Explanation of the Knee-like Feature in the DAMPE Cosmic $e^- + e^+$ Energy Spectrum

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Abstract

The DArk Matter Particle Explorer, a space-based high precision cosmic-ray detector, has just reported the new measurement of the total electron plus positron energy spectrum up to 4.6 TeV. A notable feature in the spectrum is the spectral break at $\sim$0.9 TeV, with the spectral index softening from $-3.1$ to $-3.9$. Such a feature is very similar to the knee at the cosmic nuclei energy spectrum. In this work, we propose that the knee-like feature can be explained naturally by assuming that the electrons are accelerated at the supernova remnants (SNRs) and released when the SNRs die out with lifetimes around $10^5$ years. The cut-off energy of those electrons have already decreased to several TeV due to radiative cooling, which may induce the observed TeV spectral break. Another possibility is that the break is induced by a single nearby old SNR. Such a scenario may bring a large electron flux anisotropy that may be observable by the future detectors. We also show that a minor part of electrons escaping during the acceleration in young and nearby SNRs is able to contribute to a several TeV or higher energy region of the spectrum.

Key words: cosmic rays – ISM: supernova remnants – pulsars: general

1. Introduction

The DArk Matter Particle Explorer (DAMPE), which is one of the new generation space-borne instruments for measuring cosmic rays (CRs), has been running in orbit for nearly two years. Recently, the DAMPE Collaboration published their first result of the high energy CR electron plus positron ($e^- + e^+$) spectrum from 25 GeV to 4.6 TeV, with the data recorded between 2015 December 27 and 2017 June 8 (DAMPE Collaboration 2017). The measurement of DAMPE is very precise due to its unprecedentedly high energy resolution and strong electron/proton discrimination (Chang 2014). This measurement provides direct evidence of a spectral break at $\sim$0.9 TeV for the first time, which is consistent with the spectral break around 1 TeV that is detected indirectly by ground-based experiments, such as H.E.S.S and VERITAS (Aharonian et al. 2009; Staszak 2015). The DAMPE spectrum shows another interesting feature at $\sim$1.4 TeV, although it is not significant right now. Meanwhile, the uncertainties above 3 TeV are large at present, and spectral features are still possible at the high energy end.

The most notable and clear feature of the DAMPE spectrum is the break at $\sim$0.9 TeV. This feature is very similar to the “knee” of the cosmic nuclei energy spectrum, which has been observed by ground-based experiments for more than 50 years (Amenomori et al. 2011; Bartoli et al. 2015). The origin of the knee is still under debate due to the lack of direct measurement in space with clear identification of nuclei species. One natural explanation is that the knee is caused by the acceleration limit in the CR sources (Hörandel 2004). Similarly, the break feature at the electron spectrum may also be caused by the cut-off energy of electrons, which is much lower than that of nuclei because of the large radiative energy loss of the electron.

Supernova remnants (SNRs) have long been considered to be major sources of galactic CRs (Baade & Zwicky 1934; Ginzburg & Syrovatsky 1961; Blasi 2013). The electron injection of an SNR is often assumed to have happened at the birth time of the SNR (Delahaye et al. 2010; Di Mauro et al. 2014). However, this is true only when the delay time (the time from birth to CR injection) of the injection is far less than the age of the SNR. In this work, we consider a more realistic injection picture for SNRs. CRs are largely released from an SNR when the SNR dies as a CR factory at an age of $\sim 10^2$ years (Berezhko & Völk 2000; Caprioli et al. 2010a). Meanwhile, the maximum energy of electrons in a mature SNR should decrease with time, due to significant radiative cooling. As we will show, an evolution time of $\sim 10^3$ years corresponds to a cut-off energy of $\sim$ TeV for electrons, which can explain the TeV break detected by DAMPE. A similar motivation can also be found in Thoudam & Hörandel (2011).

On the other hand, spectral features in the electron spectrum are often expected in the TeV region, which could be produced by young and nearby CR sources (Shen 1970; Kobayashi et al. 2004). The final released population mentioned above can hardly account for remarkable spectral features at such high energy. However, if a minor part of electrons can escape from the SNRs during the acceleration process, the young and nearby SNRs may contribute such a high energy component. We will show below that the spectral index of this population of electrons can be very hard, which is necessary for a distinctive spectral structure in high energies.

In this work, we use the electrons released at the final stage of SNRs to explain the DAMPE result, and also consider the contribution from the electrons possibly released during the acceleration process. Besides, CR positrons contribute $\sim$10% of the total $e^- + e^+$ flux, which has been measured by space-borne detectors with magnetic spectrometers, such as PAMELA and AMS-02 (Adriani et al. 2013; Accardo et al. 2014). The “positron excess” is one of the most important findings in CR research. Thus we attempt to explain the DAMPE $e^- + e^+$ spectrum and the positron fraction ($e^+/(e^- + e^+)$) of AMS-02 (Accardo et al. 2014) simultaneously to obtain a complete picture. We consider pulsars as the sources of high energy positrons.

This paper is organized as follows. In Section 2, we introduce the propagation of CR electrons and positrons ($e^\pm$)
after their injection into the interstellar medium (ISM), and show the calculation of the $e^\pm$ spectrum at the Earth. In Section 3, we describe the picture of electron escape for SNRs, and also introduce the positron sources. In Section 4, the fitting results are presented and analyzed. Then we discuss a possible scenario to reproduce the TeV spectral break by a single nearby source in Section 5. Finally, we conclude in Section 6.

