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Propagation of cosmic-ray electrons in the Galaxy

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Abstract

We formulate the global propagation model of cosmic-ray electrons including the source region, which is currently considered to be supernova remnants (SNRs). The model is characterized by the escape rate of electrons from SNRs into the interstellar space. It becomes clear that the energy index of the escape rate influences the high energy side of the interstellar spectrum and makes it possible to explain the observed data up to 2 TeV in the case of source spectral index smaller than 2.2 that is expected from the radio spectrum in SNRs. The escape lifetime of electrons in SNRs is also discussed by using the ratio of the radio flux in two regions: SNRs and the Galaxy. The result shows the mean lifetime in SNRs of $\sim 10^4$ yr around 1 GeV, which corresponds to the SNR age in the Sedov phase.

Keywords: Cosmic-ray electrons; Propagation; Supernova remnants; A leaky box

1. Introduction

The supernova remnants (SNRs) are most likely sources of cosmic-ray electrons because the non-thermal radio emission from SNRs indicates the existence of high energy electrons in SNRs. Duric et al. (1995) have investigated the galaxy M33 and estimated the ratio of the total SNR emission to the Galactic background emission. They have concluded that SNRs are enough to be the candidate of cosmic-ray sources. In this paper we apply the similar estimate to our Galaxy.

The simplest model of the cosmic-ray propagation is a leaky box model that has been used for estimation of the escape length of cosmic rays in the Galaxy. The source index of cosmic rays is expected to be 2.1–2.4 from the nuclei data: the value of 2.1–2.2 is given by the difference between the proton spectral index of 2.7 (e.g. Menn et al., 2000) and the rigidity index of the escape length of 0.5–0.6 from the B/C and sub-Fe/Fe ratios (e.g. Ptuskin et al., 2001), or 2.4 is given by the index of 0.3 expected from the Kolmogorov's law of turbulent magnetic field. Meanwhile, the average radio index of 0.5–0.6 in SNRs (Green, 2004) indicates the index of 2.0–2.2.

For the first step we present the global model in which the source region is regarded as a leaky box and distinguished from the interstellar space. We focus on the escape rate of electrons from SNRs, which is given by inversion of the escape lifetime. The ratio of the electron escape lifetime in SNRs to the lifetime in the Galaxy is estimated from the ratio of the radio flux in these two regions. Under this estimate around 1 GeV and the assumption of the energy power-law of the escape rate, we discuss the effects of the escape lifetime of electrons in SNRs to the interstellar electron spectrum.

2. Propagation model including source region as a leaky box

Cosmic-ray electrons lose energy by several different processes while they travel in the interstellar medium.

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The synchrotron and inverse Compton loss processes are dominantly effective above a few GeV. Those loss rates are written by:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -bE^2,$$

$$b[\mathrm{Ge\ V^{-1}\ s^{-1}}] = 1.02 \times 10^{-16}\left(W_{\mathrm{photon}} + \frac{\langle B^2\rangle}{8\pi}\right)[\mathrm{eV/cm^3}],$$

in which $\langle B^2\rangle/8\pi$ is the mean square of the Galactic magnetic field strength in $\mathrm{eV/cm^3}$ and W_{photon} is the density of the interstellar radiation field in $\mathrm{eV/cm^3}$. We choose $\langle B\rangle$ to be 6 μG (Webber et al., 1980). W_{photon} becomes $0.82\ \mathrm{eV/cm^3}$, because of the ultraviolet part to be negligible, visible of $0.26\ \mathrm{eV/cm^3}$, infrared of $0.31\ \mathrm{eV/cm^3}$, and the 2.7 K blackbody radiation to be $0.25\ \mathrm{eV/cm^3}$ (Cox and Mezger, 1989). The sum gives the energy loss coefficient in the Galaxy,

$$b_2 = 2.0 \times 10^{-16}\ \mathrm{Ge\ V^{-1}\ s^{-1}}. \tag{1}$$

2.1. Formulation

The synchrotron radiation from SNRs is observed in the wide range including the radio and X-rays, emitted by high energy electrons. Thus it is evident that the electrons having a spectrum exist inside the SNR. We regard a SNR as one leaky box and estimate the leakage rate from SNR, if the stable flux in the source region is assumed as the first approximation.

