Energy Spectrum and Confinement Time of Cosmic-ray Electrons

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ABSTRACT

The observations of primary electrons have been performed with emulsion chambers by 11 balloon flights since 1968. Including new data, we have an improved observed spectrum, ranging from 30 GeV to a few TeV, which is consistent with our previous data. Combing with other data, we derive the confinement time of electrons in the Galaxy. The result is [0.7-2.2]x10^7yr, which is consistent with the recent observed data by radio isotope. For more detailed analysis of the electron spectrum, we discuss the constraint of the model based on the possible origin of super nova sources.

1. INTRODUCTION

Cosmic-ray electrons are revealing several important aspects of astrophysical significance. At a higher energy side beyond 1TeV, electrons can not travel far distance because of the synchrotron and inverse Compton losses. They must be produced within the past less than about 10^5 years and the sources should be nearby the solar systems. Extending the observations to further high energy side, it might be possible to identify the nearby sources, if electrons are in fact produced from the individual sources [1]. In the medium energy regions, say 10 to 100GeV, the spectrum bends by the synchrotron losses which gives us a clue for the confinement time of electrons inside the Galaxy. However because of the difficulty of the observations, the definitive conclusion was difficult to be derived.

We first describe our recent observations on the electron spectrum. Analyzing the spectrum combining with other data, we derive the confinement time on the basis of Leaky Box Model. However, since synchrotron radiation by high energy electrons from Super Nova Remnants is observed, it is quite possible that at least a certain fraction of the electrons is produced from SNR. We then estimate this effect in the scheme of Nested Leaky Box Model by analyzing the relative intensity of the radio flux from SNR and the Galaxy. The results indicate the effect is minor to discuss the confinement time of electrons in the Galaxy.

2. OBSERVATIONS

After our previous paper [2], we continued the observation of primary electrons by balloon–borne emulsion chambers. Summarizing 11 flights since 1968, the total effective exposure factor becomes 588,848 [m^2 sr sec] excluding edge area that was not used in the analysis. The emulsion chamber used in these experiments provides the most suitable instrument to measure primary electrons. Namely, it permits efficient detection of events with the aid of high sensitive X-ray films. Also it allows precise incident particle identification, accurate energy determination and a large effective area of the detectors with a large acceptance. Our emulsion chamber consists typically of a stack of 24 detection layers. Each layer is made up an emulsion plate, X-ray films and a lead plate. We now incorporate high sensitivity screen–type X–ray films, such as Fuji G8–, G12– and newly provided GS–RIO [3] which are combinations of Gd_2O_2S:Tb phosphor screen and a green sensitive Fuji X–ray film. The detection threshold of these X–ray films is improved to about 150 GeV.

The contribution of atmospheric secondary electrons is carefully examined under Approximation A of Cascade Theory by using the observed data of the atmospheric γ–ray spectrum [2]. In Figure 1, primary electron energy spectrum in the form of E^3xFlux, derived from all of our data, is shown along with the data of Golden et al.[4] and Tang [5] together with the results derived from the Galactic radio wave intensities [6].

The resulting primary electron energy spectrum, J(E), in the form of a power law is well represented by

$$J(E)=(1.5\pm0.3) \times 10^{-4} [100\mathrm{GeV} / E]^{3.3\pm0.1} \ [m^{-2}sr^{-1}sec^{-1}GeV^{-1}], \qquad [1]$$

and is consistent with our previous data [2].