2. Propagation of Galactic Electrons and Positrons

The propagation process of $e^\pm$ can be described by the diffusion equation with consideration of the radiative cooling during their journey:

$$\frac{\partial N}{\partial t} - \nabla (D \nabla N) - \frac{\partial}{\partial E} (bN) = Q,$$  

(1)

where $N$ is the differential number density of $e^\pm$, $D$ denotes the diffusion coefficient, $b$ is the energy-loss rate, and the source function of $e^\pm$ is denoted by $Q$. The data of DAMPE is above 20 GeV, where convection or reacceleration has little effect on $e^- + e^+$ spectrum (Delahaye et al. 2009), so the relevant terms are not included in Equation (1). The propagation zone is set as a cylindrical slab, with a radius of 20 kpc and a half thickness of $z_h$. The diffusion coefficient is usually assumed to be $D(E) = \beta D_0(R/1 \text{ GV})^\delta$, where $D_0$ and $\delta$ are both constants, $\beta$ is the velocity of particles in the unit of light speed, and $R$ is the rigidity of $e^\pm$. We adopt the propagation parameters given by the DR2 model (the revised diffusion reacceleration model) in Yuan et al. (2017): $D_0 = (2.08 \pm 0.28) \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $\delta = 0.500 \pm 0.012$, and $z_h = 5.02 \pm 0.86$ kpc. This DR2 model is the best performing model in Yuan et al. (2017) when fitting to the latest B/C data of AMS-02 (Aguilar et al. 2016). The energy-loss rate has the form of $b(E) = b_0(E)E^2$, where $b_0(E)$ is decided by synchrotron and inverse Compton radiation of $e^\pm$. We set the interstellar magnetic field in the Galaxy to be 1 $\mu$G to get the synchrotron term (Han & Qiao 1994; Delahaye et al. 2010). The inverse Compton term refers to the calculation of Schlickeiser & Ruppel (2010), in which a relativistic correction to the scattering cross-section is considered.

The general solution of Equation (1) can be obtained by the method of Green’s function (Ginzburg & Syrovatskii 1964), which is written as

$$N(E, r, t) = \int_{E_0}^{E} \int_{t_0}^{t} dE_0 dt_0 \frac{Q(E_0, r_0, t_0)}{E} \times \frac{b_0(E)}{b(E)} \exp \left( -\frac{(r - r_0)^2}{\lambda^2} \right) \delta(t - t_0 - \tau),$$  

(2)

The infinite three-dimensional solution can be a good approximation for the high energy case (Kobayashi et al. 2004; Fang et al. 2017b), which takes the form of

$$G(E, r, t; E_0, r_0, t_0) = \frac{1}{(\pi \lambda^2)^{3/2} b(E)} \times \exp \left( -\frac{(r - r_0)^2}{\lambda^2} \right) \delta(t - t_0 - \tau),$$  

(3)

where

$$\tau = \int_{E_0}^{E} \frac{dE'}{b(E')} \approx \frac{1}{b_0} \left( \frac{1}{E} - \frac{1}{E_0} \right),$$  

(4)

and

$$\chi^2 = 4 \int_{E_0}^{E} \frac{D(E')}{b(E')} dE' \approx \frac{4D_0[1 - (E/E_0)^{1-\delta}]}{b_0(1 - \delta)E^{2-\delta}}.$$  

(5)

For a point source with burst-like injection, the source function is $Q(E, r, t) = Q(E)\delta(r - r_e)\delta(t - t_e)$. Setting the location of the Earth as $r = 0$ and the present time as $t = 0$, and substituting this source function expression into Equation (2), we obtain the spectrum contributed by a source with distance $r$ and age $t$:

$$I(E, r, t) = \frac{c}{4\pi} N(E, r, t) = \frac{c}{4\pi^{3/2}\lambda^2} \frac{b(E^*)}{b(E)} \times \exp \left( -\frac{r^2}{\lambda^2} \right) Q(E^*, t_0)dt_0,$$  

(6)

where $E^* = E/(1 - b_0E)$. As to a point source with continuous particle injection, the source function is written as $Q(E, r, t) = Q(E, t)\delta(r - r_e)$. Similarly, we get the spectrum in this case:

$$I(E, r, t) = \int_{t_{\text{min}}}^{t_{\text{max}}} \frac{c}{4\pi^{3/2}\lambda^2} \frac{b(E^*)}{b(E)} \exp \left( -\frac{r^2}{\lambda^2} \right) Q(E^*, t_0)dt_0,$$  

(7)

where $t_{\text{max}}$ is the smaller one between the age $t$ and $1/(b_0E)$, and we set $t_{\text{min}}$ to be $r/c$ since the superluminal case should be rejected.

3. Galactic Sources of Electrons and Positrons

3.1. An Electron Escaping Scenario of SNRs

Particles can be boosted to very high energies via the first-order Fermi acceleration in the shock wave of an SNR (Axford et al. 1977; Krymskii 1977; Bell 1978a, 1978b; Blandford & Ostriker 1978). Accelerated CR particles are trapped in the SNR for $\sim 10^5$ years until the shock dissolves into the ISM. However, adiabatic energy losses during the expansion of the SNR prevents the released CR nuclei to reach the high energies as observed, thus the additional particle escape process during the acceleration is required (Caprioli et al. 2010b). Hence, CR particles injected from SNRs can be divided into two populations: CRs escaping from the upstream region during the Sedov phase, and CRs released in the final stage of SNRs (Caprioli et al. 2010a; Bell 2015). In this work, we adopt the above picture for the electron injection of SNRs to explain the DAMPE data.

3.1.1. Electron Spectra of SNRs

To obtain the injection spectrum, we apply the result of Zirakashvili & Aharonian (2007), in which the method of the asymptotic solution is used to get analytical expressions for electron spectra in SNRs. Under the assumption that the energy losses of electrons are dominated by the synchrotron radiation, the electron momentum distribution in the very high energy range at the shock can be solved analytically from the transport
equation as
\[ f_0(p) = \sqrt{b_0(p) / p} \exp \left( -\frac{\gamma^2}{u^{\frac{1}{3}}(1 + \sqrt{\kappa})^2} \right) \times \int_0^p b_0(p') D(p') dp', \]  
where $b_0(p)$ is the downstream synchrotron energy-loss rate, $D(p)$ is the diffusion coefficient in the downstream, $\gamma = 3\sigma / (\sigma - 1)$ with $\sigma$ denoting the shock compression ratio, $u_1$ denotes the upstream shock speed, and $\kappa$ is the ratio of the magnetic field of the upstream to that of the downstream. In the case of nominal Bohm diffusion with $D(p) = p c^2 / 3 e B$, where $e$ is the electric charge and $B$ is the downstream magnetic field, it can be inferred from Equation (8) that
\[ f_0(p) \propto p^{1/2} \exp(-p^2 / p_0^2), \] where the cut-off momentum is written as
\[ p_0 = 4.3 \text{ TeV}/c \left( \frac{u_1}{300 \text{ km s}^{-1}} \right) \left( \frac{B}{30 \mu G} \right)^{-1/2}, \] if we take the standard compression factor $\sigma = 4$ and $\kappa = 1 / \sqrt{11}$ as in Zirakashvili & Aharonian (2007). In the low energy region, the energy losses can be neglected, and the transport equation reduces to the simplest diffusion-convection equation. Then $f_0(p)$ can be expressed by the well-known form
\[ f_0(p) \propto p^{-4} \] for $\sigma = 4$.

