Interpretation of TeV electron and positron data with a single source

Bohan Xie1,a

1Department of Physics, Washington University in St. Louis, One Brookings Drive, St. Louis, MO 63130, USA
aE-mail: bohan.x@wustl.edu

Abstract. In recent years, many experiments, for example, like AMS-02, CALET, DAMPE, HESS and Fermi-LAT, have enhanced their precision in detecting the flux of cosmic rays, especially for high energy particles. We aim to interpret the electrons and positrons data above 1 TeV by using a model considering supernova remnants (SNRs) and the single pulsar as the major sources of electrons and positrons. We explain the rationality of applying the continuous scenario model for the single pulsar. We use the data above and choose seven parameters (d, t, \( \gamma_e \), \( E_{tot} \), \( Q_{SNR} \), \( \gamma_{SNR} \), \( E_{c,SNR} \)) to perform the best fit for electrons and positrons flux at Earth. We perform the fit for the data above 1 TeV and 10 GeV to analyze how the single pulsar and SNRs contribute to the total flux. We also find that the fit ranges we choose for the parameters have a significant influence on the result. By considering this effect, a further analysis on the best fit by constraining \( \gamma_e \) and \( E_{c,SNR} \) shows that the pulsar PSR B0656+14 can provide most of the flux to the data above 1 TeV.

1. Introduction
In recent years several experiments have measured with unprecedented precision the flux of cosmic rays (CRs). Among all the different CR species, electrons (\( e^- \)) and positrons (\( e^+ \)) are of particular interest because they lose energy much more efficiently than protons and thus very-high-energy particles are related to local sources. The Alpha Magnetic Spectrometer (AMS-02) experiment has released the flux of electrons and positrons \([1, 2]\) in an energy range between 0.5-1000 GeV with an uncertainty that is as low as a few %. CALET and DAMPE experiments have released the flux of the combined flux of electrons and positrons since they do not have a magnet on board and it is thus not possible to distinguish the electric charge of the CR \([3, 4]\). Moreover, the HESS Collaboration has measured the combined spectrum up to the energy of a few tens of TeV \([5]\). These data are extremely important for the physics of CRs as we will discuss in this paper.

The interpretation of the \( e^- \) and \( e^+ \) data is still under debate. The low energy \( e^- \), i.e. below 10 GeV, is well explained with the secondary production given by the interaction of cosmic rays with the atoms of the interstellar medium. Instead, the high-energy \( e^+ \) are probably dominated by the acceleration of these particles by local pulsar wind nebulae (PWNe) \([6, 7]\). On the other hand, CR \( e^- \) are probably mainly produced by supernova remnants (SNRs) that accelerate CRs through a diffusive shock acceleration mechanism, also called Fermi mechanism \([6, 8, 9]\).

The interpretation of the \( e^+ + e^- \) data above 1 TeV is particularly challenging because VHE particles lose energy very efficiently and thus such energetic particles are probably emitted from individual closeby sources. In fact a 1 TeV electron under diffusion and energy losses has a typical propagation length of 1 kpc. In this paper we investigate the origin of \( e^\pm \) data above 1 TeV with the...
interpretation of one single source assuming that it emits CRs continuously in time as PWNe do. We will also try the fit of $e^+ + e^-$ data using a smooth distribution of SNRs and one single source that explains the multi TeV part. We provide the best-fit values for the distance and age of the single source that produce a good representation of the data.

The paper is organized as follows. In section 2 we explain our model for burst-like scenario and continuous scenario. We show that PWNe and SNRs are the main sources of $e^+$ and $e^-$ in our model. In section 3 we show our results and we conclude in section 4.

2. Model

$e^+$ and $e^-$ can be produced by various astrophysical sources and mechanism in our Galaxy. Pulsars for example are among the major accelerators of $e^+$ and $e^-$. Under the influence of winds and shocks, $e^+$ and $e^-$ can detach from the surface of the neutron star and initiate cascade processes in the pulsar magnetosphere, leading to the creation of a cloud of charged particles that surrounds the pulsar, which is known as a PWN. It is believed that these $e^+$ and $e^-$ can be accelerated to very high energies at the termination shock and then injected into ISM after a few tens of kyr. Burst-like injection scenario and continuous injection scenario are two different assumptions that usually are considered for the emission mechanism of $e^+$ and $e^-$ from PWNe. In the burst-like scenario, all the particles are emitted from the sources at a time equal to the age of the source ($t^*$), which means the time-dependence is a delta function $\delta(t - t^*)$ here. Instead, in the continuous injection scenario the particles are emitted with a rate that follows the pulsar spin-down energy.