Galactic SNRs have different structures: shell-type, plerion or composite-type, so that the escape rate may depend on characteristics of SNRs. If each SNR is specified by the subscript i, namely the electron spectrum N_i, the lifetime τ_i in each SNR, the mean escape rate is defined as $1/\tau_1 = (\Sigma N_i/\tau_i)/\Sigma N_i$ with the energy dependence of $\tau_1(E) = \tau_{01}E^{-\delta_1}$. Further if the total electron flux is $N_1 = \Sigma N_i$, the total escape flux from SNRs becomes $\Sigma N_i/\tau_i = N_1/\tau_1$. We roughly regard τ_1 as the lifetime of electrons in a shell-type SNR because 80% of Galactic SNRs are shell-type. If the total source spectrum, ΣQ_i, is expressed by $Q_1(E) = Q_0E^{-\gamma}$ and the energy loss rates are the same in SNRs, the electron spectrum in the source region $N_1(E)\,\mathrm{d}E$ satisfies

$$\frac{N_1(E)}{\tau_1(E)} + \frac{\mathrm{d}}{\mathrm{d}E}\left[\frac{\mathrm{d}E}{\mathrm{d}t}N_1(E)\right] = Q_1(E). \tag{2}$$

The solution has been given by

$$N_1(E) = \int_0^1 Q_1\left(\frac{E}{x}\right)\exp\left[-\int_x^1 \frac{1}{\lambda_1(E/x')}\frac{\mathrm{d}x'}{x'}\right]\frac{\mathrm{d}x}{b_1Ex^2} \tag{3}$$

$$\simeq \frac{Q_0}{b_1E^{\gamma+1}}\frac{1}{\gamma - 1 + \lambda_1^{-1}} \tag{4}$$

(Silverberg and Ramaty, 1973), where $\lambda_1 = b_1E\tau_1(E)$ means the (escape/energy-loss) lifetime ratio with the energy-loss coefficient b_1 in the source region. The spectral index changes from $-(\gamma + \delta_1)$ to $-(\gamma + 1)$ at the break energy E_1 satisfying $\gamma - 1 = \lambda_1^{-1}$, namely $\tau_1(E_1) \sim 1/b_1E_1$.

The source spectrum in the Galaxy, that is injected from SNRs into the interstellar space is therefore defined as the solution of Eq. (3) multiplied by the escape rate of $1/\tau_1(E)$,

$$Q_2(E) = \frac{N_1(E)}{\tau_1(E)} = \frac{1}{\tau_1(E)}\int_0^1 Q_1\left(\frac{E}{x}\right)\exp\left[-\int_x^1 \frac{1}{\lambda_1(E/x')}\frac{\mathrm{d}x'}{x'}\right]\frac{\mathrm{d}x}{bEx^2},$$

where spectral index changes from $-\gamma$ to $-(\gamma + 1 - \delta_1)$ at the energy E_1. If the Galaxy is also treated as a leaky box, the interstellar electron spectrum $N_2(E)\,\mathrm{d}E$ satisfies Eq. (2) with the subscript 2. Substituting the above source spectrum $Q_2(E)$ into the source function in Eq. (3), we obtain the interstellar spectrum,

$$\begin{aligned} N_2(E) &= \int_0^1 \frac{N_1(E/x)}{\tau_1(E/x)}\exp\left[-\int_x^1 \frac{\mathrm{d}x'/x'}{\lambda_2(E/x')}\right]\frac{\mathrm{d}x}{b_2Ex^2} \\ &= \frac{Q_0}{\lambda_1(E)b_2E^{\gamma+1}}\int_0^1 \mathrm{d}x\int_0^1 \mathrm{d}x' x^{\gamma-1-\delta_1}x'^{\gamma-2} \\ &\quad\times \exp\left[\frac{x^{1-\delta_1}(-1 + x'^{1-\delta_1})}{\lambda_1(E)(1-\delta_1)}\right]\exp\left[\frac{-1 + x^{1-\delta_2}}{\lambda_2(E)(1-\delta_2)}\right] \end{aligned} \tag{5}$$

$$\simeq \frac{Q_0}{\lambda_1(E)b_2E^{\gamma+1}}\frac{1}{\gamma - 1 + \lambda_1^{-1}}\frac{1}{\gamma - \delta_1 + \lambda_2^{-1}}, \tag{6}$$

in which b_2 is given by Eq. (1), $\tau_2(E) = \tau_{02}E^{-\delta_2}$ is the escape lifetime and $\lambda_2 = \tau_2(E)b_2E$. The solution is easily calculated using the numerical integration technique. The spectral index of N_2 changes from $-(\gamma + \delta_2)$ to $-(\gamma + 1)$ at the energy E_2 satisfying $\gamma - \delta_1 = \lambda_2^{-1}$ ($\tau_2(E_2) \sim 1/b_2E_2$), and further changes to $-(\gamma + 2 - \delta_1)$ at the higher break energy E_1 (see Appendix A). The above solution requires not only the Galactic parameters of b_2 and τ_2 but the source parameters b_1 and τ_1. Those parameters are connected using the radio flux as shown in the next section.

