Diffused Gamma-rays and the Cosmic-ray Propagation

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Abstract

We present analytically the spatial distribution of diffused γ-ray as well as the energy distribution. We assume our Galaxy is boundaryless both in longitudinal and the latitudinal directions, and the Galactic parameters such as the diffusion coefficient and the gas density depend on the position $\boldsymbol{r}(r, z)$.

We found both the longitudinal and the latitudinal spread of diffused γ-ray near the Galactic plane are well reproduced by $\pi^0 \to 2\gamma$ process if we choose appropriate Galactic parameters.

We also discuss the energy distribution from the Galactic plane, focussing to the enhancement problem of the diffused γ-ray, nowadays indisputable.

1. Introduction

While the γ-ray observation has opened a new window for both the astrophysics and the astronomy, it brings us also invaluable informations as well as a new puzzle for the cosmic-ray physics. For instance, most of the diffused γ-ray flux from the Galactic plane comes from the decay of neutral pions, predominantly produced by the collisions of cosmic-ray protons and the interstellar gas. Nevertheless, the observed γ-ray intensity above 1GeV is approximately of a factor of two larger than expected from local cosmic-ray flux[1]. Some authors[2] have suggested that the proton spectrum might be a flatter spectrum in central regions of the Galaxy.

In this paper, based on our propagation model[3], we present the lateral spread of diffused γ-ray near the Galactic plane, and compare EGRET data[1], and discuss a possible explanation of the above mentioned puzzle in the enhancement of the diffused γ-rays.

Before going to the numerical results, we would like to stress here that the cosmic-ray density, $N(\boldsymbol{r})$, obtained by our model is not uniform in the Galaxy, but depend on the position $\boldsymbol{r}$. We have found $N(0, 0)$, the cosmic-ray density at the Galactic center, is of approximately three times larger than $N(r_\odot, 0)$, the density at the solar system, as discussed in the next section.

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2. Proton Spectrum

Remarking the relation between the cosmic-ray density N_p and the intensity I_p is given by

$$I_p(\boldsymbol{r}; R) = \frac{v}{4\pi} N_p(\boldsymbol{r}; R), \qquad (1)$$

where R is the rigidity of the proton, and $v\,(\approx c)$ its velocity, we can write down the proton intensity at the *solar system*,

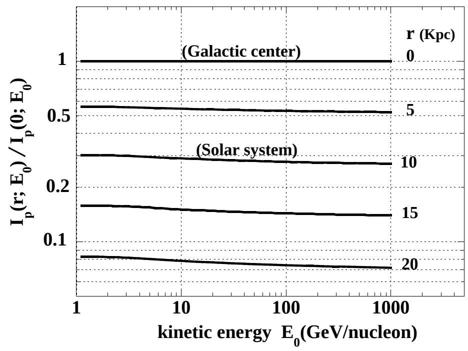

Fig.1. Relative proton intensity.

$$I_{\odot p}(R) = \frac{c}{4\pi} \frac{Q_\odot}{D_\odot} \frac{\mathcal{I}_\nu(U_{\odot,R}) \bar{z}^2 R^{-\beta}}{U_{\odot,R} I_{\nu-1}(U_{\odot,R})}, \qquad (2)$$

and

$$U_{\odot,R} = 2\nu R^{-\alpha/2} \sqrt{\frac{\sigma_p}{\sigma_\odot}}, \qquad \text{with} \ \ \sigma_\odot = \frac{D_\odot}{n_\odot c z_D^2}, \qquad (3)$$

$$D_\odot = D(r_\odot, 0), \quad n_\odot = n(r_\odot, 0), \quad Q_\odot = Q(r_\odot, 0). \qquad (4)$$

Here all variables and functions appearing above are the same as those defined in Paper I[3]. One should note $D_\odot$, $n_\odot$, and $Q_\odot$ are the diffusion coefficient, the gas density and the cosmic-ray source density at the solar system. The proton spectrum at the Galactic center, $I_{0p}(R)$ is also obtained immediately by putting $r_\odot = 0$ in Eq. (2), and then the ratio, $I_{\odot p}(R)/I_{0p}(R)$, is easily obtained.

In Fig. 1, we demonstrate the numerical result of the relative proton intensity against the intensity at the Galactic center, $I_p(r; E_0)/I_p(0; E_0)$, at five observational points, r=0(Galactic center), 5, 10(Solar system), 15 and 20Kpc, where we use the kinetic energy/nucleon in place of the rigidity R.

One finds the proton intensity at the solar system is approximately of 1/3 of the intensity at the Galactic center, while the slope doesn't change so drastically. It tells us that we have to take care of this effect, when we compare the diffused γ-ray from the Galactic plane with the proton spectrum observed at the solar system.

3. Gamma-ray Spectrum

Once we have the density of proton component observed at $\boldsymbol{r}$, $N_p(\boldsymbol{r})$, it is straightforward to estimate the γ-ray intensity at the solar system, coming from the direction $\boldsymbol{\theta}(l, b)$, (here we omit the rigidity term for the sake of simplicity)

$$\frac{dI_{\odot\gamma}(\boldsymbol{\theta})}{dld(\sin b)} = \frac{1}{4\pi} \int_0^\infty N_p(\boldsymbol{r}) n(\boldsymbol{r}) v \sigma_{p\to\gamma}\, dL, \qquad (5)$$

where $\sigma_{p\to\gamma}$ is the production cross section of γ-rays, and the integration is performed along the arrival direction of γ-rays, $\boldsymbol{\theta}(l,b)$. The production position of γ-rays, $\boldsymbol{r}(r,z)$, appearing in the above integrand is of course bounded to $r_\odot$ and (l,b,L), namely $\boldsymbol{r} \equiv \boldsymbol{r}(r_\odot; l,b,L)$. If we measure the path length L in units of $r_\odot$, i.e., $L = sr_\odot$, explicit forms of (r,z) are given by

$$r = r_\odot \mathcal{S}_{/\!/}(s), \quad \text{and} \quad z = r_\odot \mathcal{S}_\perp(s), \tag{6a}$$

$$\mathcal{S}_{/\!/}(s) = \sqrt{1 + s^2\cos^2 b - 2s\cos b\cos l}, \quad \text{and} \quad \mathcal{S}_\perp(s) = s\sin b. \tag{6b}$$

