Fitting electron spectrum from AMS-02 by pulsar electrons

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Abstract. In this work, we aim to explain the latest data of cosmic-ray electrons from AMS-02 by an electron background model and pulsar electrons. We consider an electron background model which includes primary and secondary electrons. We assume that pulsars are major sources of the electron excess. Since electrons easily lose their energy through the interstellar radiation field and the magnetic field via inverse Compton scattering and synchrotron radiation, respectively, they propagate in a short length. We adopt nearby pulsar data in the distance of 1 kpc from the Australia Telescope National Facility (ATNF) pulsar catalogue. By using a Green's function of an electron propagation model, we then fit pulsar parameters (i.e. the spectral index, the fraction of the total spin-down energy and the cutoff energy) for several cases of a single pulsar. With a combination of the electron background model, several cases of pulsar spectrum are able to explain the electron excess.

1. Introduction

An excess of electron spectrum has been measured by remarkable detectors such as AMS-02 [1], PAMELA [2], Fermi-LAT [3], H.E.S.S.[4], CALET [5] and DAMPE [6]. There are interpretations that try to explain origins of the electron excess by supernova remnants (SNRs) [7], pulsars [8] and dark matter annihilation or decay which requires the existence of new particles [9].

In this work, we try to explain the electron excess based on the latest data of electron fluxes from Alpha Magnetic Spectrometer-02 (AMS-02) mounted on the international space station [1] by electron spectrum from pulsars. We consider nearby pulsars that produce a burst-like source as the source of the electron excess instead of SNRs, which are assumed to be a stable continuous source of cosmic-ray particles. The electron data are comprehensive in between a few GeV to about 1 TeV. In our model, we consider an electron background model that consists of primary electrons from SNRs and secondary electrons from the inelastic collisions between cosmic-ray nuclei and the interstellar medium. The production of electrons from pulsars is considered as the source of the electron excess. The propagation of the pulsar electrons is determined by a solution of a Green's function of a diffusion model. We adopt nearby pulsar data in the distance of 1 kpc from the ATNF pulsar catalogue. We use the solution of the Green's function of an electron propagation model and the electron background model to find the fitting pulsar parameters, i.e. the spectral index, the fraction of the total spin-down energy and the cutoff energy, that provide the explanation for the electron excess of the AMS-02 data.

2. Method and data

In this work, we are interested in the cosmic-ray electron data from AMS-02 [1] that have revealed an electron excess against the electron background. We aim to explain the electron excess by using the pulsar electron spectrum which is explained by a Green's function of an electron propagation model. In this section, we will explain the model of the electron background and the model of the pulsar electron spectrum that we use in this work. Finally, the details for the pulsar data that we adopt from the ATNF pulsar catalogue and the method of the data fitting will also be expressed here.

2.1. The electron background

We consider that background electrons consist of primary electrons from SNRs and secondary electrons from the inelastic collisions between cosmic-ray nuclei and the interstellar medium [10]. The total flux of background electrons is given by

$$\Phi_{e^-} = \Phi_{e^-_{\text{pri}}} + 0.6\Phi_{e^-_{\text{sec}}}. \tag{1}$$

Due to the neutron production process, there are only 60 percents of secondary electrons left. The fluxes of primary and secondary electrons can be described by broken power-law functions,

$$\Phi_{e^-_{\text{pri}}} = C_1 E^{-\gamma_1}\left[1+\left(\frac{E}{E_{br1}}\right)^{\gamma_2}\right]^{-1}\exp\left(\frac{-E}{E_c}\right) \tag{2}$$

and

$$\Phi_{e^-_{\text{sec}}} = C_2 E^{-\gamma_3}\left[1+\left(\frac{E}{E_{br2}}\right)^{\gamma_4}\right]^{-1}, \tag{3}$$

where C_1 and C_2 are the normalization factor of the primary and secondary electrons, respectively, in the units of $\text{GeV}^{-1}\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$. γ_i is the spectral index, E_{br} is the break of energy in GeV and the energy cutoff, E_c, occurs only for the primary electrons. We adopt the best-fit parameters of the backgrounds from [10].