The injection spectrum of $e^\pm$ emitted by a PWN in the burst-like injection scenario can be described as [10]:

$$Q(E) = Q_0 \left( \frac{E}{E_0} \right)^{-\gamma_0} \exp \left( -\frac{E}{E_c} \right)$$

where $Q_0$ is in units of GeV$^{-1}$ and $E_c$ is the cut-off energy. We adopt $E_c = 10^2$ TeV to make sure that $E_c$ is large enough to produce $\gamma$-rays through inverse Compton scattering (ICS). Indeed, recent observations of HAWC reported an extended emission around Geminga and Monogem pulsars at energies higher than 5 TeV. This extended emission is interpreted as ICS of electrons and positrons injected from the pulsar against the interstellar radiation field [11]. Indeed, The normalization of the power law is fixed to $E_0 = 1$ GeV. Given the injection spectrum in equation (1), the total energy emitted in $e^+$ and $e^-$ in units of GeV can be obtained through [10]:

$$E_{tot} = \int_{E_1}^{\infty} dEEQ(E)$$

where we fix $E_1 = 0.1$ GeV. This is the typical value considered for the minimum energy of non-thermal electrons [12, 13]. The normalization $Q_0$ for a single PWN is obtained assuming that a fraction $\eta$ of the total spin-down energy $W_0$ emitted by the pulsar is released in form of $e^\pm$ pairs:

$$E_{tot} = \eta W_0$$

The value of $W_0$ can be computed starting from the age of the pulsar $t^*$, the typical pulsar decay time $t_0$, and the spin-down luminosity $\dot{E}$:

$$W_0 = \tau_0 \dot{E} \left( 1 + \frac{t^*}{t_0} \right)^2$$

the observed age $t_{obs}$ (where $t^* = t_{obs} + d/c$ is the actual age) and the distance $d$ for the pulsars are variables in our model, and $t_0$ is the characteristic pulsar spin-down timescale, for which we use $t_0 = \dots$
10 kyrs here. The spin-down luminosity $\dot{E}$ is as follow [14]:

$$\dot{E} = b_0 E^2$$

(5)

where $b_0 = 10^{-16}$ GeV/s. In the burst-like injection scenario the flux $N(E, r)$ of $e^\pm$ at a position $r$ (in Galactic coordinates) and energy $E$ considering an infinite diffusion halo is given by [10]:

$$N(E, r) = \frac{b(E)}{b(E)} \frac{1}{\pi \lambda^2} \exp \left( -\frac{\|\vec{r} - \vec{r}_s\|^2}{\lambda^2} \right) Q(E_s)$$

(6)

where $b(E)$ is the energy loss function, $r_s$ indicates the source position, and $\lambda$ is the typical propagation scale length:

$$\lambda^2 = \lambda^2(E, E_s) = 4 \int_{E_s}^{E} dE' K(E')$$

(7)

with the diffusion coefficient $K(E)$ given by $K(E) = K_0(E/1\text{GeV}) \delta$. $E_s$ is the initial energy of $e^\pm$ that cool down to $E$ in a loss time $\Delta \tau$:

$$\Delta \tau(E, E_s) = \int_{E}^{E_s} \frac{dE'}{b(E')} = t - t_{\text{obs}}$$

(8)

We show the plot of the propagation length $\lambda$ in figure 1 for sources of age 10, 100 and 1000 kyrs. The value of $\lambda$ is larger for older sources because the particles travel for more time in space. Moreover, the $\lambda$ function has a cut-off at smaller energies if the source is older. This is due to the fact that there is a maximum energies for particles reaching the Earth related to the age of the source. The older is the source and the smaller is the maximum energy. In the continuous injection scenario and with a homogeneous diffusion in the Galaxy, the flux $N_e(E, r, t)$ of $e^\pm$ at an energy $E$, a position $r$, and time $t$ is given by the following equation [15]:

$$N_e(E, r, t) = \int_{t_0}^{t} dt_0 \frac{b(E_s(t_0))}{b(E)} \frac{1}{(\pi \lambda^2(t_0, t, E))^\frac{3}{2}} \times \exp \left( -\frac{\|\vec{r} - \vec{r}_s\|^2}{\lambda(t_0, t, E)^2} \right) Q(E_s(t_0))$$

