SPECTRA OF COSMIC RAY ELECTRONS AND DIFFUSE GAMMA RAYS WITH THE CONSTRAINTS OF AMS-02 AND HESS DATA

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ABSTRACT

Recently, AMS-02 reported their results of cosmic ray (CR) observations. In addition to the AMS-02 data, we add HESS data to estimate the spectra of CR electrons and the diffuse gamma rays above TeV. In the conventional diffusion model, a global analysis is performed on the spectral features of CR electrons and the diffuse gamma rays by the GALRPOP package. The results show that the spectrum structure of the primary component of CR electrons cannot be fully reproduced by a simple power law and that the relevant break is around 100 GeV. At the 99% confidence level (C.L.), the injection indices above the break decrease from 2.54 to 2.35, but the ones below the break are only in the range of 2.746–2.751. The spectrum of CR electrons does not need to add TeV cutoff to also match the features of the HESS data. Based on the difference between the fluxes of CR electrons and their primary components, the predicted excess of CR positrons is consistent with the interpretation that these positrons originate from a pulsar or dark matter. In the analysis of the Galactic diffuse gamma rays with the indirect constraint of AMS-02 and HESS data, it is found that the fluxes of Galactic diffuse gamma rays are consistent with the GeV data of the Fermi-Large Area Telescope (LAT) in the high-latitude regions. The results indicate that inverse Compton scattering is the dominant component in the range of hundreds of GeV to tens of TeV, respectively from the high-latitude regions to the low ones, and in all of the regions of the Galaxy the flux of diffuse gamma rays is less than that of CR electrons at the energy scale of 20 TeV.

Key words: cosmic rays – gamma rays: diffuse background

1. INTRODUCTION

Recently, AMS-02 reported their results of cosmic ray (CR) observations. Below TeV, the spectra of CR protons and electrons can be described by the high-precision data (Aguilar et al. 2014b; Aguilar et al. 2015). However, above TeV, CR spectra have many uncertainties. In the conventional model, CR production and propagation are governed by the same mechanism at energies below 10¹⁵ eV (Berezinskii et al. 1990). Thus, the TeV spectra of CRs may be predicted to match the data below TeV. In pilot studies of CR measurement, the predicted spectra of CRs are often used to analyze the background subtractions, identification of chemical composition, etc.

In the conventional model of CRs, CR electrons are divided into primary and secondary particles. Just like primary CR nucleons, primary electrons are speculated to be created from supernova remnants (SNRs), and the injection spectra can be described by a simple power-law feature derived from the diffuse shock acceleration (Blandford & Eichler 1987). The secondary electrons and positrons are created during collisions of CR nucleons (proton-dominant) with the interstellar gas, and also have a simple feature of spectra derived from the CR protons. The secondary electrons and positrons both contribute to the astrophysical background of CR electrons, as well as the primary electrons.

In recent years, it has been found that the ratio of the CR positron flux to the combined flux of CR electrons and positrons (positron fraction) keeps increasing in some energy ranges, which is not consistent with the conventional astrophysical background data and is called positron excess (PAMELA Collaboration et al. 2009; Adriani et al. 2010; Fermi LAT Collaboration et al. 2012; Aguilar et al. 2013; Accardo et al. 2014). The possible sources of positron excess are not only of astrophysical origin, such as nearby pulsars (Hooper et al. 2009; Profumo 2011) and supernovae remnants (Blasi 2009; Ahlers et al. 2009) but also dark matter, which produces the excessive CR positrons through annihilation or decay. Lately, AMS-02 have reported the precise measurements of CR electrons and positrons (Aguilar et al. 2014b) and updated the positron fraction (Accardo et al. 2014). The flux of CR electrons is in the range of 0.5–700 GeV and cannot be fully described by a single power-law spectrum (Aguilar et al. 2014b). The latest data of AMS-02 show the features of positron excess explicitly.

The spectral features of CRs are often used to explore their origins. In the AMS-02 data, as the maximal value of positron fraction is 0.159 at 305 GeV (Accardo et al. 2014), the maximal flux of CR positrons is almost 20% of the primary electrons. And the flux of CR positrons in the astrophysical background is about 1% of the primary electrons at 305 GeV. Thus, if pulsars, dark matter, or the other sources could produce the same flux of CR electrons as CR positrons, the experimental data of CR electrons would imply that the flux of positron excess has a special feature that is distinguished from a single power-law spectrum. In this paper, using the difference between the CR electrons and positrons fitting to the AMS-02 data, we attempt to extract the astrophysical background of primary electrons to analyze the origins of CR electrons.

As in the AMS-02 data, the maximum energy of CR positrons and electrons is below 1 TeV, so in order to analyze the TeV flux of CR electrons, HESS experimental data are added. The measurements of HESS electrons are taken from an array of imaging atmospheric Cherenkov telescopes and do not discriminate the CR electrons from CR positrons (HESS electrons, i.e., HESS electron and positron). The uncertainties of HESS electron data are mainly from the subtraction of
hadronic background and discrimination against gamma-ray events (H.E.S.S. Collaboration et al. 2008). The very high-energy flux of HESS electrons is described by an exponentially cutoff power law with an index of 3.05 ± 0.02 and a cutoff at 2.1 ± 0.3 TeV in the range of 700 GeV–5 TeV (H.E.S.S. Collaboration et al. 2008). The low-energy extensions of the HESS electron measurements are from 340 GeV to 1.7 TeV, with a break energy at about 1 TeV (H.E.S.S. Collaboration et al. 2009). After the HESS data is reported, the spectrum of the CR electrons is often described by a broken power law with a break at 2 TeV (Fermi LAT Collaboration et al. 2010).