2.2. Model of electron spectrum from pulsars

The electrons propagation can be determined by a diffusion equation which is a function of diffusion parameters, loss rate and source term [11]. By using a Green's function, the solution of the electrons spectrum in a function of energy E, time t and pulsar distance $\boldsymbol{r}$ can be given by

$$\psi\left(E,t,\boldsymbol{r}\right) = \frac{1}{2}\frac{Q_0}{\pi^{3/2}r_{\text{diff}}^3}\left(1-\frac{E}{E_{\text{max}}}\right)^{\gamma-2}\left(\frac{E}{\text{GeV}}\right)^{-\gamma}\exp\left(-\frac{E}{(1-E/E_{\text{max}})E_c}\right)\exp\left(-\frac{r^2}{r_{\text{diff}}^2}\right), \tag{4}$$

where $E_{\text{max}} = (b_0 t)^{-1}$ is the maximum energy of electrons after the propagation and γ is the spectral index. The electrons can lose their energy through inverse Compton scattering via interstellar radiation field, i.e. low energy photons of cosmic microwave background, star light and dust emission, and synchrotron radiation via magnetic field which provide the loss rate $b_0 = 1.4\times10^{-16}\ \text{GeV}^{-1}\text{s}^{-1}$. The diffusion length r_{diff} is explained in [11]. E_c is the cutoff energy.

Q_0 is the normalization factor related to the total injection energy E_{tot} which is expressed by

$$E_{\rm tot} = \int_{E_{\rm min}}^{\infty} EQ\left(E,t,\boldsymbol{r}\right) dEd\boldsymbol{r}dt, \tag{5}$$

where $E_{\rm min} = 0.1$ GeV and $Q\left(E,t,\boldsymbol{r}\right)$ is the source term of electrons provided by pulsars. The pulsar electron spectrum is described in a power-law energy spectrum in a term of delta fuctions,

$$Q\left(E,t,\boldsymbol{r}\right) = Q_0\left(\frac{E}{\rm GeV}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right) \delta\left(\boldsymbol{r}\right)\delta\left(t\right). \tag{6}$$

Finally, $E_{\rm tot}$ can be written in the term of a fraction of the total spin-down energy η, the spin-down luminosity of the pulsar $\dot{\varepsilon}$, the age of pulsar t and the typical luminosity decay time τ_0 which is equal to 10 kyr, as given by

$$E_{\rm tot} = \eta\dot{\varepsilon}t\left(1 + t/\tau_0\right). \tag{7}$$

2.3. The pulsar catalogue and the fitting method

We use data of nearby pulsars in the distance of 1 kpc which are observed by the ATNF pulsar catalogue. The catalogue provides the distance $\boldsymbol{r}$, the age t and the spin-down luminosity $\dot{\varepsilon}$ for individual pulsars. The catalogue reveals that the age of the nearby pulsars is in the order of 10^4 to 10^{10} years, and the spin-down luminosity is in the order of 10^{28} to 10^{35} ergs^{-1}.

By using the electron background model and the parameters of pulsars provided by the ATNF catalogue, we are able to constrain the other parameters, i.e. the spectral index γ, the fraction of the total spin-down energy η and the cutoff energy E_c by fitting the modeled electron spectrum with the measured electron spectrum from AMS-02.

We provide the fitting parameters for each pulsar. We use the χ^2 to test the best-fit for the pulsar spectrum. The ratio of χ^2 with degrees of freedom is given by

$$\frac{\chi^2}{\rm df} = \frac{\sum \frac{\left({\rm Model}_i - {\rm Observed}_i\right)^2}{\sigma_i^2}}{51 - 3}, \tag{8}$$

where σ_i represents the uncertainty of the observed data and the degrees of freedom is expressed by 51 observations and 3 fitted parameters.