(9)
where the integration over $t_0$ is included since the PWN releases $e^\pm$ continuously in time. The expression for the injection spectrum is now time-dependent:

$$Q(E,t) = L(t) \left( \frac{E}{E_0} \right)^{-\gamma} \exp \left( -\frac{E}{E_c} \right)$$

and the total energy emitted by the source is given by:

$$E_{tot} = \int_0^T dt \int_{E_1}^{E_2} dEEQ(E,t) = \int_0^T dtL(t)$$

$L(t)$ is the magnetic dipole braking:

$$L(t) = \frac{L_0}{\left( 1 + \frac{t}{\tau_0} \right)^2}$$

Figure 2. Flux of electrons and positrons from a pulsar with different distances taken from 0.1 to 2 kpc. We fix the age of the source to 100 kyrs. The left plot is for a continuous injection while the right panel shows the result for the burst like injection scenario.

Figure 3. Same as figure 2 for a pulsar with different ages from 10 to 10000 kyrs.
Finally, the flux of $e^\pm$ at Earth is given by:

$$\Phi_{e^\pm}(E) = \frac{c}{4\pi} N_e(E, r = d, t = t^*)$$

where $d = |r - r_s|$ is the distance to the source.

As a result, we have four parameters to account for the spectrum of the accelerated particles generated by PWNe: $d$, $t$, $\gamma$, $E_{tot}$. With this model, we can calculate the prediction for the $e^\pm$ flux at Earth. In figure 2 we show the flux of $e^\pm$ as a function of the particle energy $E$ in different distances for both burst-like case and continuous case. For the burst-like case, we show the plot for sources of distance 0.1, 0.2, 0.6 and 0.8 kpc. The flux will increase with the energy of the particles until it encounters the cut-off energy. The cut-off energy shown in burst-like case is interpreted by the following equation when we set $E_f=0$:

$$E_f = \left[\frac{1}{\gamma - \alpha + 1} + E^\alpha_{\gamma - 1}\right]^{-\frac{1}{\alpha + 1}}$$

where $E_f$ is the final energy of the particles and $E_i$ is the initial energy, which is equal to the cut-off energy when the final energy is 0. We should also notice that the cut-off energy is only relevant to the age of the pulsar, so the cut-off energy is the same for different distances. For the continuous case, we show the plot for sources of distance 0.1, 0.2, 0.4, 0.6, 0.8 and 1 kpc. The flux will increase with the energy until it suffers a break in an energy range around few TeV, and then it will decrease with a slower rate. Moreover, the larger the distance, the more the spectrum at TeV energies will shrink to the break point. It is obvious that the flux of $e^\pm$ decreases with the increase of the distance for both cases according to equation (6) and equation (9).

In figure 3 we predict the flux of $e^\pm$ in different ages $t$ for both cases. For the burst-like case, we show the plot for the sources of age 10, 30, 60, 100, 200 and 500 kyrs. The flux will increase with the energy and will not change with the age, which matches to equation (6). The cut-off energy will decrease with the age, which is interpreted by equation (14). For the continuous case, we show the plot for sources of age 50, 500, 1000, 2000, 5000, 10000 kyrs. Here the larger intervals are just to make the plot more clear. Each plot is similar to that in the case for different distances and since the integration of the flux is done over the age, according to equation (9), the flux is dependent on the age, which is smaller when the age is larger. Besides, the flux will suffer the break at an smaller energy range when the age is older. The results above are detailed in [16, 17, 18, 19, 20], which analyzed the case for different ages. We note that the sharp cut-off at TeV energies in burst-like case is due to the energy loss
during the propagation of $e^+$ in the Galaxy for synchrotron and ICS cooling. However, for the continuous case, the increasing values of $\tau_0$ will allow the production of higher $e^+$ and ICS $\gamma$-ray fluxes at TeV energies. In figure 4, we show the plot of flux for both the burst-like case and the continuous case. In the burst-like case, the flux will increase with the energy until it reaches the cut-off energy, while in the continuous case, the flux will increase faster and this increasing trend will stop at a break point around few TeV. The positions of the breaking point and the cut-off energy are similar which is interpreted above. Then the flux will decrease in continuous case according to the spectrum of synchrotron and ICS. In addition, a part of most energetic $e^+$ is released much later than the time of the pulsar birth, which means that since these particles are characterized by a larger propagation length $\lambda$ (figure 1), once the release time is longer, they are allowed to reach the Earth and to generate TeV $\gamma$-ray. Besides, the predictions for the continuous case tend to the burst-like case when $t_0$ is small enough and similar result is also shown in the case for different distances when $d$ is small enough. Compared to the observational data, it is reasonable for us to apply the continuous scenario model to do the fit.