2.2. Estimates of source parameters

The key parameter τ_1 of this model cannot be estimated directly, therefore we estimate it from the ratio of the radio flux in SNRs to the background flux in the Galaxy. The lifetime ratio τ_1/τ_2 around 1 GeV is replaced with the electron number ratio N_1/N_2 as follows. The ratio of the electron spectrum in SNRs to the spectrum in the Galaxy is approximately calculated from Eq. (4) divided by Eq. (6) as

$$\frac{N_1(E)}{N_2(E)} = \frac{\tau_1(E)}{\tau_2(E)}(1 + (\gamma - \delta_1)\lambda_2).$$

The Galactic parameter λ_2 (1 GeV) has the value of $\sim$0.1 from the coefficient b_2 in Eq. (1) and the escape lifetime $\tau_2 \simeq 2\times 10^7 E^{-1/3}$ yr which corresponds to 9.4 g/cm^2 (Ptuskin et al., 2001) in the hydrogen density $n_{\rm H} = 0.3$ cm^{-3}. Therefore the lifetime ratio τ_1/τ_2 approximates N_1/N_2 at 1 GeV.

If the observed radio flux $S(\nu)$ has the spectral index $-\beta$ around the frequency ν, the electron spectrum $N(E)\,\mathrm{d}E$ producing this flux in the magnetic field B is expected to be

$$N(E)\,\mathrm{d}E = \frac{S(\nu)}{Y(\beta)\nu^{-\beta}} B^{-(\beta+1)} E^{-(2\beta+1)}\,\mathrm{d}E,$$

where $Y(\beta)$ only includes β and does not sensitive to β. This formula gives the relationship between the escape lifetime ratio τ_1/τ_2 and the radio flux ratio S_1/S_2, in which $S_1(\nu) \propto \nu^{-\beta_{\rm S}}$ is the total radio flux from the Galactic SNRs, and $S_2(\nu) \propto \nu^{-\beta_{\rm G}}$ is the whole background radio flux in the Galactic disk.

$$\frac{\tau_1}{\tau_2}(1\ \mathrm{GeV}) = \frac{S_1(\nu_{\rm S})}{S_2(\nu_{\rm G})}\left(\frac{B_S}{B_G}\right)^{-1} = \frac{S_1(\nu_{\rm S})}{S_2(\nu_{\rm S})}\left(\frac{B_S}{B_G}\right)^{-(\beta_{\rm G}+1)}, \tag{7}$$

where 1 GeV electrons emit the radiation of the frequency $\nu_{\rm S}$ and $\nu_{\rm G}$ in the magnetic field $B_{\rm S}$ of SNRs, and in the Galactic magnetic field $B_{\rm G}$ respectively. Further we used the relationship of $\nu_{\rm S}/\nu_{\rm G} = B_{\rm S}/B_{\rm G}$ and assume that $\beta_{\rm S}$ and $\beta_{\rm G}$ do not change between $\nu_{\rm S}$ and $\nu_{\rm G}$.

The flux S_1[W/Hz] is estimated from the average flux $S_{\rm Av}$ multiplied by the total number of SNRs, $n_{\rm S} = n_0\pi R^2$ with the Galactic radius R[kpc]. The flux S_2[W/Hz] is estimated from the intensity in the polar direction, $I_{\rm p}(\nu)$[W/(m^2 sr Hz)] with the distance L[kpc]. The calculation gives $S_2 = I_{\rm p}(\nu)(4\pi/L)\times V_{\rm G} = 8\pi^2R^2I_{\rm p}(\nu)$, where the Galactic volume $V_{\rm G} \simeq \pi R^2 \times 2L$ is substituted. The flux ratio is finally expressed as