Galactic diffuse gamma rays are related to CRs interacting with the interstellar medium (ISM), which includes interstellar gas, interstellar radiation fields (ISRFs), magnetic fields, etc. With the interstellar gas, CR nucleons produce neutral pions ($\pi^0$), which decay into gamma rays (Dermer 1986). Because CR protons are dominant in the components of CR nucleons, the flux of $\pi^0$-decay diffuse gamma rays is mainly associated with CR protons. Because the measurement flux of CRs above 10 GeV (due to the rigidity of CRs) at the Earth is the same as the interstellar spectrum and below 10 GeV the interstellar spectrum may be transformed into the observed value at Earth by the solar modulation potential $\phi$ (Gleeson & Axford 1968), the spectral features of diffuse gamma rays may be analyzed with the measurement data of CRs. The experimental data of CR protons has been recently reported by the CREAM (Yoon et al. 2011), PAMELA (PAMELA Collaboration et al. 2011a), and AMS-02 (Aguilar et al. 2015) experiments. Based on these measurement data, the flux of $\pi^0$-decay diffuse gamma rays can be calculated in the CR propagation model. Besides the interaction of CR nucleons with the ISM, CR electrons produce gamma rays by Bremsstrahlung and by IC scattering with ISRFs. Thus, the experimental data of diffuse gamma rays may be used to indirectly constrain the interstellar spectrum of CR electrons. Furthermore, with the constraint of CR particles and diffuse gamma-ray data, the component discrimination of diffuse gamma rays can be performed to explore the distributions of the ISM and ISRFs.

In this paper, we choose the diffuse gamma-ray data of Milagro to constrain the IC component predicted by CR electrons above TeV. The Milagro experiment is a water Cherenkov detector on air-shower arrays and has reported the diffuse gamma-ray spectra of inner the Galaxy ($l \in [30^\circ, 65^\circ]$) and the Cygnus region ($l \in [65^\circ, 85^\circ]$) in the range of Galaxy latitude $b \in [-2^\circ, 2^\circ]$ (Abdo et al. 2008). The fluxes of the inner Galaxy are consistent with the predictions of the optimized GALPROP model (Strong et al. 2004; Prodanović et al. 2007; Porter et al. 2008) and the fluxes of Cygnus region apparently exceed the theoretical predictions of the background (Abdo et al. 2008). As the subtractions of the isotropic background and the unknown point sources from the two regions are not indicated (Abdo et al. 2008) and the predicted CR electrons of optimized GALPROP model are not yet verified by the experimental data, the Milagro experimental data can provide an upper-limit constraint to the spectrum of CR electrons predicted by the AMS-02 and HESS data.

In this paper, based on the fluxes of CR electrons and protons, all of the components of diffuse gamma rays are predicted in the conventional diffuse model by the GALPROP package (Strong & Moskalenko 1998; Strong et al. 2004; Prodanović et al. 2007; Porter et al. 2008). In order to verify the predicted diffuse gamma rays below TeV, we choose the two regions of high latitudes in the public data of the Fermi-Large Area Telescope (LAT). As the fluxes of detected sources at those regions are weaker than the other regions (T. F.-L. Collaboration 2012), Fermi-LAT data may strongly constrain the prediction of the models based on AMS-02 and HESS data. We also analyze the components of diffuse gamma rays and try to establish some hints regarding the gamma-ray excess of the Cygnus region. Comparisons are also drawn between the fluxes of diffuse gamma rays, CR electrons, and CR protons.

This paper is organized as follows. In Section 2 we outline the formulas concerned with the propagation of CRs and the calculation of diffuse gamma-ray emission. In Section 3 we describe the data selection and the strategy of the data fitting in a number of propagation models. In Section 4 we describe the analysis of CR electrons and diffuse gamma rays. The conclusions are given in Section 5.

2. CR PROPAGATION AND DIFFUSE GAMMA-RAY EMISSION

In the conventional model, CR production and propagation are governed by the same mechanism at energies below $10^{17}$ eV. CR propagation is often described by the diffusion equation (Berezinskii et al. 1990):

$$\frac{\partial \psi}{\partial t} = \nabla(D_{xx} \nabla \psi - V_x \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \dot{\rho} \psi - \frac{p}{2} (\nabla \cdot V_e) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_{\tau}} \psi + q(r, p)$$

(1)

where $\psi(r, p, t)$ is the number density per unit of total particle momentum, which is related to the phase space density $f(r, p, t)$ as $\psi(r, p, t) = 4\pi p^2 f(r, p, t)$. $D_{xx}$ is the spatial diffusion coefficient parameterized as

$$D_{xx} = \beta D_0 \left( \frac{\rho}{\rho_0} \right)^{\delta_1/2},$$

(2)

where $\rho = p/(Z e)$ is the rigidity of the CR particles, and $\delta_1/2$ is the index below (above) a reference rigidity $\rho_0$. The parameter $D_0$ is a normalization constant and $\beta = v/c$ is the ratio of the velocity $v$ of the CR particles to the speed of light. $c, V_e$ is the convection velocity related to the drift of CR particles from the Galactic disk due to the Galactic wind. The diffusion in momentum space is described by the re-acceleration parameter $D_{pp}$ related to the Alfvén speed $V_a$, i.e., the velocity of turbulences in the hydrodynamical plasma, whose level is characterized as $\omega$ (Berezinskii et al. 1990; Seo & Ptuskin 1994):

$$D_{pp} = \frac{4V_a^2 p^2}{3D_{xx} \delta (4 - \delta_1^2)(4 - \delta_1)\omega},$$

(3)

where $\delta_1 = \delta_1$ or $\delta_2$ is the index of the spatial diffusion coefficient. $\dot{\rho}, \tau_f$, and $\tau_\tau$ are the momentum loss rate, the timescales for fragmentation, and the timescales for radioactive decay, respectively. The momentum loss rate of CR electrons is not the same as that for CR nucleons, and the relevant expressions are found in Appendix C of Strong & Moskalenko (1998).
The source $q(r, p)$ of the primary particles is described as a broken power-law spectrum multiplied by the assumed spatial distribution (Strong & Moskalenko 1998):

$$q_A(R, z) = q_0 c_A \left( \frac{\rho_p}{\rho_{p0}} \right)^\gamma \left( \frac{R}{R_0} \right)^x \times \exp \left[ -\frac{\xi R - R_0}{R_{0.2}} - \frac{|z|}{0.2 \text{kpc}} \right] ,$$

(4)

where $\eta = 0.5$, $\xi = 1.0$, and the parameter $q_0$ is normalized with the propagated flux. $c_A$ is the relative abundance of the $A$th nucleon. The reference rigidity $\rho_{p0}$ is described as the breaks of the injection spectrum. $\gamma$ is the power indices below (above) a reference rigidity. The flux of secondary particles is derived from the primary particle’s spectrum, spatial distribution, and interaction with the interstellar gas. The calculation of secondary particle flux is explained in Strong & Moskalenko (1998) and Kelner et al. (2009).

