Tracking origins of gamma rays in the Milky Way galaxy by a Fermi-LAT all sky map

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Abstract. We have used gamma ray data of an all sky map from Fermi-LAT to estimate a mathematical model of emission coefficient to find the origins of gamma rays in the Milky Way galaxy. The emission coefficient is defined for the first time by spherical and cylindrical distributions which are explained by dark matter annihilation and astrophysical sources, respectively. We have provided parameter values from our fitting by least chi-square method. Our parameters for cylindrical distribution are compatible with previous studies, except the thickness of the galactic disk which 10 times bigger than the previous studies since they have set the value of the thickness as 0.100 kpc for a thin cylindrical disk of the Milky Way galaxy but we have considered the whole range of latitude for the all sky map. It indicates that our model has provided a thicker galactic disk than the others. In addition, we have provided the parameter values of spherical distribution which we can apply to constrain properties of dark matter particles in the Milky Way galaxy for future studies.

1. Introduction
Gamma rays are produced by energetic astrophysical sources such as pulsars and supernovae which locate in the cylindrical disk of the Milky Way galaxy [1]. Theoretically, they can also be produced by dark matter annihilation via prompt emission, final state radiation and inverse Compton scattering [2]. Unlike astrophysical sources, dark matter are distributed in a spherical dark matter halo. Fitting a gamma ray map with different shapes of distributions, i.e. cylindrical and spherical shapes, can lead us to a better understanding of the origins of gamma rays.

In this work, we aim to explain the distribution of gamma rays in the Milky Way galaxy by fitting a gamma ray all sky map from Fermi-Large Area Telescope (LAT) with a mathematical function which is a combination of cylindrical and spherical shapes.

2. A model of emission coefficient
According to the assumption that gamma rays can be created by astrophysical sources with a cylindrical distribution and dark matter annihilation with a spherical distribution, unlike the other previous studies, we assume that the emission coefficient can be determined by

\[
\epsilon(l, b, s) = Ar^{-\alpha}(l, b, s) + Br^2(l, b, s)e^{-\frac{R(l,b,s)}{R_0} - \frac{|Z(b,s)|}{Z_0}},
\]

where \( R(l,b,s) \) and \( Z(b,s) \) are the distance and the height above the galactic plane, respectively.
where \( l, b \) and \( s \) are longitude, latitude and the distance along the line of sight in the galactic coordinate. \( Ar^{-\alpha}(l, b, s) \) represents the spherical shape of the emission coefficient in our model. We have adopted \( Br^\beta(l, b, s)e^{-\frac{R(l, b, s)}{R_0} - \frac{|Z(b, s)|}{Z_0}} \) from [3] to represent the cylindrical shape of the emission coefficient, where \( Br^\beta(l, b, s) \) is the emission coefficient that exponentially decreases in radial and vertical distributions. \( R_0 \) and \( Z_0 \) are radial and vertical dependencies, i.e. the radius and the thickness of the galaxy, respectively. The radial distance in the plane of the galactic cylindrical disk is given by

\[
R(l, b, s) = \sqrt{s^2\cos^2(s) + R_{\text{sun}}^2 - 2R_{\text{sun}}\cos(b)\cos(l)},
\]

where \( R_{\text{sun}} = 8.5 \) kpc and the thickness of the cylindrical disk is

\[
Z(b, s) = ss\sin(b).
\]

The radial distance \( r \) of any point measured from the galactic centre is defined by

\[
r(l, b, s) = \sqrt{R^2 + Z^2}.
\]

We leave \( A, B, \alpha, \beta, R_0 \) and \( Z_0 \) as free parameters for the fitting. Finally, the intensity of gamma rays is the integral along the line of sight of the emission coefficient,

\[
I(l, b) = \int_0^\infty \epsilon(l, b, s)ds.
\]

3. Data preparation

We have adopted the gamma ray data of an all sky map with the energy band 0.3 - 0.5 GeV from Fermi-LAT [1]. The data were collected by pixelization to a ring-ordered map. The data can be located by pixel characteristics, i.e. HEALPix coordinates. In this work, we have used the resolution parameter of 256 and ring pixel ordering to locate the data in the galactic coordinate. We have then obtained the intensity of the data by transform the unit of “counts cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)” into “GeV cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) sr\(^{-1}\)” We have divided the data into 180 \times 360 bins according to latitudes and longitudes of the data in the galactic coordinate. The width of each bin is 1\(^\circ\) \times 1\(^\circ\) of the latitude and the longitude. The intensity of each bin is represented by the mean intensity in that bin. The Fermi-LAT all sky map of the energy band 0.3 - 0.5 GeV is shown in figure 1.