$$\frac{S_1}{S_2} = \frac{S_{\rm Av}\times n_0}{8\pi I_{\rm p}}. \tag{8}$$

The parameters in the above equation have the following values: The radio flux from SNRs at the frequency of 1 GHz or 408 MHz gives the electron intensity around 1 GeV in the magnetic field of several 10 μG. The average flux of 51 SNRs with the known distance in the Green's catalog (Green, 2004) gives the value of $S_{\rm Av} = (1.7\pm 0.4)\times 10^{17}$ W/Hz at $\nu_{\rm S} = 1$ GHz. The Galactic background radio flux in the polar direction is given as $I_{\rm p}$ (1 GHz) $= 3.9\times 10^{-22}$ W/m^2 sr Hz (Peterson et al., 1999; Komori, 2003). The coefficient n_0 becomes 1.3×10^{-39} m^{-2}, that is estimated from the accumulated number of SNRs within a distance R from the Sun. The recent catalog (Green, 2004) gives 54 SNRs having reliable distance which are accumulated and shown in Fig. 1 with the early data set of 125 SNRs in Milne's catalog (Milne, 1979). The two data sets are consistent within 3 kpc. Thus we derived the value of n_0 from the regression line below 3 kpc. At present, 231 SNRs are detected (Green, 2004), however almost nearby SNRs within several kpc seem to be counted in 54 SNRs.

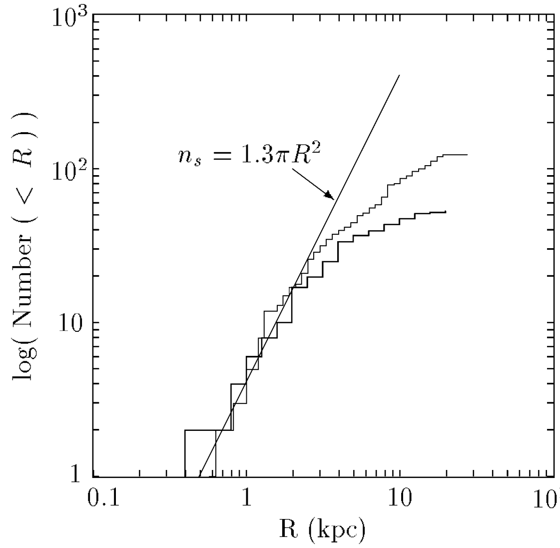

Fig. 1. Accumulated number of SNRs within the distance R from the Sun. Two data sets are given: the thickline is made up of 54 SNRs in Green's catalog (Green, 2004) and the thinline is 125 SNRs in Milne's catalog (Milne, 1979). The regression line is assumed to be proportional to R^2.

Substituting these values in Eq. (8), we obtain the flux ratio S_1/S_2 (1 GHz) $= 2.3\times 10^{-2}$. Similarly, at the different frequency $\nu_{\rm S} = 408$ MHz, the average flux $S_{\rm Av} = (2.8\pm 0.7)\times 10^{17}$ W/Hz (Clark and Caswell, 1976), and the Galactic radio flux $I_{\rm p}$ (408 MHz) $= 7.6\times 10^{-22}$ W/m^2 sr Hz gives the ratio S_1/S_2 (408 Hz) $= 1.9\times 10^{-2}$. Duric et al. (1995) have indicated the ratio of the radio emission to be 10^{-3}–10^{-2} in the M33 galaxy. Thus our results correspond to the upper limit of their estimation. These estimates of the flux ratio give the lifetime ratio of Eq. (7) as

$$\frac{\tau_1}{\tau_2} = 2\times 10^{-2}\left(\frac{B_{\rm S}}{B_{\rm G}}\right)^{-(1+\beta_{\rm G})}$$

with the Galactic radio spectral index $\beta_{\rm G} = 0.6$–0.7. The value of $B_{\rm S}$ is not well known, however, the magnetic field strength of several SNRs are now investigated from the measurements of X-ray and gamma ray emissions. The Crab nebula which is the prototype plerion has the average magnetic field strength of 170 μG given by HEGRA (Aharonian et al., 2000). For shell-type SNRs, the magnetic field strength is generally smaller than that of the Crab nebula. In the case of typical shell-type SNR, SN1006, the CANGAROO observation has reported 4–8 μG (Tanimori et al., 1998), however, such a small value remains controversial. On the other hand the arguments of particle acceleration using the X-ray morphology of SN1006 observed by Chandra require 20–85 μG (Yamazaki et al., 2004) or $\sim$100 μG (Berezhko et al., 2003). As the $B_{\rm S}$ represents the average magnetic

