources within the ROI, the spectral parameters are fixed at the 3FGL catalog values, except for their normalizations, which are allowed to be free. A total of 22 point sources are selected, allowing the normalizations to be free; these sources are marked as black diamonds in Figure 1. For sources outside the ROI, all spectral parameters are fixed at the 3FGL catalog values.

The Galactic diffuse background and isotropic gamma-ray background are given by the templates “gll\_iem\_v06.fits” and “iso\_P8R2\_SOURCE\_V6\_v06.txt,” which are available in the FSSC, while their normalizations are allowed to vary.

2.3. The LMC Sources

2.3.1. The LMC Point Sources and Extended Sources

The LMC sources are categorized into two subparts, namely, the point ones and the extended ones.

We include four newly identified point sources (namely P1, P2, P3, P4) in the LMC field in the analysis, which correspond to PSR J0540–6919, PSR J0537–6910/N157B, a gamma-ray binary CXOU J0536–6735, and N132D, respectively (Ackermann et al. 2016; Corbet et al. 2016). Their positions were determined by Ackermann et al. (2016).

Different templates are used for the extended sources found in the LMC field (Abdo et al. 2010b; Ackermann et al. 2016). Three spatial templates are considered and plotted in Figure 2:

1. \textit{G template.} Two-dimensional Gaussian template model for four sources (“G1,” “G2,” “G3,” “G4”), which is called the “analytic model” in Ackermann et al. (2016).

2. \textit{D template.} A template model with the “Disk” and “30 Doradus” being modeled as a two-dimensional Gaussian. This template is used for the LMC in Abdo et al. (2010b) and is archived in the latest Fermi-LAT extended source template catalog.\footnote{https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr\_catalog/}

3. \textit{H template.} A gas model of the ionized hydrogen employing the Southern H-Alpha Sky Survey Atlas intensity distribution (H$_{\alpha}$) for the LMC diffusion region (Gaustad et al. 2001). The template is also used in the comparative analysis of gas models (Abdo et al. 2010b; Ackermann et al. 2016). We considered it because the gamma-ray emission of the LMC correlates better with ionized gas than the emission of other gases or the total gas (Abdo et al. 2010b; Ackermann et al. 2016), which might trace the population of young and massive stars.

2.3.2. Photon Spectral Models

The photon models of the LMC sources depend on the selection of energy bands. The first selection divides 0.06–100 GeV into 12 independent energy bands logarithmically (i.e., performing spectral analysis on each independent energy band; hereafter the independent analysis). The second is to select a broad energy band (hereafter the broadband analysis), which combines the several independent energy bands.

(1) For the independent analysis, we assume a single power-law (PL) function to be the photon emission model of all LMC sources, as used in Ackermann et al. (2013):

\[
F(E) = K (E/E_0)^{-\Gamma_1},
\]

where $K$ is the normalization, $E_0$ is the pivot energy of 200 MeV (hereafter all $E_0$ in other equations are fixed at 200 MeV), and $\Gamma_1$ is the PL index. For a narrow energy band in the independent analysis, $\Gamma_1$ is fixed at a common value of 2 (Foreman et al. 2015).

(2) For the broadband analysis, several photon emission models are employed. As discussed below, the broadband analysis is performed only for the G template. Therefore, we discuss the models for the G template. For the G1 component, we test the goodness of fit with two models, i.e., PL and broken power law (BPL). The BPL model is given by:

\[
F(E) = K (E/E_0)^{-\Gamma_1} \left[1 + (E/E_{br})^{(\Gamma_2-\Gamma_1)/\Gamma_3}\right]^{-\Gamma_3},
\]
where $\Gamma_1$ and $\Gamma_2$ are the PL indices before and after the break energy $E_\gamma$, and $s$ is the smoothness of the break, which is fixed at 0.1 (Ackermann et al. 2013).