SNRs are another main accelerators of Galactic CRs. By scattering repeatedly upstream and downstream of the shock wave that generated by the stellar explosion, charged particles can gain energy each time they cross the shock front. This mechanism of diffusive shock acceleration gives a power-law spectrum of accelerated particles described as [21]:

$$Q(E) = Q_{0,SNR} \left( \frac{E}{E_0} \right)^{-\gamma_{SNR}} e^{-\frac{E}{E_{c,SNR}}}$$  \hspace{1cm} (15)

where $E_0 = 1$ GeV. The normalization $Q_0$ is related to the the total energy emitted in electrons by SNRs:

$$E_{tot} = \int_{E_{min}}^{E_{max}} E Q(E) dE$$  \hspace{1cm} (16)

where we define $E_{min} = 0.1$ GeV. Therefore, we have three parameters to describe this spectrum: $Q_0$, or equivalently $E_{tot,SNR}$, the spectral index $\gamma_{SNR}$ and the cut-off energy $E_{c,SNR}$.

In our model, we consider the parameters as follow will influence the flux of $e^+$ in different energies: $d$, $t$, $\gamma_e$, $E_{tot}$ for pulsars and $Q_{0,SNR}$, $\gamma_{SNR}$, $E_{c,SNR}$ for SNRs. By combining these parameters, we can have different $e^+$ flux while changing the values of these parameters. With this method, we will provide the prediction of $e^+$ flux at Earth compatible with the observations from the data above.

3. Result

In this section, we fit the $e^+$ flux data from AMS-02, CALET, DAMPE, HESS and Fermi-LAT with the flux from supernova remnants and pulsar wind nebulae using the seven parameters of the model described above. To avoid the influence of secondary production of $e^+$, the energy range we fit is always above 10 GeV [21]. We remind that at 10 GeV the secondary production is more than one order of magnitude smaller than the flux from SNRs. We start by performing the fit for the data above 1 TeV and considering only the flux from a single pulsar. We obtain a $\chi^2$ value of 42 with 34 data points. Therefore, in this case the free parameters are $d$, $t$, $\gamma_e$, $E_{tot}$ for the pulsar. In figure 5 we show the best fit obtained for $d = 0.30$ kpc, $t = 132$ kyr, $\gamma_e = 2.80$, $E_{tot} = 57$ GeV. The single pulsar can fit well the data above 1 TeV meaning that only one source could dominate the electron plus positron flux.
We also notice that the fit ranges we choose for the parameters have a significant influence on the result. For example the value of $E_{c,SNR}$ we run with the fit varies in the range $[10, 10000]$ GeV and the obtained value is 30 GeV that is much smaller than the result in [21], which is around few TeV. We decide thus to make further test to verify how a variation of the intervals for $E_{c,SNR}$ can bring in the final results. In figure 7 and figure 8 we provide the best fit considering different ranges for $\gamma_e$ and $E_{c,SNR}$. In figure 7, we show the best fit for data above 10 GeV limiting the lower bound of $E_{c,SNR}$ to 0.1, 1 and 10 TeV, and the range of $\gamma_e$ is $[1.5, 3.5]$. The $\chi^2$ values we find for the three cases are comparable 387, 370 and 371. In case the lower bound for $E_{c,SNR}$ is fixed to 0.1 TeV, the best fit parameters are $d = 0.23$ kpc, $t = 155$ kyr, $\gamma_e = 2.73$, $E_{sol} = 57$ GeV, $Q_{0,SNR} = 550$, $\gamma_{SNR} = 3.88$. For the case with lower limit fixed to 1 TeV, the best fit parameters for the pulsar slightly change to are $d = 0.36$ kpc, $t = 150$ kyr and $\gamma_e = 2.56$. Finally, for the lower bound fixed to 10 TeV we obtain $d = 0.35$ kpc, $t = 150$ kyr, $\gamma_e = 2.61$.