Assuming the energy spectrum of γ-rays produced by the proton interaction with hydrogen gas,

$$\sigma_{p\to\gamma}(R_\gamma, R)dR_\gamma = \sigma_p \varphi_\gamma\Big(R_\gamma, \frac{R_\gamma}{R}\Big)\frac{dR_\gamma}{R}, \tag{7}$$

we have

$$\frac{dI_{\odot\gamma}(\boldsymbol{\theta}; R_\gamma)}{dl d(\sin b)} = \frac{r_\odot}{4\pi}\int_{R_\gamma}^\infty \varphi_\gamma\Big(R_\gamma, \frac{R_\gamma}{R}\Big)\frac{dR}{R}\int_0^\infty N_p(\boldsymbol{r}; R)n(\boldsymbol{r})v\sigma_p ds, \tag{8}$$

where σ_p is the inelastic p-p collision, and R_γ is the γ-ray energy. We don't present here the explicit form of φ_γ because of limited space, but give only the numerical results of the above integration in the next section. We will report separately the detail of the production cross section of γ-rays, reproducing well the accelerator data of p-p collisions nowadays available in the wide energy range $1 \sim 1000\,\text{GeV}$ in laboratory system.

4. Numerical Results and Discussion

In Fig. 2, we show the longitudinal distribution of diffused γ-rays with the energy range of 1-2GeV obtained by EGRET[1]. We show three cases of the radial scale heights of the gas density, r_n=12.5, 15.0, and 17.5Kpc, while the scale height vertical to the disk, z_n, is fixed to 0.5Kpc, since the longitudinal distribution depends on weakly z_n. Other parameters are not so sensitive to the longitudinal distribution, which are set so that the data of the secondary to primary ratio[4] is well reproduced (see Ref. [4] for explicit numerical values).

In Fig. 3, we show the latitudinal distribution of the diffused γ-rays with the energy range of 1-2GeV. We show three cases of the scale heights of the gas density vertical to the disk, z_n=0.3, 0.5, 0.7Kpc, while the radial scale height, r_n, is fixed to 15Kpc, since the latitudinal distribution depends on weakly r_n.

One should note that we show only the *relative* intensity of the diffused γ-ray in Figs. 2 and 3, and the absolute value will be reported in the conference.

We found z_n=0.5Kpc, r_n=15Kpc seems to reproduce well the observed data, while the contributions of metagalactic and/or the inverse compton γ-rays

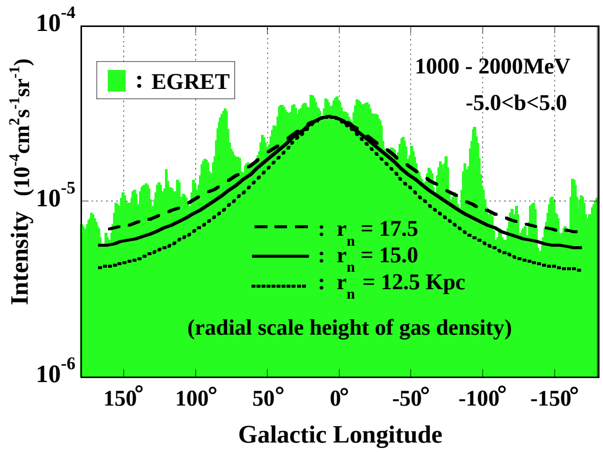

Fig. 2 Longitudinal distribution of diffused γ-ray.

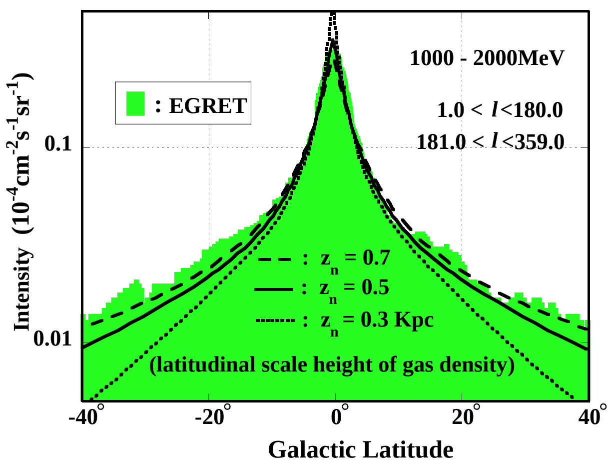

Fig. 3 Latitudinal distribution of diffused γ-ray.

component become significant in higher latitude in Fig. 3. One might note that the value z_n=0.5Kpc is much larger than the current one, $\sim$ 0.15Kpc. The long tail in the gas density normal to the disk also might be consistent with the enhancement of γ-ray energy spectrum.

Numerical calculation for the energy spectrum is unfortunately not in time for the present paper, but we will report it in the conference.

1. Hunter S. et al. 1997, ApJ 481, 205
2. Mori M. 1997, ApJ 478, 226
3. Hareyama M., Nakazawa M., Saito C., Suzuki R., and Shibata T., in this proceeding (OG 1.3, ID 8516-1).
4. Hareyama M., Nakazawa M., Saito C., Suzuki R., and Shibata T., in this proceeding (OG 1.3, ID 8516-2).