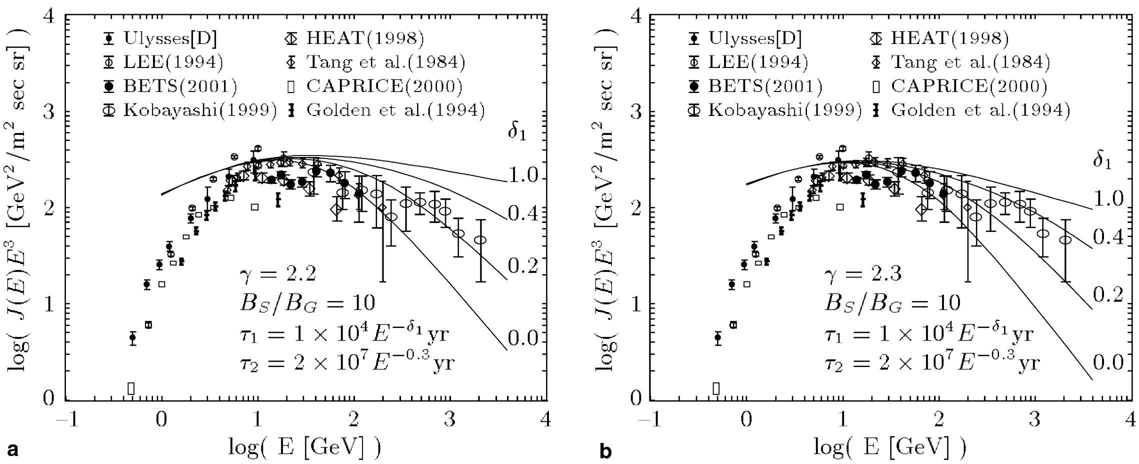

Fig. 2. Interstellar electron spectra calculated from the model of Eq. (5) with different values of δ_1 that is the energy index of escape lifetime in SNRs. Source index γ is 2.2 (a) and 2.3 (b) and other parameters are shown in the figure. The curves are compared with the observed data of Kobayashi et al. (1999); Torii et al. (2001), and Tang (1984). The best fit curve has the break energy of $E_2 = 10$ GeV, and $E_1 = 400$ GeV ($\gamma = 2.2$) or $E_1 = 900$ GeV ($\gamma = 2.3$). These curves do not fit the data below 10 GeV and are not extended to lower energies, because the calculation does not include heliospheric modulation effects.

field of the extended region of radio emission, it becomes smaller than these values of the acceleration site. We consider that B_S roughly presents the average strength of shell-type SNRs which occupy 80% of Galactic SNRs. Therefore B_S seems to be below several 10 μG and B_S/B_G to be below or around 10 as the Galactic magnetic field is $B_G = 5$–7 μG (Webber et al., 1980; Zweibel and Heiles, 1997). Thus in the case of the ratio $B_S/B_G = 10$, τ_1/τ_2 has the value of $(5 \pm 1) \times 10^{-4}$, and the lifetime $\tau_2 = 2 \times 10^7$ yr gives $\tau_1 = 1 \times 10^4$ yr. Consequently, the electrons around 1 GeV stay in the SNRs for the rather long period of $\sim 10^4$ yr which corresponds to the SNR age in the Sedov phase.

At the end of this section, the interstellar solutions of Eq. (5) with the source index $\gamma = 2.2$, 2.3 are indicated in Fig. 2 with the observed data. The curves with different values of δ_1 are shown in the case of $B_S/B_G = 10$. We realize that the value of δ_1 influences the high energy region and is consistent with our data (Kobayashi et al., 1999) at $\delta_1 = 0.2 \pm 0.1$ ($\gamma = 2.2$) and 0.4 ± 0.2 ($\gamma = 2.3$). If the source index $\gamma \leqslant 2.2$, the value of δ_1 is smaller than 0.2. These small value of δ_1 indicates that the electrons in SNRs are confined intensively. On the other hand, if $\gamma \geqslant 2.4$, δ_1 is nearly equal to unity; the model reduces the simple leaky box model and the confinement of cosmic rays does not exist.

3. Conclusions

We have formulated the global propagation model of cosmic-ray electrons treating the source region as a leaky box. This is the first step of modeling of the electron propagation including the source region. The key parameter, the electron escape lifetime in SNRs has been estimated from the radio flux from SNRs and the Galactic background radio flux. As the 80% of Galactic SNRs are shell-type, we suppose that the magnetic field in SNRs is nearly 10 times the strength of the Galactic magnetic field. In this case the lifetime of 1 GeV electrons in SNRs becomes $\sim 10^4$ yr, which corresponds to the SNR age in the Sedov phase.