In the high energy cut-off region, both the spatially integrated spectra in the upstream $F_1(p)$ and downstream $F_2(p)$ have relations with $f_0(p)$ as $\propto p^{-1} f_0(p)$, and subsequently $\propto p^{-1/2} \exp(-p^2 / p_0^2)$ (Zirakashvili & Aharonian 2007). While in the low energy part, the momentum distribution of the upstream is $f_1(x, p) = f_0(p) \exp(u_1 x / D_1) \ (x = 0 \text{ for the shock front and } x < 0 \text{ for the upstream region})$, which means $F_1(p) \propto p^{-3}$ under the Bohm diffusion. Then the downstream integrated spectrum is approximately given by $F_2(p) \propto p^{-5}$, which can be derived from the boundary condition at the shock front (Zirakashvili & Aharonian 2007). The integrated spectra change gradually from the single power-law form to the form of $p^{-1/2} \exp(-p^2 / p_0^2)$ when $p$ tends to be $p_c$. Since in the cut-off region the exponential term overwhelms the $p^{-1/2}$ term, we can approximate the integrated spectra in the whole energy range by
\[ F_1(p) \propto p^{-3} \exp(-p^2 / p_0^2), \] and
\[ F_2(p) \propto p^{-5} \exp(-p^2 / p_0^2). \]

### 3.1.2. Electrons Released at the Final Stage

As we have described above, electrons injected by SNRs may consist of a final released component (population A hereafter) and a component escaping during the acceleration (population B hereafter). We assume all the SNRs dissolve into the ISM and massively release their electrons in the same evolution time of $t_{\text{end}}$ (the typical age of the Sedov phase of an SNR is $\sim 5 \times 10^{4} \text{ years}$ (Yamazaki et al. 2006; which means $t_{\text{end}} \geq 5 \times 10^{4} \text{ years}$). This indicates that population A can only be contributed by SNRs older than $t_{\text{end}}$, and the injection time of a source with an age of $t$ is $t_0 = t - t_{\text{end}}$. We use the smooth radial distribution of Lorimer (2004) for all of the SNRs with $t > t_{\text{end}}$ to calculate the spectrum of population A.

For smooth distributed sources with the continuous injection, the observed spectrum can also be derived by Equation (2):
\[ I(E) = \int_0^E dt \int_0^t d\tau \int_0^{\tau_{\text{max}}} d\varphi_0 \frac{c}{4\pi^{3/2} \lambda^3} \frac{\sigma}{\varphi_0} b(E^*) \exp \left( -\frac{\gamma^2}{\kappa} \right) f \rho(r_0, \varphi_0) \varphi_0 Q(E^*), \] where $f = 4 \text{ century}^{-1} \text{ galaxy}^{-1}$ is the explosion rate of SNR in the Galaxy, $\rho(r, \varphi)$ is the normalized distribution centered on the solar system, $E^* = E/(1 - b_0 E_0)$, and $\tau_{\text{max}} = \min \{20 \text{ kpc}, c t_0\}$. Population A should be a mixture of upstream and downstream electrons, so according to Equations (11) and (12), we write the injection spectrum of population A as
\[ Q(E) = Q_{0,A}(E/1 \text{ GeV})^{-\gamma_A} \exp(-E^2 / E_0^2), \] where $Q_{0,A}$ is the normalization, $\gamma_A$ is the power-law index, and $E_0$ denotes the cut-off energy, which is decided by Equation (10). For the integrated spectra of the upstream and downstream, we have $\gamma_A = 1$ and $\gamma_A = 3$ respectively. However, population A should be dominated by the downstream electrons, so $\gamma_A$ should be between 2 and 3.

For an SNR that has gone through the free expansion phase, the shock velocity can be expressed as
\[ u_1 = 3.9 \times 10^8 \text{ cm s}^{-1} E_{51}^{1/3} n_{\text{ISM}}^{-1/3} \left( \frac{t_{\text{evo}}}{10^3 \text{ years}} \right)^{-3/5} \text{ for } t_{\text{evo}} < 4 \times 10^4 E_{51}^{4/17} n_{\text{ISM}}^{-9/17} \text{ years}, \] and
\[ u_1 = 2.3 \times 10^7 \text{ cm s}^{-1} E_{51}^{11/51} n_{\text{ISM}}^{-4/17} \left( \frac{t_{\text{evo}}}{10^5 \text{ years}} \right)^{-2/3} \text{ for } t_{\text{evo}} > 4 \times 10^4 E_{51}^{4/17} n_{\text{ISM}}^{-9/17} \text{ years, where } t_{\text{evo}} \text{ is the evolution time of the SNR, } E_{51} \text{ is the initial energy of SN ejecta in units of } 10^{51} \text{ erg, and } n_{\text{ISM}} \text{ is the number density of ISM in units of } 1 \text{ cm}^{-3}. \] Here we take the typical value $E_{51} = n_{\text{ISM}} = 1$ for them. If we assume a typical magnetic field of 10 $\mu G$ for the SNR environment, then we have the magnetic field in the downstream as $B = 30 \mu G$ for $\kappa = 1 / \sqrt{11}$. Then for an SNR stepping into the radiative phase, the cut-off energy $E_\gamma$ is simply determined by $t_{\text{evo}}$ through Equations (10) and (16). Taking the typical lifetime of SNRs as $t_{\text{end}} = 10^5 \text{ years}$, the corresponding $E_\gamma(t_{\text{end}})$ is 3.2 TeV, and the break in the observed spectrum should begin at lower energy due to the cooling of electrons in the propagation. Such a behavior is consistent with the TeV break in the DAMPE data. In the following fitting procedures, we set $Q_{0,A}$, $\gamma_A$, and $t_{\text{end}}$ as the free parameters of population A.