In this paper, the CR propagation Equation (1) is solved by the package GALPROP v5.4, which is based on a Crank–Nicholson implicit second-order scheme (Strong & Moskalenko 1998). In order to solve the equation, a cylindrically symmetric geometry is assumed. And the spatial boundary conditions assume that the density of CR particles vanishes at the boundaries of radius $R_0$ and half-height $Z_0$. At the top of the atmosphere of the Earth, CR particles are affected by solar winds and the heliospheric magnetic field. The force-field approximation is used to describe this effect and the solar modulation potential $\phi$ denotes the force-field intensity (Gleeson & Axford 1968). In this paper, we take $\phi = 0.70 \text{ GV}$ (best-fit value based on Model A in the next section) and ignore the difference of $\phi$ between the experimental data.

In the three components of Galactic diffuse gamma-ray emission, the $\pi^0$-decay component is calculated with the simulation of inelastic $p-p$ collisions producing secondary particles (Strong & Moskalenko 1998; Kelner et al. 2009), whose spectrum is mainly derived from the propagated CR protons. The IC component is calculated by the appropriate formalism based on the spatial and angular distribution of ISRFs in the GALPROP code (Strong et al. 2000). The Bremsstrahlung component is mainly from the contribution of CR electrons and positrons, whose calculation is explained in Strong et al. (2000).

In this paper, the calculations of the CR propagation and the diffuse gamma-ray emission are cross-checked with the results from the GALPROP web run (Vladimirov et al. 2011).

3. DATA SELECTION AND FITTING SCHEMES

In order to analyze the different constraints on the experimental data, the combinations of AMS-02, HESS, and Milagro data are divided into four types, which are denoted as models A, B, C, and D, respectively. Models A, B, and C are used to analyze CR electrons that are constrained by the data of AMS-02, HESS, and Milagro. Model D is set up to analyze the $\pi^0$-decay component of diffuse gamma rays with AMS-02 protons, in which the source item of the primary electrons is irrelevant and referred to as model B.

The numerical solution of the CR propagation equation (Equation (1)) is performed by GALPROP (Strong et al. 2000) in the conventional re-acceleration diffusion model, which does not involve the convection of CR particles on the Galactic disk. In our previous paper, it was found that the propagation parameters, half-height $Z_{0h}$, diffuse parameters $D_0$ and $\beta (\beta = \beta_{1,2})$, and Alfvén speed $V_a$, and power indices $\gamma_{1,2,3}$ below (above) a reference rigidity of CR protons, can be determined alone from the AMS-02 data: proton flux ($P$) and the ratio of Boron to Carbon flux ($B/C$; Jin et al. 2014). In this paper, alongside these parameters, we also add the normalization constant of CR protons, $N_p$, and the parameters concerned with primary electrons.

The source item (4) of primary electrons in GALRPOP is described by the use of the normalization constant $N_e$, the two reference rigidities (breaks) $\rho_{p1,2}$ and the three power indices $\gamma_{1,2,3}$. The defaults of the first and second reference rigidities are at 4 GV and 1 PV, respectively, in the conventional model of GALPROP. In this paper, because the maximal energy of GALRPOP grids is fixed at 100 TeV, the 1 PeV break of CR electron spectrum makes the third index invalid. Thus, the models with a 1 PV subscript describe a CR electron spectrum of a simple power law and have no breaks above GeV in the calculations of GALRPOP. In this paper, as the spectrum of CR electrons is focused above GeV, the first reference rigidity $\rho_{p1}$ is not used in the fitting schemes. Based on the second reference rigidity and the two power indices below (above) the reference rigidity, we divide the fitting schemes into three cases: two free breaks, one free break, and the fixed break. Two free breaks means that the two reference rigidities and the three power indices are free. One free break means that the default of the second reference rigidity is at 1 PV. The fixed break means that the second reference rigidity is 2 TV from the feature of HESS electron spectrum.

The CR electrons of AMS-02 theoretically involve the primary and secondary components. The primary component is not measured directly by experimental instruments. In order to analyze the relevant experimental value, the primary component of the AMS-02 electron data may be extracted from the difference between AMS-02 electrons and positrons based on the hypothetical models. In our previous paper, we concluded that the interpretation of positron excess favors the annihilation of dark matter or the charge symmetry decay of dark matter (Jin et al. 2013). In this paper, we generally assume that the sources relevant to the positron excess produce the charge symmetry particles in the final state, which means that the flux of CR electrons is not measured directly by experimental instruments.
Table 2

| Exp.($\chi^2$) | AMS-02(72, 67, 73) | HESS(8, 10) | Milagro(1, 1) |
|---------------|-----------------|-------------|--------------|
| $\chi^2_P$    | $\chi^2_B/C$    | $\chi^2_e$  | $\chi^2_{e\bar{e}}$ | $\chi^2_{\gamma}$ | $\chi^2_{\gamma}/N$ | $\chi^2/N$ |
| A             | 91.04           | 75.98       | 42.77        | ...           | ...           | ...    | 209.79 | 0.99 |
| $\chi^2_{TV}$ | 107.64          | 63.60       | 130.78       | ...           | ...           | ...    | 302.03 | 1.43 |
| B             | 107.45          | 63.71       | 126.97       | ...           | ...           | ...    | 298.13 | 1.41 |
| $\chi^2_{VV}$ | 91.02           | 76.02       | 42.91        | 13.58         | 13.65         | ...    | 237.17 | 1.04 |
| B             | 113.71          | 60.59       | 129.49       | 56.75         | 50.01         | ...    | 410.55 | 1.79 |
| $\chi^2_{PV}$ | 112.82          | 61.01       | 125.77       | 24.71         | 42.60         | ...    | 366.90 | 1.60 |
| C             | 90.66           | 76.86       | 42.79        | 13.81         | 13.47         | 5.04   | 5.69   | 248.32 | 1.07 |
| D             | 91.28           | 76.10       | ...          | ...           | ...           | ...    | 178.24 | 1.26 |

Note. $\gamma^1$ and $\gamma^2$ denote the galactic skies $l \in [30^\circ, 65^\circ]$ and $l \in [65^\circ, 85^\circ]$. The added models C and D are used to limit the higher-energy spectra of CR electrons and protons rather than the HESS data.