3. Results

We have selected 65 possible pulsars in the distance of 1 kpc and adopted parameters such as the distance $\boldsymbol{r}$, the age t and the spin-down luminosity $\dot{\varepsilon}$ of each pulsar from the ATNF catalogue. We have adopted the best-fit parameters for the electron background model from [10]. We then constrain parameters such as the spectral index γ, the fraction of the total spin-down energy η and the cutoff energy E_c in our model for each pulsar to find the best fitting compared with the measured electron spectrum from AMS-02.

From 65 pulsars, there are 8 pulsars whose spectrum can explain the AMS-02 electron data well. The results of electron spectrum from the 8 pulsars, i.e. J0954-5430, J1825-0935, J0659+1414, J1732-3131, J1731-4744, J1809-2332, J2337+6151 and J1740-3015, are presented in figure 1 together with χ^2/df. The best-fit parameters of each pulsar are shown in table 1. They are young pulsars with ages less than 3×10^5 years and the spin-down luminosity $\dot{\varepsilon}$ are more than 4×10^{33} erg/s. Due to the high energy loss and low total injection energy, older pulsars and pulsars with the spin-down luminosity $\dot{\varepsilon}$ less than 4×10^{33} erg/s are unable to provide the electron spectrum at energy higher than 100 GeV where the electron excess starts to rise against the background. Surprisingly, the spectral index γ for the 8 pulsars is all equal to 1.50 where the fraction of the total spin-down energy η and the energy cutoff E_c are varied.