Finally, in figure 8, we show the best fit for data above 10 GeV limiting the upper bound of $\gamma_e$ to 2.0 and 2.2, and the range of $E_{c,SNR}$ is $[1000,10000]$ GeV. The $\chi^2$ values we obtain for these two cases are 453 and 478. Therefore, limiting the upper bound of $\gamma_e$ to 2.0 or 2.2 worsens significantly the fit. For the upper bound below 2.0, the best fit parameters are $d = 0.59$ kpc, $t = 307$ kyr while for the case with 2.2 are $d = 0.59$ kpc, $t = 325$ kyr.
Figure 7. Best fit with the lower bound of the SNRs cut-off energy fixed to 0.1, 1 and 10 TeV. We show the SNR contribution with green line, the PSR contribution with red line. (a) is the lower bound of cut-off energy fixed to 0.1 TeV; (b) is the lower bound of cut-off energy fixed to 1 TeV; (c) is the lower bound of cut-off energy fixed to 10 TeV.

Figure 8. Best fit with the upper bound of $\gamma_e$ fixed to 2.0 and 2.2. We show the SNR contribution with green line, the PSR contribution with red line. (a) is for $\gamma_e$ fixed to 2.0 and (b) is for 2.2.

4. Conclusion

In this paper we have provided the prediction of $e^\pm$ flux at Earth with a model considering PWNe and SNRs as the main accelerators. We use the continuous scenario for the model of PWN acceleration. In this model, seven parameters are used to do the best fit: $d$, $t$, $\gamma_e$, $E_{\text{60G}}, Q_{0, \text{SNR}}, \gamma_{\text{SNR}}$ and $E_{\text{c,SNR}}$. We find that the limitations we take for each parameters will significantly influence the result of the best fit.

In this paper, we focus on $\gamma_e$ and $E_{\text{c,SNR}}$. For $E_{\text{c,SNR}}$, a larger lower bound of cut-off energy will constrain the SNRs to contribute more on TeV band, which can lower the contribution of PWNe on high energies. In addition, this effect also lowers the contribution of PWNe on lower energies obviously. When we choose the lower bound of cut-off energy as 1 TeV, we get the best $\chi^2$ value and the cut-off energy for this case is 2283 GeV.

For $\gamma_e$, the larger the upper bound of $\gamma_e$, the more the SNRs contribute on TeV band. Moreover, since the upper bound we choose is relatively small, the contribution of SNRs is much larger than that of PWNe over all energies.

A single pulsar with an age of about 110-160 kyr and a distance of 0.2-0.4 kpc can provide most of the flux to the data above 1 TeV. Looking into the ATNF pulsar catalog [22], there is one source with age and distance compatible with our result. This is the pulsar PSR B0656+14 located at a distance of 0.288 kpc and with an age of 111 kyr.
Acknowledgments
I would like to express my gratitude to my supervisor M. Di Mauro, for his instructive advice and useful suggestions on my work.