For point source P1, its photon flux can be modeled with a PL with an exponential cutoff (PLC):

$$F(E) = K(E/E_0)^{-\Gamma_1}\exp(-E/E_\gamma),$$

(3)

where $E_\gamma$ is the exponential cutoff energy. Other extended sources (G2, G3, G4) and point sources (P2, P3, P4) are all modeled by a PL photon spectrum with photon index $\Gamma_1$ being free for the broad energy bands, which is different from the independent analysis of the narrow energy bands. Our model selection is consistent with that in Ackermann et al. (2016).

2.4. Results

2.4.1. Results of the Independent Analysis

In the independent analysis, we divide the LAT gamma rays between 60 MeV and 100 GeV into 12 logarithmic spaced energy bands, each of which has a spectrum fitted by a PL photon model with a fixed photon index of 2.0.

The spectral results in the three templates can be found in Figure 3, in which both the extended and point sources are plotted. As a good residual count map is obtained and the value of “like2obj.getRetCode()” is zero, the fits are thus considered to be good in each independent band. The results of the large-scale disk in the three templates can be found in Table 1. We discuss the results for each template as follows.

1. G template. The G template is useful for distinguishing extended sources from point sources. Apparently, the 60 MeV–100 GeV spectrum of the G1 component cannot be fit by a PL function, thus we will test the fitting goodness with two functions, a PL and a BPL. Three other extended components can be fitted by a PL function within the uncertainties. The spectrum of the point source P1 decays rapidly up to $\sim$4 GeV, which could be fit by a PLC function. The three other point sources can be modeled with a PL function.

2. D template. The emission of the Disk component rises before several hundred MeV and decays up to 100 GeV. The 30 Dor component is observed in 8 independent energy bands, while in 4 other energy bands no significant emission is detected from the 30 Dor component. We understand this to indicate that the luminous point sources P1 and P2 lie near the center of the 30 Dor component. The source P1 shows an initial fast decay and then exhibits no significant emission. The source P2 is observed in three higher-energy independent bands ($>5$ GeV). The emission of the source P3 is detected in three lower-energy bands ($<5$ GeV). The P4 source is decomposed in six energy bands, which can be fitted by a PL function.

3. H template. The emission of the H component rises quickly before 300 MeV, followed by a flat spectrum behavior up to 1 GeV, and then decays to 100 GeV. For the source P1, we obtained the low-level emission in two independent energy bands ($>5$ GeV). The emission of the source P3 is detected in three lower-energy bands ($<5$ GeV). The P4 source is decomposed in six energy bands, which can be fitted by a PL function.

\footnote{https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/extended/extended.html}
which can account for the dim emission and non-detection of P1 and P2, respectively.

Among the three templates, the G template is the best one to decompose the LMC extended and point sources in the independent energy bands. In order to obtain the spectrum of a pure large-scale disk component (G1), we perform an analysis using the G template in the sections below.

2.4.2. Results of the Broadband Analysis

As shown in Figure 3, the spectrum of the independent analysis in the G template has a rapid rise below about 500 MeV and then transits to a much softer spectrum. To quantify the significance of the spectral break, we perform comparative fitting in two broadband energy ranges, i.e., 0.06–2.45 GeV and 0.06–100 GeV. The former energy range

Figure 3. Gamma-ray spectral data of the LMC extended components and point sources, from our independent analysis. Top panel: the G template; middle panel: the D template; bottom panel: the H template. In order to make the spectrum behavior visible, the upper limits are not plotted.
Typically, it is not far from 1.0.

which a characteristic

to test whether the BPL is still a good function to

covers the six independent energy bands and is close to the
ergy range (0.06–2 GeV) used in Ackermann et al. (2013), in

which a characteristic $\pi^0$ decay feature is reportedly found in
two Galactic SNRs. The latter energy range is selected in order
to test whether the BPL is still a good function to fit the
gamma-ray emission up to 100 GeV.

