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Diffuse gamma-ray emission of the galactic disk and Galactic Cosmic-Ray spectra

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Assuming that supernova shocks accelerate Galactic cosmic rays and that the shock compression ratio is supernova remnant (SNR) age dependent, the source injection spectrum from an ensemble of SNRs is calculated by considering the SNRs age distribution in the galaxy. The calculated spectrum is used to obtain the cosmic-ray spectrum in the galaxy and the resulting diffuse gamma-ray spectrum is compared with the EGRET data. Some results on the observed cosmic-ray spectra are also discussed.

1. Introduction

Above ∼ 1 GeV, the diffuse Galactic γ-ray spectrum measured by the Energetic Gamma Ray Experiment Telescope (EGRET) exceeds significantly the spectrum calculated using the locally measured proton and electron spectra [2]. Explaining the excess requires a proton spectrum with index ∼ 2.4−2.5 [1] which is much flatter than 2.75, the locally measured vaue. Many authors have given different views to explain the excess (as is briefly mentioned in [8]). In a recent paper [3], it has been pointed out that there is no firm relationship between the radio spectral index and the age of the remnant. But, shock acceleration theory predicts a correlation between the spectral index and the shock velocity (which in turn relates with the SNR age) as [9]

$$q(t) = \frac{4M(t)^2}{M(t)^2 - 1} \tag{1}$$

where $M(t) = U(t)/c_s$ is the Mach number of the shock defined as the ratio of the shock velocity $U(t)$ to the sound speed of the unshocked intersteller medium c_s and t is the SNR age in years.

2. SNR age distribution

Considering only the shell type SNRs whose ages are known as is given in Table 1 of [3], a statistical analysis gives a relation between surface brightness Σ and age of SNRs as

$$\Sigma = (1.7 \pm 1.9) \times 10^{-18} t^{-0.62\pm0.1} W m^{-2} Hz^{-1} sr^{-1} \tag{2}$$

The best fit line is shown in Fig.(1a). This decrease of the brightness with SNR age is expected because of the decrease of the number of energetic particles, due to energy loss and escape from the SNR, and the increase of the SNR size with age. The ages of all the remaning shell type SNRs whose ages are not known but whose surface brightness are known (e.g as given in [4]) are calculated by using equation 2. The normalized distributions of the ages in the galactic regions: Region I ($330 < l < 30$) and Region II ($30 < l < 330$) are shown in Fig.2. The distributions can be fitted with the gaussian

$$n(x) = a_0 exp[-0.5((x - a_1)/a_2)^2] \tag{3}$$

where $x = log_{10}t$. The fitted parameters for the two regions are given in Table 1. It is found that the SNRs in Region I has a mean value of age ∼ 12000 yrs, much younger than those in Region II which has a mean value ∼ 27000 yrs.

Table 1. Fitted parameters for age distribution in the two galactic regions

Fit parameter	Region I $(330 < l < 30)$	Region II $(30 < l < 330)$
a_0	0.246	0.236
a_1	4.096	4.425
a_2	0.884	0.971

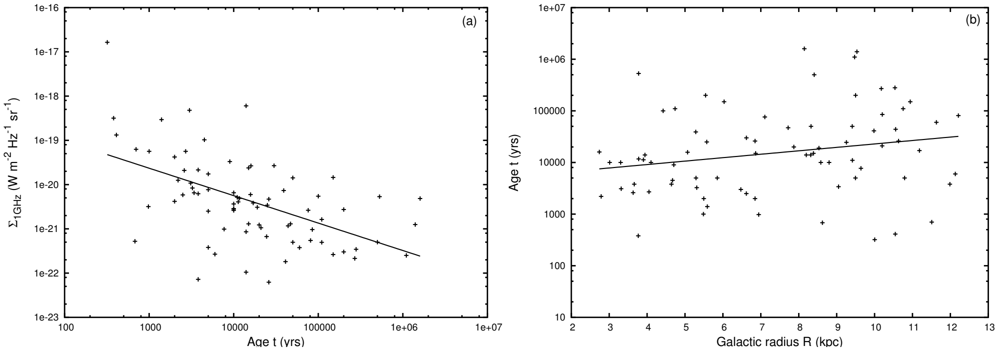

Figure 1. (a) Plot of surface brightness Σ against age t and (b) Plot of age against galactic radius R. Both the plots are for 77 shell-type SNRs whose ages are given in [3]. The solid line is the best fit line.