The astrophysical journal, 811:154 (11pp), 2015 October 1

4. RESULTS

In Tables 1 and 2, the best-fit $\chi^2$ that is relevant to the $e^- - e^+$ case in models A-B and the $e^-$ case in models A-D are shown, respectively. The total data points and the ratio of total $\chi^2$ to the total data points in each model are listed in the last two columns. In all of the models, the best-fit $\chi^2$ relevant to the AMS-02 P and B/C is almost around the data points of the experimental data. Thus, the theoretical CR proton flux and B/C are consistent with the AMS-02 data. As seen in Figure 1, the CR proton flux and B/C are not distinctly discriminated between models. In Tables 3 and 4, the propagation parameters relevant to the best-fit $\chi^2$ have differences that are only within 5% between the models. This implies that the propagation parameters are strongly constrained by the high-accuracy data of AMS-02 Proton and B/C and do not take the apparent uncertainties into account for the calculation of CR electrons and positrons. In our previous paper (Jin et al. 2014), the uncertainties of the propagation parameters were analyzed in detail; the relevant errors and contours at the 95% confidence level (C.L.) are shown in Table 2 and Figure 2, respectively. Based on the previous sampling data, the limited fluxes of CR electrons and positrons are predicted. In Figure 2, the positron fraction and the fluxes of CR electrons and positrons with the uncertainties of propagation parameters at the 95% C.L. are shown. From the limited regions, it is found that the 10 GeV, the positron fraction and fluxes of CR positrons have errors around 30%, and the errors of CR electron flux are less than 10%. For the $e^-$ case in model D, the best-fit $\chi^2$ shows that the flux of n$^0$-decay gamma rays, derived from CR protons, is not much less than the flux from the Milagro data in the errors of AMS-02 data. As seen in the first rows of Figure 1, the high-energy flux of CREAM Protons matches the extension of AMS-02 Protons, which means that the CR protons in the AMS-02 data are very difficult to fit to the excess of diffuse gamma rays from the Milagro experiments.

4.1. The Spectra of CR Electrons

In the last rows of Figure 1, the fluxes of CR electrons, the total number of CR electrons and positrons, and the primary electrons are drawn. As seen in Tables 1 and 2, in two cases from models A-B, the ratio of the best-fit $\chi^2$ to the data points of the AMS-02 electrons are all less than 2, which means that all of the models are consistent with the AMS-02 electron data. As $\chi^2$ is relevant to the AMS-02 P and B/C, it is difficult to distinguish the differences between these models. As the ISM is almost equivalent to each other, the spectral features of secondary positrons and electrons with a simple power-law spectrum do not contribute to the changes of the primary electron structure in the constraint of these models.
In the $e^- - e^+$ and $e^- e^+$ cases of model A, the $\chi^2$ relevant to the 1 PV break (means a simple power-law spectrum) is around the data points of the $e^- - e^+$ and $e^- e^+$ experimental data, which is seen in Tables 3 and 4. It is justified that the data of AMS-02 electrons imply that the basic feature of the power law and the primary electrons is the dominant component of CR electrons. The maximal value of the positron fraction from AMS-02 is less than 20% and is also in line with this feature.
In order to explore the CR electron spectrum structure’s limit to a power law, we perform some analysis of confidence intervals to illustrate the changes of the second reference rigidity $\rho_{\text{ref}}$ and the two indices $\gamma_2^B$ and $\gamma_3^B$ in the source item of primary electrons. In the first row of Figure 3, the allowed regions of the second reference rigidity and the third index in the $e^- - e^+$ cases and the $e^-$ cases in model A-B are shown at the 99% C.L. In the second row of Figure 3, the allowed regions of the second and third indices in the $e^- - e^+$ cases and the $e^-$ cases in model A-B are also shown at the 99% C.L.

In the $e^- - e^+$ case of model A, the confidence intervals of the third index are not constrained in reasonable ranges, but the maximum of the third index is the only one that is limited. From the left column of Figure 3, where the third index is at maximum, 2.674 at the 99% C.L., the second reference rigidity drops to 50 GV and the second index is near 2.749. The difference of 0.075 between the second and third indices at the reference 640GV means that from the constraint of AMS-02 data alone, the primary electron spectrum is not excluded from a simple power law at the 99% C.L. Nevertheless, in the $e^- - e^+$ case of model B, this situation is changed. The confidence intervals of the third index and the second reference rigidity are constrained in the narrower ranges. At the 99% C.L. the third index decreases from 2.54 to 2.35, but the second index’s values are only in the range of 2.746–2.751. Thus, the spectrum of primary electrons above 100 GeV depends on whether or not HESS data is included and the spectrum of primary electrons favors this feature, which is more complex than a simple power law. Before AMS-02 releases the measurement data of CR electrons, Feng et al. (2014) already predicted this feature theoretically. These results imply that the spectrum of the primary electrons needs a different interpretation than the conventional astrophysical background, such as the nearby SNRs (Mauro et al. 2014), asymmetrically charged dark matter, etc. In the $e^-$ case of model A, the confidence intervals of the second and third indices and the second reference rigidity are completely constrained by AMS-02 data alone. As seen in the right column of Figure 3, at the 99% C.L., the difference between the second and third indices is significant. Thus, the theoretical CR electrons that are constrained by AMS-02 electrons have an obvious structure, which implies that the components are in excess of the astrophysical background. For the $e^-$ case in model B, the difference between the second and third indices is much less than that for model A. In Table 5, the bounds of the propagation parameters from the $e^- - e^+$ and $e^-$ cases of model B are listed. $B^f_{\text{Min}} - e^+$ and $B^f_{\text{Max}} - e^+$ respectively represent the minimal and maximal fluxes of primary electrons in the $e^- - e^+$ case of model B. $B^f_{\text{Min}}$ and $B^f_{\text{Max}}$ are the same as the $e^- - e^+$ case, but for the $e^-$ case of model B.