Given an input photon model, the probability of obtaining
the data as observed is noted by $L$, which is the product of the
probabilities of obtaining the observed counts by the LAT in
each bin, i.e.,

$$L = \prod_k \frac{m_k^{n_k} e^{-m_k}}{n_k!} = e^{-N_{\text{pf}}} \prod_k \frac{m_k^{n_k}}{n_k!},$$

where $k$ is an index over image pixels in both space and energy,
$m_k$ indicates the number of counts predicted by the model at
pixel $k$, $n_k$ is the observed number of counts at pixel $k$, and
$N_{\text{pf}}$ is the total number of observed counts.\(^{(10)}\)

We calculate the test-statistic value (TS) defined as

$$-2 \log(L_0/L_i),$$

where $L_0$, $L_i$ corresponds to the likelihood value for the cases without the G1 component and with the G1 component, respectively (Mattox et al. 1996). Since the BPL is a nested model with two additional degrees of freedom (dof) more than the PL, a significant change can be reached when

\[ \Delta \text{TS} \text{ is larger than 25 } (\sim 5\sigma) \text{ from the BPL to the PL, where} \]

\[ \text{https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html} \]
Notes.

a Normalizations in units of $10^{-10} \text{cm}^2 \text{s}^{-1} \text{MeV}^{-1}$.

b Photon index of PL or BPL (pre-break).

c Photon index of BPL (post-break).

d Break energy of BPL.

The TS defined as $2 \log (L_s / L_0)$, where $L_s$, $L_0$ corresponds to the likelihood value for the the case with the G1 or without the G1. $\Delta$TS is the change in TS from BPL to PL, which approximately follows a $\chi^2$ distribution.

$\Delta$TS approximately follows the $\chi^2$ distribution (Ackermann et al. 2013; Harris et al. 2014).

First, we fit the spectrum between 0.06 GeV and 2.45 GeV with the PL and the BPL functions. The BPL yields a significantly larger TS value than the PL, with an improvement of $\Delta$TS $= 66$ (see Table 2), i.e., a statistical significance of $\sim 8.1\sigma$. The photon index is $\Gamma_1 = 1.48 \pm 0.09$ below the break energy of 497 $\pm 78$ MeV, above which the photon index is $\Gamma_2 = 2.35 \pm 0.11$. Second, we test if the BPL model can fit the data in a broader energy range, i.e., 0.06--100 GeV. The BPL still yields a larger TS value, with an improvement of $\Delta$TS $= 180$, i.e., a statistical significance of $\sim 13.4\sigma$ over the PL. The photon index is $\Gamma_1 = 1.39 \pm 0.03$ below the break energy of 532 $\pm 20$ MeV, above which the photon index is $\Gamma_2 = 2.40 \pm 0.03$. The results in both broad energy bands show that the BPL is the better function to fit the gamma rays of the G1 component, indicating that a break at $\sim 500$ MeV exists in the spectrum of the large-scale disk component of the LMC.

2.4.3. Comparative Analysis without the Data between 60 and 200 MeV

To compare with the results in the literature (Ackermann et al. 2016), we perform the spectrum analysis on the Fermi-LAT data after removing the data of 60--200 MeV, i.e., in the energy ranges of 0.2--2.45 GeV and 0.2--100 GeV. The results are shown in Table 2. In the former energy range, the PL model gives a photon index of about 2.0, which is softer than that included in the data below 200 MeV. The BPL has an improvement of $\Delta$TS $= 32$ to the PL, i.e., a statistical significance of $\sim 5.7\sigma$. This, however, is lower than the improvement in the case including the data in the 60--200 MeV range, that is $\sim 8.1\sigma$.

In the case of 0.2--100 GeV, the BPL with a break energy of 490 $\pm 18$ MeV is found to give a better fit than the PL. However, the change in a TS of 70, say $\sim 8.4\sigma$, is much smaller than the case including the data in the 60--200 MeV range, that is $\sim 13.4\sigma$.

The significant improvement of the fit when including the low--energy data of 60--200 MeV favors the existence of the $\pi^0$ decay bump in the gamma-ray spectrum of the LMC disk.

The 60--200 MeV data also provide extra flux points to constrain the physical model parameters statistically; see Section 4.

3. The Physical Models

In this section, we explore the origin of the diffuse gamma-ray emission using the physical models. We consider two radiation models for the gamma-ray data between 60 MeV and 100 GeV, i.e., the electron bremsstrahlung model and the neutral pion decay model.