3. Galactic cosmic-ray spectrum

Acceleration of cosmic rays in plane, steady shocks in which the cosmic rays do not influence the shock structure produces a power law spectrum of the form [5,6]

$$f(p,t) = q(t)p^{-q(t)} \int^{p} dp' g(p',t) p'^{\,q(t)-1} \tag{4}$$

where $f(p,t)$ is the isotropic accelerated particle distribution function at time t arising from an injected distribution $g(p',t)$ at time t. For constant injection of monoenergetic particles of momentum p_0 with density n_0,

$$f(p,t) = \frac{n_0}{4\pi p_0^3} q(t)(p/p_0)^{-q(t)} \tag{5}$$

Multiplying this by the SNR age distribution function and integrating from t_0 to t_f, the start and end of the Sedov phase respectively, the particle spectrum from an ensemble of SNRs is calculated as

$$f(p) = \frac{n_0}{4\pi p_0^3} \int_{t_0}^{t_f} q(t)(p/p_0)^{-q(t)} n(x) dt \tag{6}$$

For particles injected at 1 KeV into a shock with initial Mach number $M_0 = 10$, the particle energy spectrum resulting from equation (6) is used as the source term $Q(E,z) = Q_0(E)\delta(z)$, injected into the galaxy at the galactic plane, i.e. $z = 0$. Then, the cosmic ray electron spectrum in the galaxy is given by the solution of the following stationary, one dimensional convection-diffusion equation

$$\frac{\partial}{\partial z}\left[D(E,z)\frac{\partial N}{\partial z} - V(z)N\right] + \frac{\partial}{\partial E}\left\{\left[\frac{1}{3}\frac{\partial V}{\partial z}E - \beta(E,z)\right]N\right\} + Q(E,z) = 0 \tag{7}$$

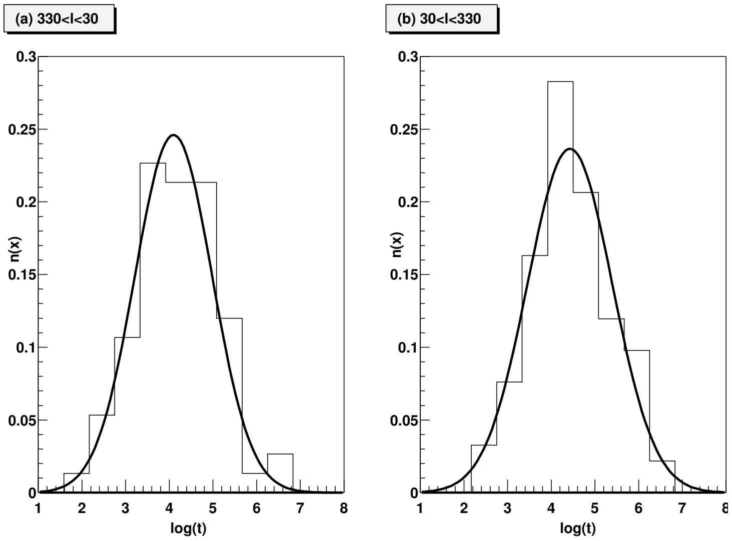

Figure 2. Normalised distributions of SNR ages in sky regions: (a) Region I (330<l<30) for 75 shell-type SNRs (b) Region II (30<l<330) for 92 shell-type SNRs. $x = log_{10}t$, where t is the SNR age. The thick curve is the fitted gaussian.