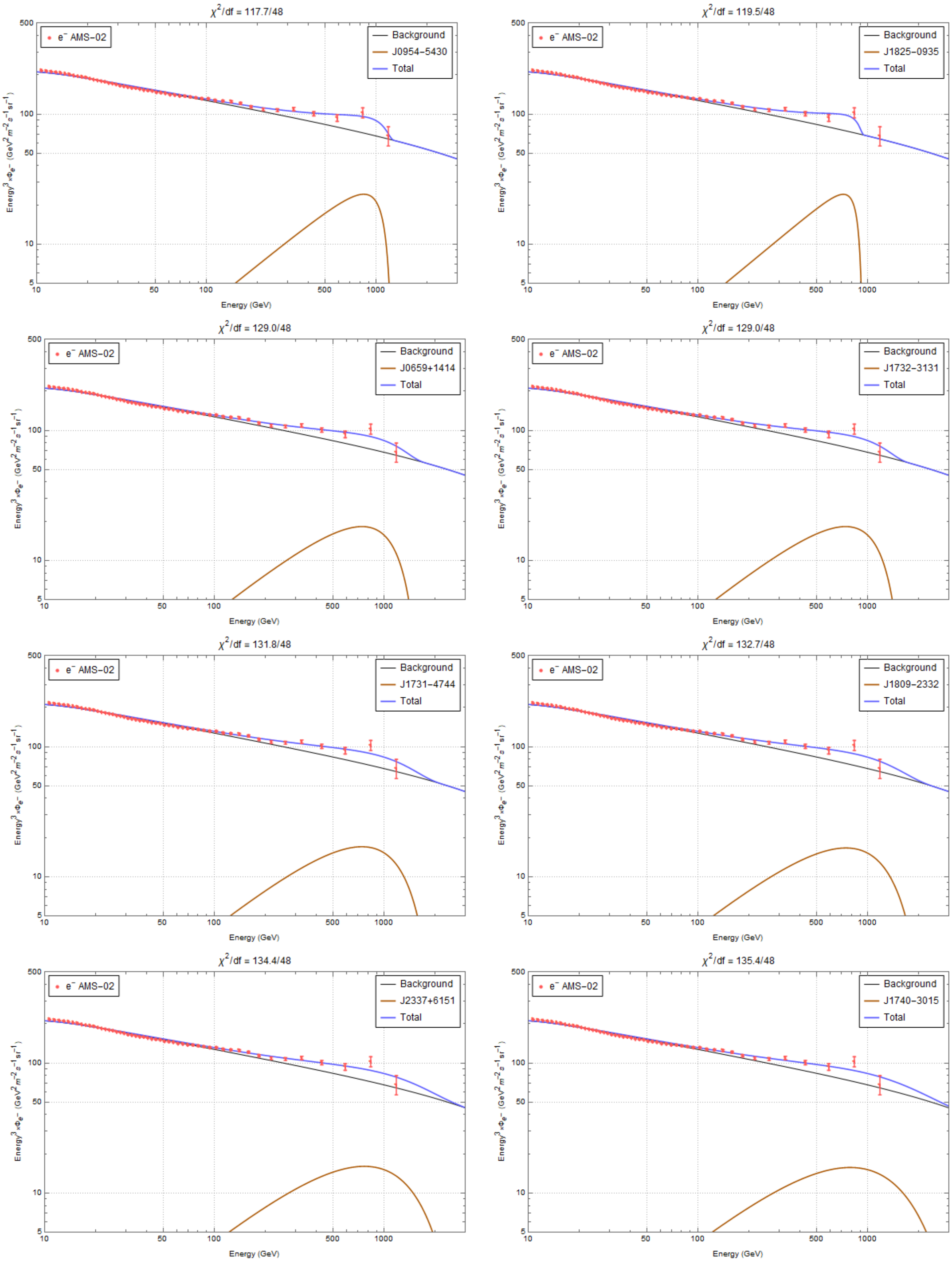

Figure 1. Cosmic-ray electron flux from AMS-02 (red dots) compares with modeled electron flux (blue line) which is a combination of background electron flux (black line) and electron flux from a single pulsar (brown line) for 8 pulsars that provide electron spectrum cover the electron excess.

Table 1. The best-fit parameters of 8 pulsars.

Parameters	$\boldsymbol{r}$ (kpc)	t (years)	$\dot{\varepsilon}$ (erg/s)	γ	η	E_c (GeV)
J0954-5430	0.433	1.71×10^5	1.60×10^{34}	1.50	0.693	3834
J1825-0935	0.300	2.33×10^5	4.50×10^{33}	1.50	1.92	5000
J0659+1414	0.288	1.11×10^5	3.80×10^{34}	1.50	0.415	1463
J1732-3131	0.640	1.11×10^5	1.50×10^{35}	1.50	0.105	1463
J1731-4744	0.700	8.04×10^4	1.10×10^{34}	1.50	1.64	1156
J1809-2332	0.880	6.76×10^4	4.30×10^{35}	1.50	0.0445	1066
J2337+6151	0.700	4.06×10^4	6.30×10^{34}	1.50	0.349	920
J1740-3015	0.400	2.06×10^4	8.20×10^{34}	1.50	0.308	838

4. Conclusions

We have used an electron background model and a model of pulsar spectrum to explain the latest data of cosmic-ray electrons from AMS-02. We have considered an electron background model which includes primary and secondary electrons and we have adapted the background model from [10]. We have used a pulsar spectrum model which is a solution of a diffusion equation in a function of diffusion parameters, loss rate and source term. We have adopted nearby pulsar data in the distance of 1 kpc from the Australia Telescope National Facility (ATNF) pulsar catalogue which provides parameters such as the distance $\boldsymbol{r}$, the age t and the spin-down luminosity $\dot{\varepsilon}$ of each pulsar. We have constrained parameters of pulsars in the pulsar spectrum equation, i.e. the spectral index γ, the fraction of the total spin-down energy η and the cutoff energy E_c, to find the best-fit parameters to explain the AMS-02 data.

We have found that the pulsar spectrum from 8 pulsars, i.e. J0954-5430, J1825-0935, J0659+1414, J1732-3131, J1731-4744, J1809-2332, J2337+6151 and J1740-3015, combine with the electron background fit well with the cosmic-ray electron data from AMS-02. The pulsars are younger than 3×10^5 years and the spin-down luminosity $\dot{\varepsilon}$ are more than 4×10^{33} erg/s otherwise, they are unable to provide the electron spectrum that can explain the electron excess at energy higher than 100 GeV. In the future, we aim to extend our model for double and triple pulsars with the purpose to find a better explanation of the cosmic-ray electron sources.

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