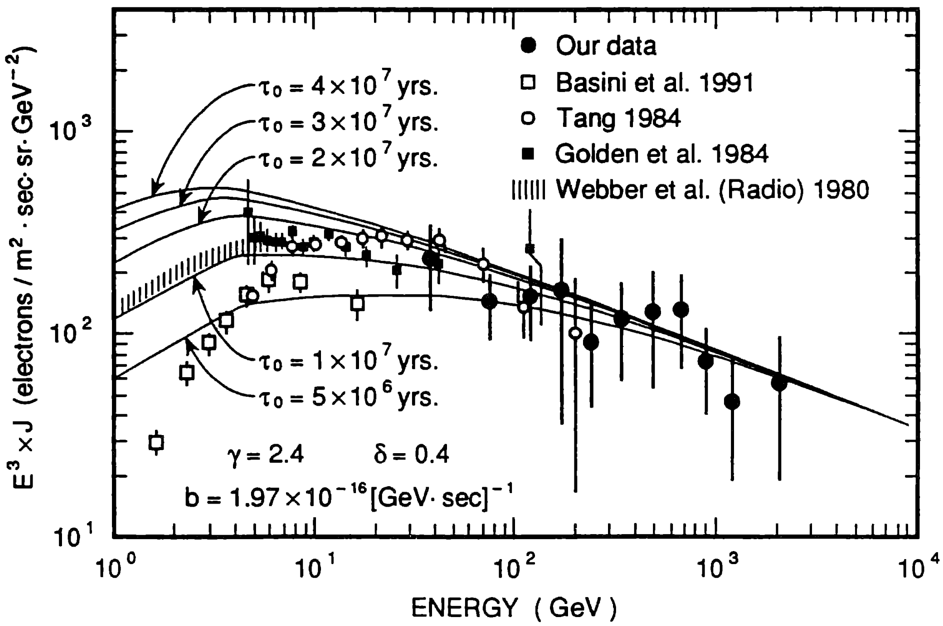

Fig. 1 : Observed Spectrum of Cosmic-ray Electrons. Solid line is due to the LBM.

3. THE CONFINEMENT TIME OF ELECTRONS INSIDE THE GALAXY

From the spectrum shown in Fig. 1, it is most likely the bending of the spectrum exists between 10GeV and 40GeV, although the statistics of the data are not good enough. Assuming the leaky box model, we have a relation of the cosmic ray confinement time in the Galaxy to this bending energy as shown in Figure 2.
Here we assume

1. Cosmic ray electrons are produced in the source region with power law energy spectrum of the form: $N(E)dE = E^{-\gamma}dE$.
2. Energy loss of cosmic ray electrons above a GeV can be written as
$dE/dt = -bE^2$, with $b = 1.02\times10^{-16} (W_{ph} + \langle H^2\rangle/8\pi)$ [GeV sec]$^{-1}$

We take for the most probable value of b as 1.97×10^{-16} [GeV sec]$^{-1}$, by adapting 6.7 μG[1.11 eV / cm^3] for the Galactic magnetic field [6], 0.26eV /cm3, 0.31eV /cm^3 [7], and 0.25 eV/cm^3 for energy density of visible, infra-red and 3 K microwave respectively.

In the Leaky Box Model, the leakage life time τ is related the bending point, Ec as

$$E_c = [(\gamma-1)b\tau_o 5^{\delta}]^{-1/(1-\delta)} \quad \text{with} \quad \tau = \tau_o\,(5\mathrm{GeV}/E)^{\delta}.$$

Taking the value of spectral exponent, γ , as $\gamma = 2.7 - \delta$, we have the confine time of

$$\tau_o = (0.7\text{-}2.2) \times 10^7 \text{ yr} \qquad \text{for} \qquad \delta = 0.4\text{-}0.6$$

$$\tau_o = (1.3\text{-}2.2) \times 10^7 \text{ yr} \qquad \text{for} \qquad \delta = 0.6$$

It is to be noted that the confinement life time obtained by the electron spectrum is accurate enough when compared to other isotope measurements. Observations of the ratio of ^{10}Be / ^{9}Be have been performed by various authors, and results of the confinement time are scattered ranging 6×10^6 yr to 2.2×10^7 yr [8]. A recent summary by Shapiro et al [9] combining all observed data by putting appropriate weight to each datum suggested the most probable value of the confinement time to be

$$(0.79\text{-}1.43) \times 10^7 \text{yr} \quad \text{or} \quad (0.64\text{-}1.28) \times 10^7 \text{ yr}$$

depending on the cross sections of this reaction. The confinement time as derived from ^{26}Al / ^{27}Al, $(4.1\pm 2.4) \times 10^7$ yr, still suffers from large errors in the observed data.