The escape rate from SNRs influences the interstellar electron spectrum above a few hundred GeV. The energy index of the escape rate is smaller than 0.6, if the source spectral index is 2.0–2.2 expected from the average radio index of SNRs. If the index is larger than 2.4, the confinement of cosmic rays in SNRs does not exist.

In SNRs,electrons are ejected from the acceleration site, diffuse in the source region and lose energy through the synchrotron radiation in the source's magnetic field. The more realistic model including the space variables in the source region will be provided in the next step.

Appendix A. Detailed calculations for electron spectrum

The solutions of the propagation model, Eqs. (3) and (5) are precisely investigated; the approximated expressions clearly indicate the spectral changes and the break energy.

The Eq. (4) is proved as the exponential term in the solution of Eq. (3) is expanded as

$$\begin{aligned}
&\exp\left[\frac{-1 + x^{1-\delta}}{\lambda(E)(1-\delta)}\right] \\
&\quad = \exp\left[\frac{-1 + 1 + (1-\delta)\log x + ((1-\delta)\log x)^2/2! + \cdots}{\lambda(1-\delta)}\right] \\
&\quad \simeq x^{1/\lambda}.
\end{aligned}$$

The equation $\gamma - 1 = \lambda^{-1}$ gives the break energy $E_1 = [(\gamma - 1)b\tau_{01}]^{-1/(1-\delta)}$, and at this energy the spectrum changes from $N(E) \sim \lambda(E)/(bE^{\gamma+1}) \propto E^{-(\gamma+\delta)}$ to $N(E) \sim 1/(bE^{\gamma+1}(\gamma - 1)) \propto E^{-(\gamma+1)}$.

The exponential terms in Eq. (5) is similarly expanded as

$$\exp\left[\frac{x^{1-\delta_1}(-1 + x'^{1-\delta_1})}{\lambda_1(1-\delta_1)}\right] \exp\left[\frac{-1 + x^{1-\delta_2}}{\lambda_2(1-\delta_2)}\right] \simeq x'^{1/\lambda_1} x^{1/\lambda_2},$$

thus the Eq. (6) is derived.

The solution of Eq. (5) has two break energy of E_1 and E_2, which are given by $\gamma - 1 = \lambda_1^{-1}$ and $\gamma - \delta_1 = \lambda_2^{-1}$, respectively.

$$E_1 = [(\gamma - 1)b_1\tau_{01}]^{-1/(1-\delta_1)},$$
$$E_2 = [(\gamma - \delta_1)b_2\tau_{02}]^{-1/(1-\delta_2)}.$$

E_1 depends on the source parameters b_1 and τ_1 and represents the energy at which the synchrotron energy loss rate balances with the escape rate from SNRs. E_2 is similarly the break energy in the Galaxy.

In general E_1 is larger than E_2 because of $b_1\tau_1 < b_2\tau_2$. Thus the spectrum changes as

$$N_2(E) \sim \frac{\tau_2(E)}{E^\gamma} \propto E^{-(\gamma+\delta_2)} \quad E < E_2,$$
$$N_2(E) \sim \frac{1}{b_2(\gamma - \delta_1)} \frac{1}{E^{\gamma+1}} \propto E^{-(\gamma+1)} \quad E_2 < E < E_1,$$
$$N_2(E) \sim \frac{1}{b_1 b_2(\gamma - 1)(\gamma - \delta_1)} \frac{1}{E^{\gamma+2}\tau_1(E)} \propto E^{-(\gamma+2-\delta_1)} \quad E_1 < E,$$

It can be seen that the index of the highest energy side, $\gamma + 2 - \delta_1$ is larger than the index of the simple leaky box model by $1 - \delta_1$.

The above expressions shows that the energy index δ_1 of the escape lifetime in SNRs appears at the high energy side, while δ_2 appears at the low energy side. It is important to notice that when $\delta_1 \to 1$, $E_1 \to \infty$ and the solution of Eq. (5) is reduced to the simple leaky box model solution with the single break energy E_2. Another point to notice is that if $\delta_1 = \delta_2 = \delta$, Eq. (5) becomes the difference of two simple leaky box model solutions as

$$N_2(E) = \frac{Q_0}{b_2 E^{\gamma+1}} \int_0^1 \mathrm{d}x \frac{x^{\gamma-2}}{\lambda_1/\lambda_2 - 1} \left\{ \exp\left[\frac{-1 + x^{1-\delta}}{\lambda_1(1-\delta)}\right] - \exp\left[\frac{-1 + x^{1-\delta}}{\lambda_2(1-\delta)}\right] \right\}.$$

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