### 3.1.3. Electrons Escaping during the Acceleration

Population B is made up of accelerated electrons that are not advected to the downstream, but escape from the upstream of the shock of an SNR. Obviously, the injection of population B should be a continuous process for each SNR. For those SNRs with age $t > t_{\text{end}}$, the injections last from $t$ to $t - t_{\text{end}}$, while for
a source younger than $t_{\text{end}}$, the injection should last from $t$ to now. The arrival spectrum of an SNR with continuous injection can be calculate with Equation (7). For $t > t_{\text{end}}$, $t_{\text{max}} = \min\{t, 1/b_0 E\}$ and $t_{\text{min}} = \max\{t - t_{\text{end}}, r/c\}$; while for $t < t_{\text{end}}, t_{\text{max}}$ and $t_{\text{min}}$ are defined as in Section 2. The injection spectrum can be expressed as

$$Q(E, t_0) = \tilde{Q}_{0,B}(E/1 \text{ GeV})^{-1} \exp\left\{ -E^2/[E_{r}(t - t_0)]^2 \right\},$$

where $t_0$ is the injection time, $\tilde{Q}_{0,B}$ is the constant rate of injection, which has the unit of GeV$^{-1}$ s$^{-1}$.

Equation (11) indicates that the integrated spectrum in the upstream takes the form of $\propto E^{-1}$ in the low energy part. We adopt this high spectrum as the power-law term of the injection spectrum of population B, as shown in Equation (17). We mentioned in Section 3.1.2 that the momentum distribution of the upstream takes the form of $f_i(x, p) = f_i(p) \exp[u_i x/D_i(p)]$ in the low energy region, which implies a harder spectrum for a farther distance from the shock front. This is because the diffusion scale is larger for electrons with higher energy. If one believes a larger diffusion scale equals a larger chance of escape, the injection spectrum should be even harder than $\propto E^{-1}$. We do not intend to investigate the specific mechanisms of particle escape in the present work, but discuss a scenario of free escape in Appendix A.

The cut-off energy for a continuous injection SNR is time dependent, which can be inferred from Equations (10), (15), and (16). The assumptions about $E_{\text{p}}$, $\eta_{\text{p},\text{SM}}$, and $B$ are kept the same with those in Section 3.1.2. For an SNR with an age of $t$, when it releases electrons at $t_0$, it has evolved for a time of $t_{\text{evol}} = t - t_0$. Thus the cut-off energy should be $E_{c}(t - t_0)$.

We treat $\tilde{Q}_{0,B}$ as a free parameter. For old sources contributing to population B, their contributions are submerged in population A. This means that their $\tilde{Q}_{0,B}$ cannot be restricted by the data. On the other hand, the high energy end of DAMPE still reserves the possibility of spectral features above $\sim 3$ TeV. Such features can be produced by young and nearby sources contributing to population B, so we only focus on this kind of SNR. SNRs within 1 kpc included by the Green’s catalog (Green 2014) are displayed in Table 1. All of them are younger than $\sim 5 \times 10^4$ years. We choose them as the sources of population B, and assume that they share a common $\tilde{Q}_{0,B}$ in the following fitting procedures.

### Table 1

| Name             | Other Name | $r$ (kpc) | $t$ (kyr) |
|------------------|------------|-----------|-----------|
| G254.3+5.7       | ...        | 0.9       | 26        |
| G74.0–8.5        | Cygnus Loop| 0.54      | 10        |
| G114.3+0.3       | ...        | 0.7       | 7.7       |
| G127.1+0.5       | R5         | 1.00      | 25        |
| G156.2+5.7       | ...        | 1.00      | 20.5      |
| G160.0+2.6       | HB9        | 0.8       | 5.5       |
| G263.9–3.3       | Vela       | 0.29      | 11.3      |
| G266.2–1.2       | Vela Jr.   | 0.75      | 3         |
| G347.3–0.5       | RX J1713.7–3946 | 1.00 | 3.2 |

**Note.** One can refer to (Di Mauro et al. 2014) and references therein for parameters of these sources. For parameters given in the form of interval in Di Mauro et al. (2014), we take the mean values here.

### 3.2. Positrons

Although SNRs are expected to mainly account for the features of the $e^- + e^+$ spectrum of DAMPE, extra positron sources are needed to explain the “positron excess” observed by PAMELA and AMS-02. In this work, we use a single powerful pulsar as the high energy $e^+$ source, and test two different known pulsars. Besides, the calculation of the secondary positron is also briefly mentioned.

#### 3.2.1. Pulsars

Electron/positron pairs are produced in the strong magnetic field of pulsars through the electromagnetic cascade (Daugherty & Harding 1982). The details of the injection spectrum of pulsars is described in Appendix B. In this work, the injection spectrum of a pulsar can be determined by three parameters: the conversion efficiency from the total spin-down energy of the pulsar to injected electrons or positrons, $\eta_{\text{pwn}}$, the spectral index of its pulsar wind nebula (PWN), $\gamma_{\text{pwn}}$, and the cut-off energy of its PWN, $E_{\text{c,pwn}}$.

First, we adopt PSR J0940–5428 to be the single source of the positron excess. The reason of choosing this pulsar is given in Appendix B. PSR J0940–5428 is a Vela-like pulsar (Crawford & Tiffany 2007) with a distance of 0.38 kpc, an age of $4.2 \times 10^3$ years, and a spin-down energy of $1.34 \times 10^{49}$ erg. It is also detected as a $\gamma$-ray pulsar (Hou et al. 2011). There is no further information about its injection spectrum provided by observations. So in the following model discussions, we set all the parameters of the injection spectrum of PSR J0940–5428, i.e., $\eta_{\text{pwn}}$, $\gamma_{\text{pwn}}$, and $E_{\text{c,pwn}}$ as free variables. As we assume a continuous injection for pulsars, the spectrum at the Earth should be calculated by Equation (7).