Based on the best fits and bounds of CR electron and primary electron fluxes, the CR positron spectrum may be predicted from their differences between the $e^-$ and $e^- - e^+$ cases in models A-B. In Figure 4, the predicted CR positron flux and positron fraction are drawn with the color lines. In these lines in Figure 4, some are derived from the differences between the best-fit fluxes of the CR electrons of the $e^-$ cases and the primary electrons of the $e^- - e^+$ cases in models A-B. The relevant best-fit parameters are shown in Tables 3 and 4. The other lines are from the differences between the maximal and minimal fluxes of the $e^-$ case and the minimal flux of the $e^- - e^+$ case in model B from Table 5. As seen in Figure 4, the rapidly damping spectrum that can be interpreted as dark matter

### Table 3

| Para. | $A_{1TV}$ | $A_{1PV}$ | $B_{2TV}$ | $B_{1PV}$ |
|-------|-----------|-----------|-----------|-----------|
| $N_p$ | 1.287     | 1.299     | 1.299     | 1.300     |
| $\gamma_1^B$ | 1.607     | 1.632     | 1.607     | 1.640     |
| $\gamma_2^B$ | 2.750     | 2.723     | 2.750     | 2.715     |
| $\frac{\rho_{\text{ref}}}{\text{MeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}}$ | 0.108     | 2         | 0.128     | 2         |
| $\gamma_3^B$ | 2.520     | 5         | 2.440     | 5         |
| $\gamma_2^B - \gamma_3^B$ | -0.230    | 2.277     | ...       | -0.310    | 2.285     |

Note. The 1 PV subscript means that the spectrum of primary electrons is a simple power law. The 2 TV subscript means that the spectrum of CR electrons has a 2 TV break (Fermi LAT Collaboration et al. 2010). The units of $N_p$ and $\gamma_1^B$ are both $10^{-9} \text{MeV} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, $\rho_{\text{ref}}$, $Z_0$, $dZ$, and $V_{\text{Alfvén}}$ are in units of TV, kpc, $10^{28} \text{cm}^{-2} \text{s}^{-1}$, and km s$^{-1} \text{Z} \times \text{bin}$, vertical height $Z \times \text{bin}$ in the grid of the Galactic disk, is modified as 0.2 kpc to reduce the computing times. The rest parameters of GALPROP are referred to as example 01 of WebRun (Vladimirov et al. 2011). In the numbers, the red ones are negative, which means that the spectrum of CR electrons begins to harden across the reference break.

However, the experimental data of CR electrons, such as that from the Fermi-LAT (Fermi LAT Collaboration et al. 2010), PAMELA (PAMELA Collaboration et al. 2011b), and AMS-02 (Aguilar et al. 2014b) implies that the possible structures recently formed. Specifically, the high-accuracy data of the latest AMS-02 electrons show the fine features of spectra, which are described as the positron excess against the astrophysical background. In the $e^-$ cases, the $\chi^2$ values that are relevant to model A are much less than the 1 PV break case of model A and justify these features of the spectra. As seen in Table 4, most of the absolute differences between power indices above (below) the 100 GV reference rigidity are greater than 0.2 and clearly show the breaks of the CR electron spectrum. In the $e^- - e^+$ cases, it also implies that the structure of the primary electrons is not described by a simple power law. Thus, the positron excess against a power-law spectrum does not justify the existence of the same flux of CR electron excess.

In order to explore the primary electron excess further, as the primary electrons and CR electrons of AMS-02 both do not exclude the 1 PV and 2 TV break cases, it is necessary to include HESS data. In the $e^- - e^+$ and $e^-$ cases of model B, $\chi^2$ relevant to the HESS electrons of model B are neither greater than the double data points of the HESS electrons and show that the flux of HESS electrons matches the TeV scale extension of AMS-02 electron flux. Nevertheless, the $\chi^2$ relevant to the 2 TV and 1 PV breaks are both greater than the double data points of the HESS electrons. It makes sense that the primary electrons and CR electrons constrained by AMS-02 and HESS both do not favor the 2 TeV breaks or a simple power law.
is shown, which is relevant to the difference between the best-fit fluxes of the $e^-$ and $e^- + e^+$ cases in model B. The other predicted spectra that are interpreted as pulsar wind nebulae (PWN) are found in Mauro et al. (2014).

4.2. The Spectra of the Diffuse Gamma Rays and its Comparison with CRs

In the $e^-$ cases of model C, the diffuse gamma rays of two regions from the Milagro experiments do not indirectly constrain the more high-energy spectrum of CR electrons. As seen in Table 2, the best-fit $\chi^2$ that is relevant to the AMS-02 electrons of model C is almost the same as that for model B. In Figure 1, CR electrons, CR protons, and B/C are not distinctly discriminated between models B-C. These situations indicate that the CR electrons, including the positron excess, do not derive more flux from the IC component of diffuse gamma rays to fit two regions of Milagro. In order to analyze the predicted fluxes of the diffuse gamma rays from the uncertainties of CR electrons in this context, the bounds of the diffuse gamma rays are calculated on the parameters of the $e^-$ case in model B from Table 5 by GALPROP.