3.1. The Electron Bremsstrahlung Model

In the electron bremsstrahlung model, we consider both a PL distribution $dN_e/dE_e \propto E_e^{-\Gamma_e}$ and a BPL distribution, i.e.,

$$\frac{dN_e}{dE_e} = C_e (E_e/E_{b,e})^{-\Gamma_e} \quad \text{and} \quad \frac{dN_e}{dE_e} = C_e (E_e/E_{b,e})^{-\Gamma_2}$$

below and above the break energy $E_{b,e}$, for the injected electrons. The bremsstrahlung emission flux emitted by ultra-relativistic electrons can then be given by Foreman et al. (2015):
Table 3

Derived Parameters from the Physical Models for the G1 Component

| Model                              | \(n_H \text{ cm}^{-3}\) | \(B_p \text{ G}\) | \(U_{ph} \text{V cm}^{-3}\) | \(\gamma_1\) | \(\gamma_2\) | \(E_{ph} \text{ MeV}\) | \(s_p^b\) | \(\chi^2/\text{dof}\) | \(\chi_e^{2c}\) |
|------------------------------------|-----------------|----------------|----------------|-------------|-------------|----------------|---------|----------------|-------------|
| Bremsstrahlung\(^d\)              | 0.39\(^\pm\)0.03 | 2.99\(^\pm\)0.17 | 7.80\(^\pm\)0.73 | 1.39\(^\pm\)0.11 | ... | ... | ... | ... | 7.7/6 | 1.28 |
| ...                               | 1.14\(^\pm\)0.10 | 4.94\(^\pm\)0.31 | 0.81\(^\pm\)0.62 | 2.00(fixed) | ... | ... | ... | ... | 11.9/7 | 1.70 |
| Bremsstrahlung with break\(^e\)   | 2.59\(^\pm\)0.19 | 0.08\(^\pm\)0.004 | 0.01(fixed) | 1.45\(^\pm\)0.42 | 2.41\(^\pm\)0.06 | 1318\(^\pm\)382 | 4000(fixed) | ... | 6.7/5 | 1.33 |

\(\pi^0\) decay\(^f\)                                           | ... | ... | ... | ... | ... | ... | ... | ... | 2.45\(^\pm\)0.13 | 7.6/9 | 0.85 |

Notes.

\(^a\) Electron energy spectral index and/or break energy of the injection electron spectrum.

\(^b\) \(s_p\) is the proton energy spectral index for the pion decay model.

\(^c\) The reduced \(\chi^2\). Generally a fit is acceptable when \(\chi^2\) is between 0.75 and 1.50 (Zhang et al. 2011).

\(^d\) Bremsstrahlung with an injection PL electron spectrum with all parameters free (Line 1) or with the electron spectrum index fixed (Line 2). For details please see the text.

\(^e\) Bremsstrahlung with an injection BPL electron spectrum with all parameters free (Line 1, the \(U_{ph}\) is fixed due to attacking the lower boundary) or with an electron spectrum similar to our Galaxy (Line 2). For details please see the text.

\(^f\) \(\pi^0\) decay model with all parameters free.

There are five free parameters for the bremsstrahlung model with a PL injection electron distribution, i.e., \(n_H\), \(B\), \(U_{ph}\), the normalization \((C_p)\), and the injection electron spectrum index \((\gamma_1)\). As for a BPL electron distribution, two additional free parameters are considered, i.e., the post-break spectrum index \((\gamma_2)\) and the break energy \((E_{ph})\).