Geminga pulsar is expected to be a significant $e^\pm$ contributor (Yüksel et al. 2009; Linden & Profumo 2013; Hooper et al. 2017), which is nearby ($r = 0.25$ kpc) and relatively old ($t = 3.42 \times 10^5$ year) with a large enough spin-down energy of $1.23 \times 10^{49}$ erg. We consider Geminga to be an alternative single positron source, and set its conversion efficiency $\eta_{\text{pwn}}$ and power-law index $\gamma_{\text{pwn}}$ as free parameters. The cut-off energy $E_c$ is fixed to 50 TeV, which is consistent with the observation of HAWC along with Milagro (Abdo et al. 2009; Abeysekara et al. 2017a).

Recently, there have been arresting discussions about Geminga, focusing on whether its injected $e^\pm$ can really reach the Earth (Abeysekara et al. 2017b; Hooper & Linden 2017). The spatial profile of $\gamma$-ray around Geminga implies a much slower diffusion of $e^\pm$ in this region than that in the ISM (Abeysekara et al. 2017b). However, if this slow-diffuse region is fairly small, Geminga may still contribute considerably to the observed $e^- + e^+$ spectrum (Hooper & Linden 2017).

#### 3.2.2. Secondary Positrons

Secondary positrons produced by the inelastic collision between CR nuclei and ISM are treated as the background of the exotic positron spectrum. We use the method of (Delahaye et al. 2009) to obtain the spectrum of secondary $e^\pm$. The only difference is that we adopt the intensities of incident H and He given by Corti et al. (2016). Besides, a rescaling parameter $c_e$ is introduced for the secondary component in the following fitting procedures, considering the uncertainties in the calculation.
4. Explanation of the DAMPE Data and Fitting to the Model Parameters

In this section, we present the fitting results of three different models. Here we repeat again all the components of the total $e^- + e^+$ spectrum: population A and population B of SNRs, a single pulsar as $e^\pm$ source, and secondary $e^\pm$. The differences between the three models are the choice of the single positron source, and whether population B of SNRs is included in the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Single Pulsar} & \textbf{With Pop B?} & \textbf{PSR J0940$-$5428} & \textbf{Geminga} \\
\hline
\textbf{Parameters} & \textbf{Prior Range} & \textbf{Best} & \textbf{Mean} & \textbf{Best} & \textbf{Mean} & \textbf{Best} & \textbf{Mean} \\
\hline
$Q_{0,A} \ [10^{50} \text{ GeV}^{-1}]$ & [0.1, 10.0] & 2.61 & 2.60 ± 0.10 & 2.57 & 2.57 ± 0.15 & 2.56 & 2.62 ± 0.15 \\
$\gamma_0$ & [2.0, 3.0] & 2.497 & 2.496 ± 0.012 & 2.494 & 2.494 ± 0.013 & 2.493 & 2.497 ± 0.012 \\
$t_{\text{end}} \ [10^5 \text{ years}]$ & [0.4, 5.0] & 0.55 & 1.02 ± 0.41 & 1.21 & 1.17 ± 0.41 & 1.44 & 1.58 ± 0.43 \\
$Q_{0,B} \ [10^{51} \text{ GeV}^{-1} \text{ s}^{-1}]$ & [0.0, 10.0] & ... & ... & 2.42 & 1.86 ± 1.17 & 0.82 & 1.20 ± 0.87 \\
$\gamma_{\text{pwn}}$ & [1.0, 2.7] & 2.56 & 2.54 ± 0.05 & 2.51 & 2.53 ± 0.05 & 2.00 & 1.98 ± 0.03 \\
$E_{\text{c,pwn}} \ [\text{TeV}]$ & [0.5, 5.0] & 2.19 & 3.39 ± 0.94 & 2.43 & 3.03 ± 0.86 & ... & ... \\
$\epsilon_e$ & [0.5, 5.0] & 2.84 & 2.88 ± 0.19 & 2.97 & 2.91 ± 0.19 & 0.54 & 0.86 ± 0.27 \\
\hline
$\chi^2/\text{d.o.f}$ & & 0.72 & & 0.71 & & 0.79 & \\
\hline
\end{tabular}
\caption{Fitting Results for the Three Cases}
\end{table}

Note. The reduced chi-square of each model is also shown, and “d.o.f” is the abbreviation of degree of freedom. As described in Section 3.2.1, the cut-off energy of Geminga is fixed at 50 TeV, so its best-fit value of $E_{\text{c,pwn}}$ is blank.

Figure 1. Results of the fitting to the DAMPE $e^- + e^+$ and AMS-02 $e^+/e^- + e^+$ data, with PSR J0940$-$5428 as the single positron source in the high energy region. Left panels: the electron plus positron spectrum. Right panels: the positron fraction. The results in the bottom panels include population B of SNRs, while the results in the top panels do not. In the legends, “TOT” stands for the total $e^- + e^+$ flux (or $e^+/e^- + e^+$) of all the sources, population A of SNRs are abbreviated to “Pop A,” population B are abbreviated to “Pop B,” while “J0940” stands for PSR J0940$-$5428.
calculation. We seek the best-fit models toward the $e^- + e^+$ data of DAMPE and the $e^+/e^- + e^+$ data of AMS-02, by applying the nested sampling algorithm MultiNest (Feroz & Hobson 2008; Feroz et al. 2009, 2013). We calculate the likelihood function of each experiment, assuming the noises of the measurements are Gaussian. The prior is assumed to be uniformly distributed in a given range for each parameter. The best-fit parameters, parameter means, and standard deviations of these models are compiled in Table 2.

Figures 1 and 2 show the fitting results compared with the DAMPE and AMS-02 data. As expected, the TeV break of the DAMPE $e^- + e^+$ spectrum can be reproduced in all cases, owing to the cut-off energy of population A of SNRs. The best fit $t_{\text{rad}}$ varies from $\sim6 \times 10^4$ years to $\sim1.4 \times 10^5$ years in different models, which is quite reasonable for the final release time of particles in SNRs. The corresponding cut-off energies of injection spectra of population A vary from 4.6 to 2.5 TeV. Note that the relation between $t_{\text{rad}}$ and $E_c$ of population A depends on $E_{31}$, $n_{\text{ISM}}$ and $B$, which are assumed to be constants in this work. In fact, the parameters $E_{31}$, $n_{\text{ISM}}$ and $B$ should vary among SNRs. However, we find that a common $E_c$ for population A is good enough to explain the TeV break of $e^- + e^+$ spectrum detected by DAMPE.

