Local interstellar spectra and solar modulation of cosmic ray electrons and positrons

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Abstract

Low energy cosmic rays are modulated by the solar activity when they propagate in the heliosphere, leading to ambiguities in understanding their acceleration at sources and propagation in the Milky Way. By means of the precise measurements of the $e^+$, $e^−$, $e^+ + e^−$, and $e^+/e^−$ spectra by AMS-02 near the Earth, as well as the very low energy measurements of the $e^− + e^+$ fluxes by Voyager-1 far away from the Sun, we derive the local interstellar spectra (LIS) of $e^−$ and $e^+$ components individually. Our method is based on a non-parametric description of the LIS of $e^−$ and $e^+$ and a force-field solar modulation model. We then obtain the evolution of the solar modulation parameters based on the derived LIS and the monthly fluxes of cosmic ray $e^−$ and $e^+$ measured by AMS-02. \textbf{To better fit the monthly data, additional renormalization factors for $e^−$ and $e^+$ have been multiplied to the modulated fluxes.} We find that the inferred solar modulation parameters of positrons are in good agreement with that of cosmic ray nuclei, and the time evolutions of the solar modulation parameters of electrons and positrons differ after the reversal of the heliosphere magnetic field polarity, which shows clearly the charge-sign dependent modulation effect.

Keywords: acceleration of particles — cosmic rays — solar modulation

1. Introduction

Large progresses have been achieved in the direct measurements of cosmic rays (CR) in the past decade, by space experiments including the AMS, Fermi-LAT, DAMPE, CALET, and NUCLEON, providing very important information about the origin, acceleration, and propagation of cosmic rays in the Milky Way (e.g., Gabici et al. 2019; Kachelrieß and Semikoz 2019). Nevertheless, there is still strong degeneracy among the acceleration and propagation effects (including those in the heliosphere), which hinders an unambiguous understanding of the CR problems. Very interestingly, the Cosmic Ray Subsystem (CRS) instrument on the Voyager-1 spacecraft launched more than 40 years ago keeps on operation and measuring the low-energy CR fluxes even outside the heliosphere\textsuperscript{1} (Stone et al. 2013; Cummings et al. 2016). In addition, the PAMELA and AMS-02 experiments further reported time variations of the CR fluxes with very high precisions (Adriani et al. 2013b; 2016; Martucci et al. 2018; Aguilar et al. 2018a), which are also direct relevant to the solar modulation. The Voyager-1 data, and/or the time series of CR fluxes, are very important in probing the local interstellar spectra (LIS) and solar modulation effect of CRs (e.g., Bisschoff and Potgieter 2016; Gheffi et al. 2016; Corti et al. 2016; Boschin et al. 2017; Tomassetti et al. 2017; Zhu et al. 2018; Boschin et al. 2018; Tomassetti et al. 2018; Corti et al. 2019; Wang et al. 2019).

In Zhu et al. (2018) we studied the LIS of CR nuclei from He to O with a non-parametric spline interpolation method and the force-field model of the solar modulation (Gleeson and Axford 1967; 1968), according to AMS-02 (Aguilar et al. 2017; 2018b), Voyager-1 (Cummings et al. 2016), and ACE-CRIS data. The time-evolution of the solar modulation parameters were then derived based on the monthly ACE-CRIS fluxes of CR nuclei, which are consistent with those inferred from the neutron monitors (Usoiskin et al. 2011; Gheffi et al. 2017).

In this work we extend the previous study to electrons and positrons. One of our motivations is to examine the possible differences between the LIS of electrons and that of nuclei, which may have important implication in the propagation of different particle species in the Milky Way (Lin et al. 2015). Furthermore, the differences of solar modulation effects among electrons, positrons, and nuclei may help to understand the charge-sign dependent modulation effects.

The CR electron and positron spectra and flux ratios have been measured precisely by several space experiments, such as PAMELA (Adriani et al. 2009; 2011; 2013), Fermi-LAT (Abdollahi et al. 2017), AMS-02 (Aguilar et al. 2014b; 2018a), Accardo et al. (2014); Aguilar et al. (2019a,b); DAMPE (DAMPE Collaboration et al. 2017), and CALET (Adriani et al. 2018). The Voyager-1 experiment also measure the total $e^− + e^+$ fluxes from $\sim$ 3 to $\sim$ 40 MeV outside the heliosphere (Cummings et al. 2016). Here the data obtained on top-of-atmosphere (TOA) by AMS-02 and in the local interstellar space by Voyager-1 will

\textsuperscript{1}Note that it is still possible that there is tiny residual modulation effect on the Voyager-1 spectra (Scherer et al. 2011; Kota and Jokipii 2013). In this work we assume that the Voyager-1 measurement is the LIS without considering such subtlety.

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be used. Following the method of Zhu et al. (2018), we adopt a non-parametric spline interpolation method to describe the LIS of electrons and positrons, which are then modulated under the force-field model and fitted to the long-term average data. Based on the LIS derived above and the monthly fluxes of electrons and positrons, we then derive the time-series of the modulation parameters. We are aware that the force-field model should be over-simplified in modeling the solar modulation effect. However, the more physical modulation model usually has a considerable number of free parameters and is computationally heavy (Kappl 2016; Luo et al. 2017; Potgieter and Vos 2017; Vittino et al. 2019; Kuhlen and Mertsch 2019). Thus we keep the framework of the force-field model, but with some additional renormalization factors. Also the electrons and positrons have different modulation parameters. We expect that the extended force-field approximation can reasonably reflect the main features of the solar modulation.