### 3.2. The Neutral Pion Decay Model

For the neutral pion decay model, the gamma-ray flux is calculated by the semi-analytical method proposed by Kelner et al. (2006):

\[
E^2 F_{\gamma}(E_{\gamma}) = E^2 \int_{E_p}^{\infty} c n_H \sigma_{pp} \left( \frac{dN_p}{dE_p} (E_p) f_p \left( \frac{E_{\gamma}}{E_p} \right) \right) \frac{dE_p}{E_p},
\]

(7)

where \(\sigma_{pp} = 10^{-27} (34.3 + 1.88 M + 0.25 M^2) \) (1 – \(E_{\gamma}/E_p^0\))^2 cm^2 is the cross-section of proton–proton collision, in which \(M = \ln(E_p/1\text{ TeV})\); see Equation (79) of Kelner et al. (2006). Here, \(dN_p/dE_p = C_p E_p^{-b_p}\) is the spectrum of cosmic-ray protons with \(C_p\) normalization, and \(f_p\) is the spectrum of secondary gamma rays produced in a single proton–proton collision, with \(E_p\) and \(E_{\gamma}\) the cosmic-ray proton energy and the generated gamma-ray energy, respectively. There are two free parameters in this model: the proton index \(s_p\) and the product \((C'_p)\) of the normalization of the proton spectrum \(C_p\) and the density of hydrogen atoms \(n_H\), since the \(n_H\) can be extracted from the integration.

### 4. Modeling Result and Discussion

#### 4.1. Method

For our fitting of 11 flux points, the \(\chi^2\) can be derived as

\[
\chi^2 = \sum_{i=1}^{11} \left( \frac{f_{\text{ph},i} - f_{\text{obs},i}}{\sigma^2_{f_{\text{obs},i}}} \right)^2,
\]

(8)

where \(f_{\text{ph},i}\) is the flux predicted by the physical model, and \(f_{\text{obs},i}\) is the LAT-observed flux \((E^2 F(E))\) in the \(i\)th energy bin with a corresponding error \(\sigma_{f_{\text{obs},i}}\). A \(\chi^2\) comparable with the degrees of freedom (dof) is considered as an acceptable fit, i.e., the reduced \(\chi^2\) (labeled as \(\chi^2_e\)) is between 0.75 and 1.50 (Zhang et al. 2011). After deriving a best fit, the resultant \(\chi^2\) is labeled \(\chi^2_{\text{best}}\). The 1\(\sigma\) error of a parameter is calculated by \(\chi^2_{\text{error}} = \chi^2_{\text{best}} + \chi^2_e\), while other parameters are fixed at the best-fit values. \(\chi^2_e\) can be calculated by integrating the \(\chi^2\) probability density function of the corresponding degrees of freedom to 1\(\sigma\).

In our following analysis, we also consider whether the resultant parameter values are consistent with values from other papers or observations (hereafter, reference values). For example, when Bremsstrahlung losses dominate the gamma-ray emission, \(n_H\) can be as high as 2 cm\(^{-3}\) (Kim et al. 2003). The inverse-Compton losses are not important and thus we consider a low photon energy density of \(U_{ph} = 0.57 \text{ eV cm}^{-3}\) (Israel et al. 2010), where we also set a lower boundary of \(U_{ph,\text{limit}} = 0.01 \text{ eV cm}^{-3}\). For the magnetic field strength, \(B\) could be in the range of 2–7 G (Gaensler et al. 2005; Abdo et al. 2010b; Mao et al. 2012; Foreman et al. 2015).

#### 4.2. Modeling Results

Bremsstrahlung with the PL-injected electron spectrum. First, all parameters are unified. The results can be found in Table 3. This fit is acceptable, with \(\chi^2_e = 1.28\). However, the resultant electron spectrum index of 1.39\(^\pm\)0.11 is much harder than that in our Galaxy, i.e., 2.0–2.4 (Porter & Protheroe 1997). Then we allow the electron spectrum index to vary between 2.0 and 2.4 and find that smaller values of the electron spectrum index will result in smaller \(\chi^2_e\) close to 1, which means a good fit. Fixing the electron spectrum index of 2.0 leads to a goodness that is a bit worse, \(\chi^2_e = 1.70\), but gives constraints on all parameters, i.e., \(n_H = 1.14\pm0.10\) cm\(^{-3}\), \(B = 4.94\pm0.34 \text{ \mu G}\), \(U_{ph} = 0.81\pm0.22 \text{ eV cm}^{-3}\), which are comparable to the reference values. The fit with a fixed electron spectral index is considered and plotted in Figure 4.