Then we discuss the fitting results of the three models in detail. As shown in Figures 1 and 2, the $e^- + e^+$ spectra of PSR J0940–5428 and Geminga are significantly different in the TeV region, which can be attributed to the differences between their $t$ and $E_c$. The spectral break of Geminga around 1 TeV is due to its old age: under the assumption of Equation (20), most spin-down energy of the pulsar is released in the form of $e^\pm$ in the early age of Geminga, and the high energy part of the $e^\pm$ has been effectively cooled by now. On the other hand, the very high $E_c$ ensures the spectrum of Geminga to extend to tens of TeV, which is contributed by the $e^\pm$ injected at the later age of Geminga. This implies that significant contribution from population B is not necessary to prevent a fast spectral cut-off at the high energy end of DAMPE, as shown in Figure 2.

In comparison, since PSR J0940–5428 is a much younger source, the plenty of high energy $e^\pm$ released in its early age are still energetic now. The fitting result requires a large cut-off energy of $\sim2$ TeV to suppress the spectrum at high energies and keep the break feature at $\sim$ TeV. In this case, the values of $E_1(E)$ for population A and the single pulsar both descend in several TeV. Therefore, the total $e^- + e^+$ spectrum quickly rolls off at higher energies, as shown in the left panel of Figure 1. If we expect an additional spectral feature in the TeV region, population B of SNRs is needed. The best-fit injection rate of population B is $\dot{Q}_{0,B} = 2.42 \times 10^{33}$ GeV$^{-1}$ s$^{-1}$, corresponding to a total injection energy of $\sim10^{46}$ erg for an SNR with an age of $10^5$ years (like Vela). Since the typical kinetic energy of SN ejecta is $10^{51}$ erg, only a fraction of $\sim10^{-5}$ of the total energy is required to deliver to population B.

We notice that the conversion efficiencies of the total spin-down energy to positrons are larger than 1 for the two single pulsar cases. However, this is not a crucial problem. On the one hand, the spin-down timescale $\tau_0$ is quite uncertain, which is important for the estimation of the spin-down energy. On the other hand, the single pulsar model is definitely a simplified picture. In the realistic case, $e^\pm$ should be contributed by more pulsars, which may alleviate the demand for a large $\eta_{\text{pw}}$.

The fitting requires a reasonable $\gamma_{\text{pw}}$ of 2.0 for Geminga, while the best-fit $\gamma_{\text{pw}}$ for PSR J0940–5428 is $\sim2.5$. In fact, among all the identified PWNe with measurements of radio spectral indices, only DA 495 has an electron spectral index larger than 2.5 (to be specific, 2.74; Kothes et al. 2008; Reynolds et al. 2017). The requirement of such a soft injection spectrum for PSR J0940–5428 in the fitting is attributed to its younger age and farther distance, compared with those of Geminga. In general, a source with a large $r$ and small $r$ yields a hard $e^\pm$ spectrum at the Earth, which cannot well fit the $e^+/e^- + e^+$ fraction of AMS-02. If the source accommodates the $e^+/e^- + e^+$ data at low energies, the hard positron spectrum would cause a deviation from the AMS-02 data above $\sim300$ GeV. Hence a soft injection spectrum is required for PSR J0940–5428 as the single source to explain the positron observation.

In fact, the uncertainty of 1.3% in the absolute energy scale of DAMPE could introduce a spectral shift of the $e^- + e^+$ spectrum, which is not included in the systematic uncertainty of the DAMPE Collaboration (2017). Now we would like to examine how this uncertainty affects the confidence intervals of the fitting parameters. As an example, we perform the fitting again for the case in the top panels of Figure 1, shifting the
energies of the DAMPE data to 1.3% higher or lower values, respectively. The 1σ intervals of the parameters for the two energy-shifted cases and the default case are all listed in Table 3. We find that the energy scale uncertainty has little impact on the confidence intervals of the fitting parameters except for the normalization parameters $Q_{0\Lambda}$. Below the “knee,” the spectral shift induced by energy scale uncertainty is comparable to the current total errors of DAMPE, which may affect the normalization. While above the “knee,” the current statistic uncertainties are significantly larger than the uncertainties introduced by the energy scale errors, thus the confidence interval of parameter like $t_{\text{end}}$ is mainly decided by the former.

Finally, we briefly discuss the tentative spectral feature around 1.4 TeV. If this feature is a sharp peak, a monoenergetic electron injection at 1.4 TeV from a nearby source is required, such as dark matter annihilation in a subhalo. However, if there exists some unclear uncertainties, the spectral feature would not be a strict peak. For instance, if the count number at $\sim$1.2 TeV is underestimated, the actual spectral feature should be edge-like around 1.4 TeV. We have described above that the spectrum of Geminga breaks around $\sim$1.2 TeV due to the cooling effect, which can create an edge-like feature at the TeV region, as shown in Figure 2. The precise property of this tentative spectral feature should be tested with larger statistics of further results of DAMPE.

5. A Powerful nearby SNR as the Dominant High Energy Electron Source

In the previous sections, population A is assumed to be contributed by smoothly distributed sources. In fact, electrons with $E > 1$ TeV may be mainly contributed by sources with $r < 1.5$ kpc and $t_0 < 3 \times 10^5$ years due to the radiative cooling of the traveling electrons. This condition can be derived by the criteria given in Appendix B of Kobayashi et al. (2004). For $t_{\text{end}} \approx 10^5$ years, among observed SNRs, only the Monogem Ring (MR) and Loop I can satisfy this condition. Other observed SNRs within 1.5 kpc are too young to contribute to population A. In this section, we show the scenario in which a powerful nearby SNR dominantly accounts for the TeV spectrum of population A, and choose MR as an example. We take the distance of MR to be $r_{\text{mr}} = 300$ pc (Plucinsky 2009), and set its age to be $t_{\text{mr}} = 1.1 \times 10^5$ years, which is the same as its associated pulsar PSR B0656+14 (Taylor et al. 1993).