In Figure 5, the fluxes of three components of diffuse gamma rays from some of the regions are shown. The filling regions are drawn with the maximal and minimal fluxes of diffuse gamma rays at the 99\% C.L. from Table 5. Because the $\pi^0$-decay component of diffuse gamma rays has uncertainties that are less than 2\%, the relevant regions are invisible and not shown. In the first row of Figure 5, Fermi-LAT data include the gamma rays of the diffuse, background, and point sources in the high latitudes. As shown below TeV, the total diffuse gamma rays that are predicted by the $e^-$ case in model B are consistent with the Fermi-LAT data. In the energy ranges of the Fermi-LAT data, the $\pi^0$-decay is dominant in the three

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Table 4
Best-fit Values of the Parameters Relevant to the $e^-$ Case in Models A-D

| Para. | A | A$_{TV}$ | A$_{PV}$ | B | B$_{TV}$ | B$_{PV}$ | C | D |
|-------|---|---------|---------|---|---------|---------|---|---|
| $N_e$ | 1.360 | 1.378 | 1.378 | 1.360 | 1.378 | 1.378 | 1.360 | 1.360 |
| $\gamma_1$ | 1.613 | 1.654 | 1.653 | 1.613 | 1.660 | 1.659 | 1.614 | 1.613 |
| $\gamma_2$ | 2.730 | 2.683 | 2.683 | 2.730 | 2.675 | 2.677 | 2.731 | 2.730 |
| $\nu^e_{B2}$ | 0.095 | 2 | 1000 | 0.091 | 2 | 1000 | 0.091 | 0.091 |
| $\gamma_3$ | 2.457 | 5 | 5 | 2.470 | 5 | 5 | 2.468 | 2.470 |
| $\gamma_3' - \gamma_2'$ | $-0.273$ | 2.317 | $\cdots$ | $-0.260$ | 2.325 | $\cdots$ | $-0.262$ | $-0.260$ |
| $\Delta$ | 2.952 | 2.954 | 2.956 | 2.953 | 2.955 | 2.955 | 2.957 | 2.955 |
| $D_0$ | 1.750 | 1.766 | 1.766 | 1.750 | 1.773 | 1.772 | 1.751 | 1.744 |
| $\delta$ | 0.296 | 0.296 | 0.296 | 0.296 | 0.296 | 0.296 | 0.296 | 0.297 |
| $V_{Alfven}$ | 38.61 | 39.65 | 39.64 | 38.61 | 39.00 | 39.95 | 38.58 | 38.48 |
| $N_p$ | 4.523 | 4.516 | 4.516 | 4.523 | 4.514 | 4.515 | 4.527 | 4.527 |
| $\gamma_1^p$ | 1.779 | 1.772 | 1.772 | 1.779 | 1.771 | 1.771 | 1.781 | 1.779 |
| $\gamma_2^p$ | 2.467 | 2.461 | 2.461 | 2.467 | 2.459 | 2.460 | 2.468 | 2.467 |

Note. The added models C and D are used to limit the higher-energy spectra of CR electrons and protons rather than the HESS data.
components of gamma rays. Because the flux of CR protons has few uncertainties, the uncertainties of diffuse gamma rays is mainly from the IC component predicted by CR electrons, which are represented by the filling regions of Figure 5.

As seen in the second row of Figure 5, via comparison to the data of Milagro, the flux of diffuse gamma rays that are derived from the CR protons and electrons favored by AMS-02 and HESS is weaker and is not used to interpret the gamma-ray excess of Milagro, though the relevant flux of the positron excess is well-extended by the data of AMS-02 and HESS. This implies that the interpretation of positron excess cannot spontaneously agree with the gamma-ray excess.

In the comparisons between the components of diffuse gamma rays, it is clear that the $\gamma_1$-decay gamma rays are dominant on the order of GeV. From the high-latitude regions to the low ones, the flux of the IC component is dominant on the order of hundreds of GeV to tens of TeV. This is also seen in the left panel of Figure 6. The fluxes of IC and $\pi^0$-decay components of diffuse gamma rays overlap at the middle energy regions at high and low latitudes, except for the 2 TeV break case. These results are derived from the fact that the distribution of the ISM increases from the high-latitude regions to the low ones and the fluxes of ISRFs almost have the same intensity out of the core regions of the Galaxy.

In the left panel of Figure 6, CR electrons and protons from the $e^-$ case in model C and model B are shown together. The fluxes of the all-sky diffuse gamma rays derived from these electrons and protons are also drawn. From an overall comparison, the flux of CR protons is almost 2–5 orders of magnitude greater than that of CR electrons and 4–7 orders higher than diffuse gamma rays. This means that in indirect

Table 5

| Para. | $B_{\text{Min}}$ | $B_{\text{Max}}$ |
|-------|----------------|-----------------|
| $N_p$ | 1.2856 | 1.2893 |
| $\gamma_1$ | 1.6067 | 1.6104 |
| $\gamma_2$ | 2.7517 | 2.7456 |
| $\gamma_3$ | 0.0930 | 0.1786 |
| $\gamma_4$ | 2.5350 | 2.3450 |
| $Z_3$ | 2.9527 | 2.9525 |
| $D_3$ | 1.7534 | 1.7499 |
| $\delta$ | 0.2954 | 0.2961 |
| $\nu_{\text{Alfvén}}$ | 38.647 | 38.620 |

Note. $B_{\text{Min}}$ and $B_{\text{Max}}$ respectively represent the minimal and maximal fluxes of the primary electrons in the $e^- - e^+$ cases and (right) $e^-$ cases in models A-B. (Second row): allowed regions in the $(\gamma_1, \gamma_2)$ plane at the 99% C.L. for (left) $e^- - e^+$ cases and (right) $e^-$ cases in models A-B.

As seen in the second row of Figure 5, via comparison to the data of Milagro, the flux of diffuse gamma rays that are derived from the CR protons and electrons favored by AMS-02 and HESS is weaker and is not used to interpret the gamma-ray excess of Milagro, though the relevant flux of the positron excess is well-extended by the data of AMS-02 and HESS. This implies that the interpretation of positron excess cannot spontaneously agree with the gamma-ray excess.

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In the left panel of Figure 6, CR electrons and protons from the $e^-$ case in model C and model B are shown together. The fluxes of the all-sky diffuse gamma rays derived from these electrons and protons are also drawn. From an overall comparison, the flux of CR protons is almost 2–5 orders of magnitude greater than that of CR electrons and 4–7 orders higher than diffuse gamma rays. This means that in indirect
Figure 4. (Left): the CR positron flux and (right) positron fraction derived from the differences between the CR electrons of the $e^-$ cases and the primary electrons of the $e^- + e^+$ cases in models A and B. In the lines, some are the differences between the best-fit fluxes, while others are relevant to the flux bounds from Table 5. The flux of the CR positrons and the positron fraction from the astrophysical background are calculated from the $e^- - e^+$ case in model B, whose notation is $e^+$ in the brackets. $e^-$ and $e^- - e^+$ in the brackets denote the $e^-$ and $e^- - e^+$ cases, respectively. The flux of the CR positrons (Aguilar et al. 2014b) and the positron fraction (Accardo et al. 2014) from AMS-02 are also drawn.