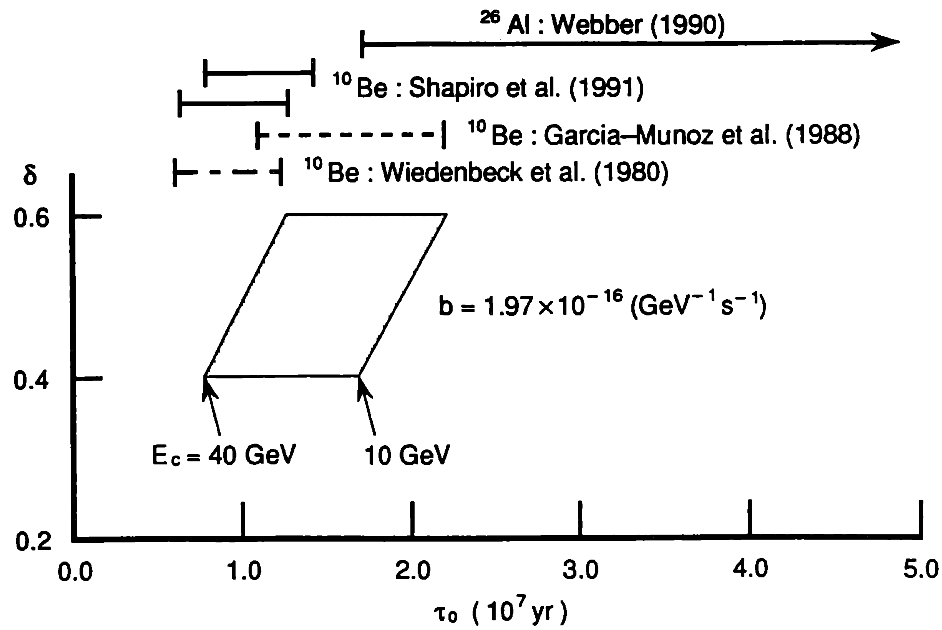

Fig. 2 : The Relation of the confinement Time and the bending Energy

4. PROPAGATION MODEL

4.1 Leaky Box Model

As for the spectral fitting , we have a reasonable agreement for the observed spectrum as shown in Fig. 1 by taking the following parameters of

$$\gamma = 2.4 \qquad \delta = 0.4 \qquad \tau_o = 1.3 \times 10^7 \text{ yr}$$

$$b = 1.97 \times 10^{-16} \text{ [GeV sec]}^{-1}, \text{ yielding } E_c = 12.8 \text{ GeV}$$

4.2 Electrons from SNR

Since the synchrotron radiation by high energy electrons is observed from supernova remnants, it is plausible to assume that at least a certain fraction of cosmic-ray electrons is produced from SNR. In this case, we need to treat the propagation of electrons by the Nested Leaky Box Model, and need to take into account of the effect of energy loss inside the source region. In order to see the effect clearly, first we assume the extreme case that all cosmic-ray electrons are produced inside the SNR, and diffuse out to the Galactic space. The important parameter in this case is α which indicates the degree of the energy loss inside SNR compared with the loss inside the Galaxy. Putting suffix S and G to those parameters in the SNR and Galaxy respectively, α is defined by :

$$b_S \tau_S = \alpha b_G \tau_G \, . \qquad (2)$$

When α is much smaller than unity, the bending point of the spectrum inside the source (E_{cS}) is larger than the bending energy (E_{cG}) due to the energy loss inside the Galaxy. In this case, the Leaky Box Model still gives a reasonable result up to a certain limited energy region below E_{cS} Then the value of α is crucial to estimate the effect of the propagation inside the source in the Nested Leaky Box Model. The evaluation of α was made by Komori and Nishimura [6], by assuming that the electrons produced from SNR is in equilibrium to the leakage of the electrons from the Galaxy,

$$N_S(E) / \tau_S = N_G(E) / \tau_G \, , \qquad (3)$$

where N(E) is the total number of electrons inside each respective region. The ratio of total radio flux from each region, $F_S(v)$ /$F_G(v)$ is calculated, by using the strength of magnetic field of H_S and H_G ineach region as

$$F_S(\nu)/F_G(\nu) = [N_S(E)/N_G(E)]\,[H_S/H_G]^{(\gamma+1)/2} = (\tau_S/\tau_G)(H_S/H_G)^{(\gamma+1)/2}$$
$$= \alpha[b_G/b_S]\,[H_S/H_G]^{(\gamma+1)/2} = \alpha[H_S/H_G]^{-2+(\gamma+1)/2} \quad (4)$$

Komori and Nishimura made careful analysis for the observed ratio for the radio flux of $F_S(\nu)/F_G(\nu)$, obtaining the value of about 10^{-2}. Since the estimated maximum value of H_S is of the order of 10^{-4} Gauss, the value of $[H_S/H_G]$ is estimated within the range between 1 and 100. Then we have a value of $\alpha = 0.01 - 0.1$ referring to the formula (4).