To calculate the electron spectrum, we consider population A to be contributed by MR and a smooth distributed SNR background. We adopt the calculation in Fang et al. (2017b), but with the electron injection introduced in the present work. The injection age of MR is $t_{\text{mr}} - t_{\text{end}}$, the cut-off energy of its injection spectrum $E_{\text{c,mr}}$ is estimated by Equations (10) and (16). The spectral index of MR $\gamma_{\text{mr}}$ and the total energy of injected electrons $W_{\text{mr}}$ are both assumed to be free. Then we

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**Table 3**

1σ Posterior Ranges of the Fitting Parameters Corresponding to the Case in the Top Panels of Figure 1, Along with the two Cases Where the Energies of DAMPE Data are Shifted by 1.3% Higher or Lower

| Energy of DAMPE | $Q_{0\Lambda}$/10$^{50}$ GeV$^{-1}$ | $\gamma_{\Lambda}$ | $t_{\text{end}}$/10$^5$ years | $\gamma_{\text{pwn}}$ | $\eta_{\text{pwn}}$ | $E_{\text{pwn}}$/TeV |
|-----------------|-----------------------------------|-------------------|-------------------------------|-------------------|-------------------|-------------------|
| $(E)$           | [2.46, 2.74]                      | [2.48, 2.51]      | [0.61, 1.43]                  | [2.49, 2.59]      | [1.00, 1.68]      | [2.44, 4.33]      |
| $(E) + \Delta E$| [2.56, 2.87]                      | [2.48, 2.51]      | [0.59, 1.36]                  | [2.49, 2.58]      | [1.03, 1.70]      | [2.45, 4.32]      |
| $(E) - \Delta E$| [2.35, 2.63]                      | [2.48, 2.51]      | [0.63, 1.44]                  | [2.49, 2.59]      | [0.97, 1.63]      | [2.39, 4.29]      |

**Note.** $(E)$ Denotes the default energy of DAMPE data, while $\Delta E$ denotes the uncertainty in the absolute energy scale of DAMPE.
perform the fitting to the DAMPE $e^- + e^+$ spectrum and the positron fraction of AMS-02 again, adopting Geminga as the single high energy positron source. Population B of SNRs is not included here. The fitting result is presented in the left panel of Figure 3; the best-fit parameters can be found in the caption. The positron fraction is similar to that in the right panel of Figure 2, and thus is not shown here.

Similar to the result in Figure 2, this scenario can also fit the DAMPE data well. The best-fit spectral index $\gamma_{\text{int}} = 2.1$ and total injection energy $W_{\text{int}} = 2 \times 10^{48}$ erg are reasonable for an SNR. The spectral shape at $\sim 1$ TeV in the model is mainly determined by the properties of MR and Geminga. Thus the TeV break of DAMPE can coincidentally be generated by one or few powerful nearby sources, as indicated by the previous works (Atoyan et al. 1995; Di Mauro et al. 2014; Fang et al. 2017b).

Meanwhile, nearby sources with young injection ages can produce significant anisotropy of $e^- + e^+$, as the dipole anisotropy of a burst-like point source can be roughly estimated by $3r/(2ct_0)$ (Shen & Mao 1971). The detection of the anisotropy may help to ascertain the contribution of high energy $e^- + e^+$ (Linden & Profumo 2013; Fang et al. 2017a; Manconi et al. 2017). Since the injection age of MR is only $4 \times 10^4$ years, we show the case that MR dominates the $e^- + e^+$ anisotropy of the model in the right panel Figure 3. We compare the predicted anisotropy with the upper limits given by the seven-year detection of Fermi-LAT (Abdollahi et al. 2017). The anisotropy produced by MR almost hits the upper limits of Fermi-LAT. Future instruments with larger acceptance and stronger electron/proton discrimination, like HERD (Zhang et al. 2014), will provide further judgment to a scenario like this. An expectation of the sensitivity of HERD with a three-year measurement is shown in the right panel of Figure 3; one may refer to Fang et al. (2017a) for the estimation of the sensitivity.

6. Conclusion

In this work, we apply an electron escaping scenario of SNRs to explain the DAMPE $e^- + e^+$ spectrum. In this scenario, most accelerated electrons are released at the final stage of the evolution of SNRs, while a minor part of electrons may escape during their acceleration process. The similar scenario has already been utilized in the research of CR protons. We also explain the $e^+/e^-$ fraction measured by AMS-02 at the same time, using a single powerful pulsar as the primary high energy positron source. Two different pulsars, PSR J0940–5428 and Geminga, are adopted respectively.

The principal conclusion is that the spectral break of DAMPE at $\sim 0.9$ TeV can be naturally explained by the final released electrons of smoothly distributed SNRs, which escape at an age of $\sim 10^3$ years of the SNRs. The reason behind this is that the electrons released at the final stage of SNRs have already cooled down to the TeV region, and the super-exponential energy cut-off of those electrons fit the data well. On the other hand, this break can also be mainly induced by a single nearby old SNR, such as MR; this case will hopefully be tested by future measurements of the anisotropy of $e^- + e^+$ flux with future instruments, such as HERD.

The common cut-off energy for final released electrons of all the SNRs is simplified. As we have mentioned in Section 4, this cut-off energy should be related to the circumstances of SNRs. For a cold and dense environment, and a hot and rarefied environment, the cut-off energy of final released electrons can be very different. The combination of these two groups of SNRs with distinct cut-off energies may produce a broken power-law spectrum extended to tens of TeV, as indicated by the latest preliminary result of H.E.S.S.\(^3\) We will leave the detailed discussion to this scenario in future works.

We also find that a minor part of electrons possibly escaping during the evolution of nearby SNRs are able to contribute significantly and generate spectral features to the TeV region, owing to the hard spectral index of the injection spectrum. Besides, if the tentative spectral feature around 1.4 TeV of the DAMPE result is proven to be an edge-like feature by further measurement, the spectrum of Geminga may give a good explanation for it. Future DAMPE result with larger statistics may help to decide what the spectrum around 1.4 TeV is really like and if there are clear spectral features in higher energies.