![Figure 1. Fermi-LAT all sky map of the energy band 0.3 - 0.5 GeV.](image-url)
In order to fit the data with the mathematical function, we have to subtract point sources in the all sky map. We have applied the technique in [4] since it succeeded to remove the most obvious structures. By following the technique, we have divided the map into 180 bins according to the angular separation $\theta$ from the galactic centre, where $\cos(\theta) = \cos(l)\cos(b)$. For each bin, we have computed the average intensity $I(\theta)_{\text{ave}}$ and estimated the standard deviation $\sigma(\theta)$. An iterative procedure was applied to discard all pixels more than $3\sigma(\theta)$ away from the average intensity $I(\theta)_{\text{ave}}$ until convergence is achieved. Finally, we have recreated a new all sky map with final $I(\theta)_{\text{ave}}$ for each bin of angular separation $\theta$. The all sky map before and after point source subtraction are shown in figure 2.

![Figure 2. Comparison of Fermi-LAT all sky map of the energy band 0.3 - 0.5 GeV before (a) and after (b) point source subtraction.](image)

We have selected the region of $90^\circ \times 90^\circ$ of latitude and longitude measured from the galactic centre to avoid the intensity from the backside of an observer who faces into the galactic centre. The all sky map with the selected region is shown in figure 3.
4. Results and discussions

Parameters $A$, $\alpha$, $B$, $\beta$, $R_0$ and $Z_0$ in equation (1) are derived by fitting the selected Fermi-LAT all sky map with the emission coefficient model in equation (5) by a least chi-square method. For the spherical distribution, $A r^{-\alpha}$, we have obtained $A = 4.728 \times 10^{-29}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ kpc$^{-2}$ and $\alpha = 1.500$. For the cylindrical distribution, $B r^\beta\exp(-\frac{R}{R_0} - \frac{|Z(b,s)|}{Z_0})$, we have obtained $B = 1.134 \times 10^{-27}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ kpc$^{-2}$, $\beta = 0.999$, $R_0 = 1.000$ kpc and $Z_0 = 1.000$ kpc. The parameter values for the spherical and cylindrical distributions are shown in Table 1 together with the values from previous studies [5–7].

Table 1. Parameters obtained from our fitting model compare with previous studies. The Unit of $A$ and $B$ is GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ kpc$^{-2}$

| Models                | $A$       | $\alpha$ | $B$         | $\beta$ | $R_0$ kpc | $Z_0$ kpc |
|-----------------------|-----------|-----------|-------------|----------|-----------|-----------|
| This work             | $4.728 \times 10^{-29}$ | 1.500     | $1.134 \times 10^{-27}$ | 0.999    | 1.000     | 1.000     |
| Lorimer 2004 [5]      | -         | -         | -           | 2.35     | 1.528     | 0.100     |
| Yusifov and Küçük 2004 [6] | -     | -         | -           | 4        | 1.25      | 0.100     |
| Paczynski 1990 [7]    | -         | -         | -           | 1        | 4.5       | 0.100     |

In contrast to other studies, we have considered spherical and cylindrical shapes for the model of gamma ray distribution in the Milky Way galaxy since we assume that the sources of gamma ray are dark matter and astrophysical sources. However there are several studies that explained the gamma ray distribution with a cylindrical shape as shown in Table 1. Since the other studies have shown the value of $B$ as density functions, we do not express theirs values in the table. For
(a) Comparison of Fermi-LAT all sky map

(b) Comparison of Fermi-LAT all sky map

Figure 4. Our model intensity of gamma ray sky map in a function of latitude $b$ and longitude $l$ (a) and in a function of angular separation $\theta$ (b). (b) The magenta line represents the observed intensity from Fermi-LAT all sky map and the blue line represents our model intensity.

the value of $\beta$ we have obtained similar value with the other studies, especially with [7]. For the value of $R_0$, our fitting model have provided similar value as [5,6]. Finally, the other studies have set the value of $Z_0$ as 0.100 for a thin cylindrical disk of the Milky Way galaxy. However since we have considered the whole range of latitude for the all sky map, our value of $Z_0$ is 10 time bigger than the other studies. It indicates that our model has provided a thicker galactic disk than the others. Our value of $Z_0$ is possible according to [3] where they also claimed that $Z_0 = 0.100$ is too thin. A modeled gamma ray sky map which created by the parameters obtained from our model are shown in figure 4 in the function of latitude $b$ and longitude $l$ together with a function of angular separation $\theta$.

For further studies, we would like to apply this fitting method to another 11 energy bands of Fermi-LAT all sky map to improve the precision of our parameters. We can apply the spherical distribution to constrain dark matter density profile in the Milky Way galaxy. We can also use the distribution function of gamma ray from our model to investigate further to the electrons and positrons distribution in our galaxy since gamma rays can be produced by energy loss processes of electrons and positrons, e.g. inverse Compton scattering.

Acknowledgments

K. Ngernphat gratefully acknowledge that this research is supported in part by the Graduate Program Scholarship from the Graduate School, Kasetsart University. G. Saowanit would like to thank DPST for a scholarship. M. Wechakama would like to acknowledge that this research project is supported by Kasetsart University Research and Development Institute (KURDI).

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