References
[1] AMS Collaboration collaboration, M. Aguilar, L. Ali Cavasonza, G. Ambrosi, L. Arruda, N. Attig, P. Azzarello et al., Towards understanding the origin of cosmic-ray positrons, Phys. Rev. Lett. 122 (2019) 041102.
[2] AMS Collaboration collaboration, M. Aguilar, L. Ali Cavasonza, B. Alpat, G. Ambrosi, L. Arruda, N. Attig et al., Towards understanding the origin of cosmic-ray electrons, Phys. Rev. Lett. 122 (2019) 101101.
[3] CALET Collaboration collaboration, O. Adriani, Y. Akaike, K. Asano, Y. Asaoka, M. G. Bagliesi, E. Berti et al., Extended measurement of the cosmic-ray electron and positron spectrum from 11 gev to 4.8 tev with the calorimetric electron telescope on the international space station, Phys. Rev. Lett. 120 (2018) 261102.
[4] Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons, Nature 552 (2017) 63-66.
[5] D. K. talk at ICRC17, https://indico.snu.ac.kr/indico/event/15/session/5/contribution/694.
[6] C. Evoli, E. Amato, P. Blasi and R. Aloisio, Galactic factories of cosmic-ray electrons and positrons, Phys. Rev. D 103 (2021) 083010 [2010.11955].
[7] S. Manconi, M. Di Mauro and F. Donato, Contribution of pulsars to cosmic-ray positrons in light of recent observation of inverse-Compton halos, Phys. Rev. D 102 (2020) 023015 [2001.09985].
[8] C. Evoli, P. Blasi, E. Amato and R. Aloisio, Signature of Energy Losses on the Cosmic Ray Electron Spectrum, Phys. Rev. Lett. 125 (2020) 051101 [2007.01302].
[9] M. Di Mauro, F. Donato and S. Manconi, On the interpretation of the latest AMS-02 cosmic ray electron spectrum, 2010.13825.
[10] T. Delahaye, J. Lavalle, R. Lineros, F. Donato and N. Fornengo, Galactic electrons and positrons at the earth: new estimate of the primary and secondary fluxes, Astronomy Astrophysics 524 (2010) A51.
[11] HAWC collaboration, A. U. Abeyesekara et al., Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth, Science 358 (2017) 911 [1711.06223].
[12] I. Büsching, O. C. de Jager, M. S. Potgieter and C. Venter, A Cosmic Ray Positron Anisotropy due to Two Middle-Aged, Nearby Pulsars?, Astrophys. J. Lett. 678 (2008) L39 [0804.0220].
[13] I. Sushch and B. Hnatyck, Modelling of the radio emission from the Vela supernova remnant, Astron. Astrophys. 561 (2014) A139 [1312.0777].
[14] C. Evoli, D. Gaggero, A. Vittino, G. D. Bernardo, M. D. Mauro, A. Ligorini et al., Cosmic-ray propagation with dragon2: I. numerical solver and astrophysical ingredients, Journal of Cosmology and Astroparticle Physics 2017 (2017) 015-015.
[15] H. Yüksel, M. D. Kistler and T. Staney, Tev gamma rays from geminga and the origin of the gev positron excess, Physical Review Letters 103 (2009).
[16] M. Di Mauro, S. Manconi and F. Donato, Detection of a -ray halo around geminga with the fermi -lat data and implications for the positron flux, Physical Review D 100 (2019).
[17] S. P. Reynolds and J. W. Keohane, Maximum energies of shock-accelerated electrons in young shell supernova remnants, The Astrophysical Journal 525 (1999) 368.
[18] Aharonian, F., Akhperjanian, A., Barrio, J., Bernloehr, K., Bost, H., Bojahr, H. et al., Evidence for tev gamma ray emission from cassiopeia a, A&A 370 (2001) 112.
[19] H.E.S.S. Collaboration collaboration, F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, A. R. Bazer-Bachi, Y. Becherini, B. Behera et al., Energy spectrum of cosmic-ray electrons at tev energies, Phys. Rev. Lett. 101 (2008) 261104.
[20] V. A. Acciari, E. Aliu, T. Arlen, T. Aune, M. Bautista, M. Beilicke et al., OBSERVATIONS OF
THE SHELL-TYPE SUPERNOVA REMNANT CASSIOPEIA a AT TeV ENERGIES WITH VERITAS, The Astrophysical Journal 714 (2010) 163.

[21] M. Di Mauro, S. Manconi, A. Vittino, F. Donato, N. Fornengo, L. Baldini et al., Theoretical interpretation of pass 8fermi-late++edata, The Astrophysical Journal 845 (2017) 107.

[22] R. N. Manchester, G. B. Hobbs, A. Teoh and M. Hobbs, The australia telescope national facility pulsar catalogue, The Astronomical Journal 129 (2005) 1993–2006.