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Appendix A
Electrons Injected from a Free-escape Boundary

To describe the injection of electrons during the acceleration, we impose the free boundary condition of $f(-x_0) = 0$ at a position $-x_0$ in the upstream of the SNR shock (Caprioli et al. 2010b). At low energies, the distribution of electrons in the upstream can be simply described by the diffusion-convection equation. The solution is expressed as

$$f(x, p) = f_0(p) \frac{\exp(u_0x/D_\perp) - \exp(-u_1x_0/D_\perp)}{\exp(-u_2x_0/D_\perp)},$$

(18)

Then we can get the escape flux $F_{\text{esc}} = D_\perp \partial f/\partial x_{\perp}$ in the whole energy range as

$$F_{\text{esc}} = \frac{u_1f_0(p)}{\exp(u_1x_0/D_\perp) - 1},$$

(19)

where \(f_0(p) \propto p^{-4} \exp(-p^2/p_0^2).\) The free-escape boundary is placed at \(x_0 = cR_{\text{sh}},\) where \(R_{\text{sh}}\) is the radius of the SNR and \(c\) is a constant (Caprioli et al. 2010a). The radius \(R_{\text{sh}}\) is derived by

\(^3\)https://indico.snu.ac.kr/indico/event/15/session/5/contribution/694
Equations (15) and (16), and the injection spectrum should be proportional to $E_{\text{esc}} R_0^2$. Here we take $c$ to be 0.01. For a larger $c$, particles escaping from the free-escape boundary are required to be much more energetic than the cut-off energy due to radiative cooling. This means that few particles could escape for a larger $c$.

In the main text, the sources of population B consist of only young and nearby SNRs. Here we would like to build a complete group of the sources of population B. Taking the birth rate of SNe of 4 century$^{-1}$ galaxy$^{-1}$ and the radial distribution of SNRs given in Lorimer (2004), we generate $4 \times 10^5$ SNRs randomly with ages from 0 to 10$^7$ years (SNRs older than 10$^7$ years can hardly contribute to the energy range in which we are interested). We calculate the injection spectra for all the sources, and use Equation (7) to obtain the observed spectrum at the Earth. The final spectrum generated with this method is drawn in Figure 4, compared with the spectrum of population B shown in the top left panel of Figure 1. The normalization of the generated injection spectrum has been adjusted to produce a comparable flux with that shown in Figure 1.

Although the contributions of distant or/and old SNRs to population B are included, the model described in this section generates a similar spectral shape with that predicted by the model in Section 3.1.3, where only young and nearby sources are considered and the integrated upstream spectrum is adopted as the injection spectrum. This is because the injection spectra from SNRs with a free-escape boundary described in this section are much harder.

Appendix B

The Injection Spectrum of Pulsars

Pulsars convert their spin-down energy partially to relativistic winds of $e^\pm$ pairs. The young or middle aged pulsar may be surrounded by an observable PWN (see Gaensler & Slane 2006 and references therein). Particles injected into the PWN are constrained in a period of time until the crush of the PWN, and then escape into the ISM (van der Swaluw et al. 2004). Thus the injection spectrum of $e^\pm$ should be the spectrum from the PWN, rather than that from the pulsar itself (Malyshov et al. 2009). The particle acceleration and escape processes in PWNe are much more complicated than those in SNRs. Here we simply assume that the injection process has the same time dependency with the spin-down luminosity of pulsars (i.e., $\propto (1 + t/t_0)^{-2}$ Pacini & Salvati 1973), and the $e^\pm$ injection spectrum of PWNe takes the form of

$$Q(E, t_0) = C \left[ 1 + (t - t_0)/\tau_0 \right]^{-2} (E/1 \text{ GeV})^{-\gamma} \times \exp(-E^2/E_0^2),$$

(20)

where $C$ is the normalization, $t$ is the age of a pulsar, and $t_0$ denotes the injection time. Meanwhile, $Q$ can be related to the total spin-down energy released by a pulsar by

$$\int_{E_{\text{min}}}^{\infty} dE \int_{r/c}^{t} dt_0 \, Q(E, t_0) E = \eta W_p,$$

(21)

where $W_p$ is the spin-down energy, $\eta$ represents the conversion efficiency to injected positrons, $r$ is the distance of the pulsar, and $E_{\text{min}}$ is set to be 0.1 GeV. We integrate the spin-down luminosity $\dot{E}$ with time to get the spin-down energy

$$W_p = \dot{E} \left( 1 + \frac{t}{\tau_0} \right).$$

(22)

where $\tau_0$ is the initial spin-down timescale of the pulsar, which has a typical value of 10 kyr (Hooper et al. 2017). $\dot{E}$ and $t$ of known pulsars are given by the ATNF catalog (Manchester et al. 2005), so for each pulsar we can perform an estimation to $W_p$. Then the injection spectrum of a pulsar is determined by three parameters: $\eta$, $\gamma$, and $E_0$.

So far, the ATNF catalog has collected 2573 pulsars. We gave a rank of all these pulsars by their potential of contribution to the arrival $e^\pm$ spectrum in Fang et al. (2017a). One may refer to Fang et al. (2017a) for the rule of this rank. Vela pulsar and PSR J0940$-$5248 are much more powerful in $e^\pm$ spectrum than other pulsars. So if we intend to reproduce the positron excess by a single pulsar, these two sources may require the smallest $\eta$. However, as we have described above, $e^\pm$ may not be injected from a PWN until the crush of the PWN. It may take thousands of years for the reverse shock of an SNR to propagate backward and collide with its PWN (Blondin et al. 2001; Hinton et al. 2011). Since the Vela pulsar has an age of $1.1 \times 10^4$ years, an injection delay of thousands of years may push it to contribute in the higher energy region of the $e^\pm$ spectrum. While for PSR J0940$-$5248, which is $4.2 \times 10^4$ years old, the injection delay may have less influence. Therefore, we choose PSR J0940$-$5248 as the single positron source in this work.

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