For a bremsstrahlung with a BPL-injected electron spectrum, initially all parameters are allowed to float. The photon energy density is attacking the lower boundary in this fitting. Thus, we fixed it at 0.01 and fit the data again. The fit is good enough to constrain all parameters and \(\chi^2_e = 1.33\). We note that the magnetic field strength \((B)\) of \(\sim 0.08 \text{ \mu G}\) is much lower than the...
reference value, i.e., 2–7 G, as discussed above. In addition, we use the same electron spectrum as that in our Galaxy, which is also used for the LMC in Foreman et al. (2015), i.e., $s_{\gamma} = 1.80$, $s_{\pi} = 2.25$, and $E_{0,\gamma} = 4$ GeV. This fit is a bit worse, i.e., $\chi^2_r = 2.04$. The derived parameters, i.e., $n_{\text{HI}} = 1.43 \pm 0.14$ cm$^{-3}$, $B = 4.84 \pm 0.35$ G, $U_{\text{ph}} = 0.6 \pm 0.13$ eV cm$^{-3}$, are comparable to the reference values. Thus, the fit with the same electron spectrum distribution as that of our Galaxy is adopted and plotted in Figure 4.

In the pion decay model, the resultant value of chi-squared, i.e., $\chi^2_r = 0.85$, implies a reasonable fit to the data. The best-fit value of the proton index ($s_{\pi}$) is $2.45 \pm 0.13$, which is consistent with the proton index (2.4) obtained by Foreman et al. (2015). Figure 4 shows the results of the pion decay model. Without fixing other parameters, the pion decay model thus is a preferred model to model the gamma-ray emission from the G1 component with an accepted $\chi^2_r$ value.

5. Discussion and Conclusion

Abdo et al. (2010a) first noticed that the gamma-ray emission of the LMC, as detected by the Fermi-LAT, is likely diffuse, i.e., it consists of two diffusion regions, Disk and 30 Doradus. Foreman et al. (2015) reanalyzed the data by employing several combinations of the ionizing gas ($H_\text{II}$) and 160 $\mu$m radiation. They found that the leptonic processes also contribute to the gamma-ray emission of the LMC, i.e., in about 3% of the Disk (excluding 30 Doradus), gamma-ray flux is from inverse-Compton and 18% is from Bremsstrahlung. Employing the high-energy photons above 200 MeV with 6 flux points, they found a proton spectrum index of 2.4.

After subtracting the bright LMC point sources detected by Fermi-LAT (Fermi LAT Collaboration et al. 2015), four diffusion components are decomposed from the LMC region in an emissivity template (Ackermann et al. 2016). In this template, they suggested different origins for these four decomposed diffusion components, i.e., E0, E2, E4, and E1+E3. The emissions from the large-scale disk (the E0 component, largely overlapping with the G1) are likely dominated by a hadronic process, while others likely have leptonic origins. For example, E2 (largely overlapping with G3) and E4 (largely overlapping with G4) could originate from the inverse-Compton process. The E1+E3 component (largely overlapping with the G2) favors a leptonic origin. Without considering the data below 200 MeV, the spectrum of E0 does not have a visible $\pi^0$ decay feature.

In this work, we analyzed the high-energy gamma-ray spectra of the large-scale disk in the LMC, including the data between 60 and 200 MeV that were not considered in previous works. We decomposed a large-scale disk, i.e., the G1 component, from other spatial components in the LMC, and, for the first time, found a spectrum break around 500 MeV for the disk. The obtained gamma-ray emission can be well reproduced by the pionic gamma rays from $pp$-collision between the gas in the LMC disk and protons with a harder spectrum than that in our Galaxy, while the bremsstrahlung emission is marginally consistent with the observed spectrum. We conclude that the current Fermi-LAT data of the LMC large-scale disk emission favor a hadronic origin, although a leptonic model cannot be ruled out completely.

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Facility: Fermi.

Software: Fermi Science Tools package (v10r0p5) (https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation).

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