Figure 5. (First row): the flux of diffuse gamma rays from the all-sky ($\ell \in [0^\circ, 360^\circ]$) of the high-latitude Galaxy (left) ($b \in [60^\circ, 90^\circ]$) and (right) ($b \in [-90^\circ, -60^\circ]$). The gamma-ray fluxes of the total, background, and other sources from Fermi-LAT (T. F.-L. Collaboration 2012) are also drawn. In the legends, DGE Total denotes the total components of diffuse gamma rays and Total denotes the total gamma rays, including the diffuse gamma rays, other sources, and the background. (Second row): the flux of diffuse gamma rays from (left) the inner Galaxy ($\ell \in [30^\circ, 65^\circ]$) and (right) the Cygnus region ($\ell \in [65^\circ, 85^\circ]$) in the range of Galactic latitude $b \in [-2^\circ, 2^\circ]$. The flux of diffuse gamma rays from Milagro (Abdo et al. 2008) and EGRET (Hunter et al. 1997) are also drawn. In the legends, Total denotes the total components of diffuse gamma rays. The filling regions are drawn from the maximal and minimal fluxes of diffuse gamma rays calculated with the parameters of Table 5. These best-fit fluxes are calculated using the parameters of the $e^-$ case in model C from Table 4. Because the $\nu^-\nu^+$ decay component of diffuse gamma rays has less uncertainties than 2%, the relevant regions are the same as the width of the best-fit lines and thus are not filled.
measurements of CR electrons and diffuse gamma rays, the main background is CR protons. For the $e^-$ case of model $B_{2TV}$, above 10 TeV the flux of diffuse gamma rays is slightly greater than that of CR electrons. And above 0.1 GeV, the flux of the $\pi^0$-decay component of diffuse gamma rays is completely beyond that of the IC component. $\pi^0$-decay is dominant in the three components of gamma rays.

In the right panel of Figure 6, the diffuse gamma rays of some typical regions derived from CR protons and electrons that are relevant to the best-fit $\chi^2$ of the $e^-$ case in model C are shown at the Galactic latitude coordinate. The 20 TeV fluxes of the CR electrons relevant to the best-fit $\chi^2$ of the $e^-$ case in model C and model $B_{2TV}$ are also shown. It is clear that in the right panel of Figure 6, if TeV extension of CR electrons has a 2 TeV break, at the regions of $b \in [-90^\circ, -40^\circ]$ and $[40^\circ, 90^\circ]$ the flux of diffuse gamma rays will be near the flux of 20 TeV CR electrons, but at the regions of $b \in [-40^\circ, 40^\circ]$ the flux of diffuse gamma rays is apparently greater than the flux of CR electrons from high to low latitudes. Nevertheless, for the $e^-$ case in model C, the flux of diffuse gamma rays is even smaller than that for 20 TeV CR electrons and the maximal difference is almost beyond the two orders. The minimal difference between these fluxes is only at the very small latitudes of the center of the Milky Way, where the flux of diffuse gamma rays is close to that of CR electrons. From these comparisons, it is clear that if the spectral features of the CR electrons constrained by AMS-02 and HESS above TeV are consistent with the experimental measurements of the future, the high latitudes of the fluxes of diffuse gamma rays will be much weaker than those of CR electrons and can be ignored in the background subtractions of indirectly measured CR electrons based on the air-shower array.

5. CONCLUSIONS

Based on the conventional diffusion model of CRs, via GALPROP we perform a global analysis of the spectral features of CR electrons and the diffuse gamma rays using the data of AMS-02 and HESS. The results show that the spectrum structure of the primary component of CR electrons is not described by a simple power law and the relevant break is around 100 GeV. Specifically, we perform some analysis of confidence intervals to illustrate the changes of the second reference rigidity and the two indices of primary electrons. At the 99% C.L., based on the constraint of AMS-02 data alone, the minimal difference between the second and third indices at the reference 50 GV is only 0.075, but the maximal difference does not converge reasonably, which means that AMS-02 data does not exclude primary electron spectra from a simple power law. With the constraint of AMS-02 and HESS data, the third index decreases from 2.54 to 2.35 at the 99% C.L., but the second index is only in the range of 2.746–2.751. Apparently, the spectrum of primary electrons favors the feature distinguished from a simple power law.

Above TeV, the often used 2 TeV break case is also analyzed. The results show that the precise AMS-02 data alone do not distinguish the 2 TeV break and a simple power law. Combining AMS-02 and HESS data, we find that the spectrum of CR electrons does not need the TeV breaks and favors a power law above 100 GeV.

With the difference between the CR electrons and primary electrons constrained by AMS-02 and HESS, the bounds of TeV extensions of positron excess are predicted. In the bounds, some spectra are damping rapidly with the energy, which is consistent with the features of dark matter annihilation and decay (Lin et al. 2015), and the others are similar to the spectra of PWN (Mauro et al. 2014).

Galactic diffuse gamma-ray emission mainly originates from the interactions of CRs with the ISM of the Milky Way and involves $\pi^0$-decay, IC scattering, and Bremsstrahlung. Based on the data of HESS, AMS-02, and Milagro, we also perform an analysis of the origins of Galactic diffuse gamma rays. Below TeV, the total diffuse gamma rays predicted by HESS and AMS-02 are consistent with Fermi-LAT data. Above TeV, the flux of the IC component, derived from the upper limit of CR electrons at the 99% C.L., does not fit to the Milagro data. Because the upper-limit fluxes of CR electrons include the same flux as positron excess, the interpretation of positron excess cannot spontaneously agree with the diffuse gamma-ray excess from the Milagro data. This also implies that except for
dark matter or pulsars, the other sources of diffuse gamma rays contribute to the measurement data of Milagro.