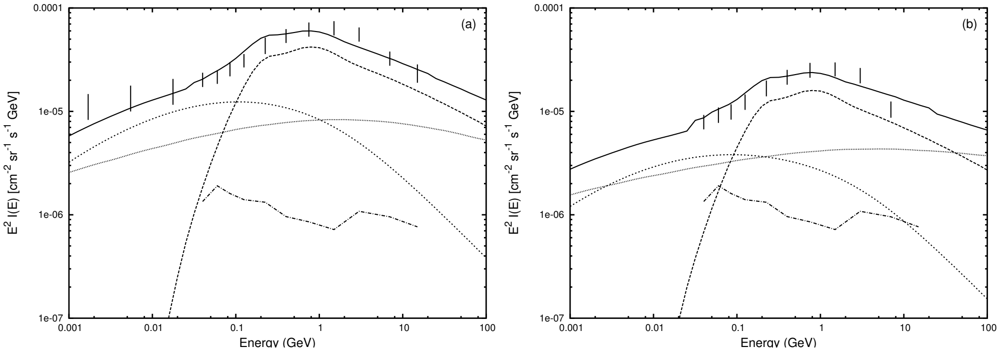

Figure 3. Diffuse γ-ray spectrum : (a) Region I (330<l<30) assuming w_p= 2 eV/cm^3, w_e= 0.06 eV/cm^3, n$_{HI}$+2n$_{H_2}$= 1 cm^{-3}, w_{MBR}= 0.25 eV/cm^3, w_{NIR}= 1.5 eV/cm^3,w_{FIR}= 0.2 eV/cm^3 (b) Region II (30<l<330) assuming w_p=1.7 eV/cm^3, w_e= 0.045 eV/cm^3, n$_{HI}$+2n$_{H_2}$= 0.45 cm^{-3}, w_{MBR}= 0.25 eV/cm^3, w_{NIR}= 0.5 eV/cm^3, w_{FIR}= 0.2 eV/cm^3. l$_d$= 15 kpc. Data points [8] : COMPTEL (long vertical bars) and EGRET (short vertical bars). Model components : π^0 decay (long dashed line), bremsstrahlung (short dashed line), IC (dot), EGRB (dot-dashed line) and total (solid line).

where N is the differential number density at a distance z perpendicular to the galactic plane, D is the diffusion coefficient, V is the convection velocity and $\beta = \frac{dE}{dt}$ is the particle energy loss rate. The transport equation for protons is obtained by adding a catastrophic loss term $[-\frac{N(E,z)}{\tau_{pp}(E,z)}]$ to the left-hand side of equation (7), where $\tau_{pp} = \frac{E}{(dE/dt)_\pi}$ is the catastrophic loss time scale and $(dE/dt)_\pi$ is the energy loss rate due to pion production. Following the exact analytical procedure presented in [7], the resulting cosmic-ray electron and proton spectra are used to calculate the diffuse γ-ray flux from the galactic disk.

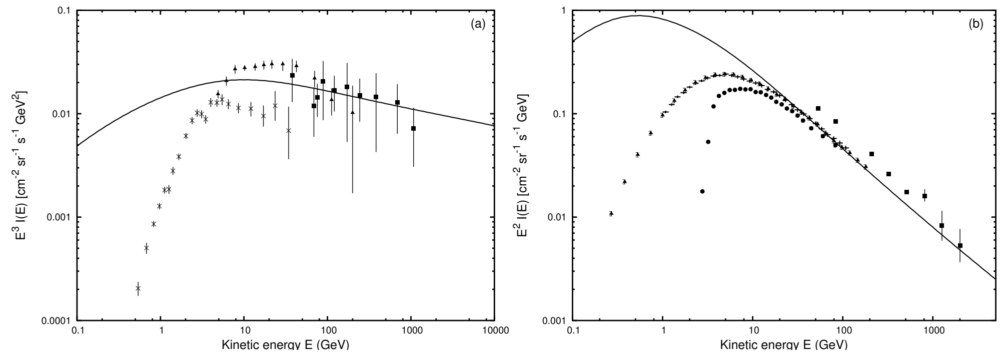

Figure 4. Cosmic-ray spectrum near the solar region. (a) Electron spectrum: Data points are ■ Nishimura 1980, ▲ Tang 1984, × Boezio 2000 (b) Proton spectrum : Data points taken from [10]. Solid line is the predicted spectrum normalised to observations at 6 GeV for electrons and 20 GeV for protons.

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4. Results and discussions

The diffuse γ -ray spectrum calculated for the two sky regions are shown in Fig.3. Considering the SNR radial distribution in both the regions, it is found that the SNR age distribution of Region I is a good representative for the galactic region within a galactic radius $R \sim 5kpc$. But, for the remaining galactic region $R > 5kpc$, the distribution of Region II gives a better representation. Using this, a crude prediction of the observed local cosmic-ray spectra is obtained from Region II by decreasing the parameter a_2 to a value of ~ 0.2, i.e. by narrowing the distribution. This approximation has a physical reason since it is found that the SNR age t increases with the galactic radius R as shown in Fig.(1b). By narrowing the age distribution, those SNRs with ages $t_1(R_1)$ which are younger and also those with ages $t_2(R_2)$ which are older than the local SNRs with ages $t_s(R_s)$, where $(R_1 < R_s < R_2)$, are removed from the distribution. The cosmic-ray spectra resulting from this narrow age distribution is shown in Fig.4.

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