In the case of Nested Leaky Box Model, we have more free parameters, giving better agreement with the observed data than in the case of the Leaky Box Model. As an example, we show a good agreement with observed spectrum in Fig. 3.

Taking this estimated value for α of 0.01 to 0.1, the bending point inside the source, E_{CS} is much larger than the bending point in the Galaxy, E_{CG} The Leaky Box Model gives the reasonable results below E_{CS} and the arguments for the Galactic confinement time discussed by using the Leaky Box Model are justified.

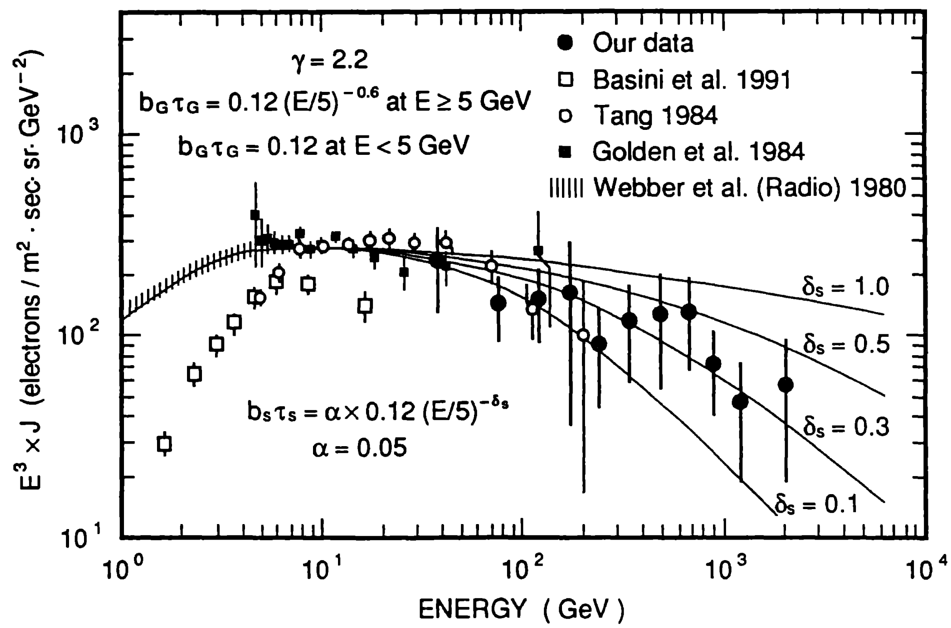

Fig. 3 : Spectral Fitting by the Nested Leaky Box Model

References:

[1] J. Nishimura, M. Fujii and T. Taira, Proc. 16th ICRC, 1, 488 (1979).
[2]. J. Nishimura, et al. Ap. J., 238, 394 (1980).
J. Nishimura, et al., Proc. 21st ICRC, 3, 213 (1990).
[3] T. Kobayashi et al., Nuovo Cimento, 104 A, 1753 (1991).
[4] R.L. Golden et al., Ap. J., 287, 622 (1984).
G. Basini et al., Proc. 21st ICRC, 2, 137 (1990).
[5] K.-K. Tang, Ap. J., 278, 881 (1984).
[6] J.M.Rockstroh and W.R.Webber, Ap.J.,224,677(1978)
W.R.Weber, G.A.Simpson and H.V.Cane, Ap.J.,236,488(1980)
Y. Komori and J. Nishimura, to be published in Astrophys. Space Sci.
[7] P. Cox and P.G. Mezger, Astron. Astrophys. Rev., 1, 49 (1989).
[8] A.J. Simpson and M. Garcia-Munoz, Space Sci. Rev., 46, 205 ,(1988)
. M.E. Wiedenbeck and D.E. Greiner, Ap. J. Lett., 239, L139 (1980).
W.R. Webber, Proc. 21st ICRC, 3, 393 (1990).
[9] M.M. Shapiro et al., Proc. 22th ICRC, 4, 304 (1991).