In the analysis of the identification of Galactic diffuse gamma rays, inverse Compton scattering (IC) is the dominant component in the range of hundreds of GeV to tens of TeV, respectively, from the high latitude to the low latitude regions. In this paper, the differences between the TeV fluxes of CR electrons and diffuse gamma rays are also analyzed. The results show that the TeV breaks of CR electron spectra determine whether the $20$ TeV flux of diffuse gamma rays is greater or less than CR electrons. The TeV extension of CR electrons that is favored by AMS-02 and HESS has no breaks of TeV and the relevant flux is greater than that of diffuse gamma rays in most regions of the Milky Way. Inversely, if TeV extension of CR electrons has a strong TeV break, the $20$ TeV flux of diffuse gamma rays is greater than that of CR electrons at the regions of $b \in [-40^\circ, 40^\circ]$. Beyond these regions, the flux of diffuse gamma rays is closer to that of CR electrons.

Because the flux of CR electrons above GeV, constrained by AMS-02 and HESS, is much greater than the diffuse gamma rays at high latitudes, background subtractions do not consider the diffuse gamma rays in the indirectly measured CR electrons based on the air-shower array. For the measurements of diffuse gamma rays, CR electrons are not a component that can be ignored in the subtraction background.

Note added: concurrent with the fitting schemes confirmed by the authors of this paper, Yu-Feng Zhou proposes that the e$^-$ → e$^+$ case of model A is the primary electron background in the research of dark matter. The relevant works will show similar fitting data, which are consistent with this paper. While we finalized the first version of the manuscript, a preprint with a similar analysis (Li et al. 2014) was uploaded to arXiv. Li et al. (2014) mainly focus on the excess components of CR electrons with Markov chain Monte Carlo and conclusions about the primary electrons that are similar to ours.

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REFERENCES

Abdo, A. A., Allen, B., Aune, T., et al. 2008, ApJ, 688, 1078
Accardo, L., Aguilar, M., Aisa, D., et al. 2014, PhRvL, 113, 121101
Adriani, O., Barbarino, G., Bazilevskaya, G., et al. 2010, ApJ, 34, 1
Aguilar, M., Alberti, G., Alpaez, B., et al. 2013, PhRvL, 110, 141102
Aguilar, M., Aisa, D., Alpaez, B., et al. 2014a, PhRvL, 113, 221102
Aguilar, M., Aisa, D., Alvino, A., et al. 2014b, PhRvL, 113, 121102
Ahlers, M., Mertsch, P., & Sarkar, S. 2009, PhRvD, 80, 123017
Ahn, H., Allison, P., Bagliesi, M., et al. 2008, ApJ, 63, 133
Berezinskii, V. S., Buitanov, S. V., Dogiel, V. A., & Ginzburg, V. L. 1990, Astrophysics of Cosmic Rays (Amsterdam: North-Holland)
Blandford, R., & Eichler, D. 1987, PhR, 154, 1
Blasi, P. 2009, PhRvL, 103, 051104
Dermer, C. 1996, A&A, 157, 223
Engelmann, J., Ferrando, P., Soutoul, A., Goret, P., & Julliuss, E. 1990, A&A, 233, 96
Feng, L., Yang, R. Z., He, H. N., et al. 2014, PhLB, 728, 250
Fermi LAT Collaboration, Ackermann, M., Ajello, M., Atwood, W. B., et al. 2010, PhRvD, 82, 092004
Fermi LAT Collaboration, Ackermann, M., Ajello, M., Allafort, A., et al. 2012, PhRvL, 108, 011103
Gleeson, L. J., & Axford, W. I. 1968, ApJ, 154, 1011
H.E.S.S. Collaboration, Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U., et al. 2008, PhRvL, 101, 261104
H.E.S.S. Collaboration, Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, A&A, 508, 561
Hooper, D., Blasi, P., & Serpico, P. D. 2009, ICAP, 0901, 025
Hunter, S., Bertsch, D., Catelli, J., Digel, T., Dingus, S., et al. 1997, ApJ, 481, 205
Jin, H.-B., Wu, Y.-L., & Zhou, Y.-F. 2013, JCAP, 11, 026
Jin, H.-B., Wu, Y.-L., & Zhou, Y.-F. 2014, arXiv:1410.0171
Kelner, S., Aharonian, F., & Bugayov, V. 2009, PhRvD, 79, 039901
Li, X., Shen, Z.-Q., Lu, B.-Q., et al. 2014, arXiv:1412.1550
Lin, S.-J., Yuan, Q., & Bi, X.-J. 2015, PhRvD, 91, 035058
Mauro, M. D., Donato, F., Fornengo, N., Lineros, R., & Vittino, A. 2014, JCAP, 2014, 006
Oliva, A., A. M. S. Collaboration, et al. 2015, AMS Results on Light Nuclei: Measurement of the Cosmic Ray Boron-to-carbon Ration with AMS02, AMS02Days, CERN
PAMELA Collaboration, Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., et al. 2009, Natur, 458, 607
PAMELA Collaboration, Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., et al. 2011a, Sci, 332, 69
PAMELA Collaboration, Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., et al. 2011b, PhRvL, 106, 201101
Porter, T. A., Moskalenko, I. V., Strong, A. W., Orlando, E., & Bouchet, L. 2008, ApJ, 682, 400
Prodanovic, T., Fields, B. D., & Beacom, J. F. 2007, ApJ, 27, 10
Profumo, S. 2011, CEJP, 10, 1
Seo, E. S., & Prasinos, V. S. 1994, ApJ, 431, 705
Strong, A. W., & Moskalenko, I. V. 1998, ApJ, 509, 212
Strong, A. W., Moskalenko, I. V., & Reimer, O. 2000, ApJ, 537, 763
Strong, A. W., Moskalenko, I. V., & Reimer, O. 2004, ApJ, 613, 956
T. F. L. Collaboration 2012, ApJ, 750, 88
Vladimirov, A., Digel, S., Jóhannesson, G., et al. 2011, CoPhC, 182, 1156
Yoon, Y. S., Ahn, H. S., Allison, P. S., et al. 2011, ApJ, 728, 122