2. Methodology

Usually the CR spectra are parameterized with power-law or broken power-law function (Moskalenko and Strong 1998; Boschini et al. 2018). However, the actual CR spectrum, either the accelerated one or the detected one, may be more complicated. More and more new features of the CR spectra have been revealed by recent observations (e.g., DAMPE Collaboration et al. 2017; An et al. 2019; Ahn et al. 2010; Atkin et al. 2018). To minimize the impact of the assumed function form of the energy spectra of CRs, following Ghelfi et al. (2016) and Zhu et al. 2018), we adopt a cubic spline interpolation method to describe the wide-band LIS of both electrons and positrons. Note that in this current work the propagation of electrons and positrons in the Milky Way is not discussed. The cubic spline interpolation is a way to get a smoothly connected piecewise function passing through a set of energy points. We work in the log(E) − log(J) space, where E is the energy of electrons or positrons in unit of GeV and J is the flux in unit of GeV m⁻² s⁻¹ sr⁻¹. The selected positions of knots x = log(E) are:

\[
x = \{-2.5, -1.4, 0.0, 0.6, 1.2, 1.8, 2.4, 3.0\}.
\]

In the low energy range the knots are sparse because the data points in such energy ranges are very limited. The corresponding fluxes \(y_{+i} = \log(J_{+i})\) and \(y_{-i} = \log(J_{-i})\) are free parameters to be fitted.

Since most of the observations are carried out near the Earth, they just give the modulated TOA spectra. As we have mentioned before, we use the force-field solar modulation model (GLEeson and AXford 1967; 1968) to link the LIS with the TOA spectra as

\[
J^\text{TOA}(E) = J^\text{LIS}(E + \Phi) \times \frac{E(E + 2m_e)}{(E + \Phi)(E + \Phi + 2m_e)}, \tag{2}
\]

where \(E\) is the kinetic energy of the particle, \(\Phi = \phi \cdot e\) with \(\phi\) being the solar modulation potential, \(m_e = 0.511\) MeV is the electron mass, and \(J\) is the differential flux of electrons or positrons. Note that here the modulation parameters for electrons and positrons, \(\phi_e\) and \(\phi_p\), are assumed to be independent and fitted simultaneously.

The \(\chi^2\) statistics is defined as

\[
\chi^2 = \sum_{i=1}^{n} \frac{(J_x(E_i, y_x, \phi_x) - J_i)^2}{\sigma_i^2}, \tag{3}
\]

where \(J_x(E_i, y_x, \phi_x)\) is the expected TOA/LIS fluxes of \(e^\pm, e^0\), \(e^+ + e^-\) or the ratios \(e^+/(e^0 + e^-)\). \(J_i\) and \(\sigma_i\) are the measured data and error for the \(i\)th data bin.

We use the Markov Chain Monte Carlo (MCMC) method (Lewis and Bridle 2002) to fit the parameters. The MCMC is based on the Bayesian framework which can minimize the \(\chi^2\) function, and give the posterior distributions of the high-dimensional parameter space with a high efficiency. The likelihood function of the model parameters is

\[
\mathcal{L}(\theta) \propto \exp\left(-\frac{\chi^2}{2}\right), \tag{4}
\]

The posterior probability of model parameters is then

\[
p(\theta|\text{data}) \propto \mathcal{L}(\theta)p(\theta), \tag{5}
\]

where \(p(\theta)\) is the prior probability of parameters \(\theta\). Here we assume flat priors of all the parameters.

We adopt the Metropolis-Hastings algorithm which generates Markov chains as follows. For a set of parameters \(\theta_i\) and its successor \(\theta_{i+1}\), we calculate an accept probability \(P_{\text{acc}} = \min[p(\theta_{i+1}|\text{data})/p(\theta_i|\text{data}), 1]\). If \(P_{\text{acc}}\) is accepted, then repeat the procedure from \(\theta_{i+1}\). Otherwise, we go back to \(\theta_i\). The procedure is continued until a convergence criterion is satisfied.

The data used in the fit include the TOA measurements of the \(e^-, e^+, e^- + e^+\) fluxes and \(e^+/(e^0 + e^-)\) ratios by AMS-02 in 2014 (Aguilar et al. 2014a,b) Accardo et al. 2014, and 2019 (Aguilar et al. 2019a,b), and the LIS of \(e^- + e^+\) measured by Voyager-1 (Cummings et al. 2016). The LIS of both \(e^-\) and \(e^+\) are assumed to monotonically decrease with energies, and the LIS of \(e^-\) is further assumed to be smaller than that of \(e^+\). The latter requirement is based on the fact that there are primary \(e^-\) accelerated at the sources. The fit determines the LIS of \(e^-\) and \(e^+\), and the average solar modulation potentials for the time from May, 2011 to November, 2013, and from May, 2011 to November, 2017 during which the measurements of \(e^-\), \(e^+, e^- + e^+\) fluxes and \(e^+/(e^0 + e^-)\) ratios by AMS-02 were made. After deriving the LIS through the above fits, the time-dependent measurements of the \(e^-\) and \(e^+\) fluxes for every Bartels rotation period (~ 27 days) are then used to derive the time-variation of the solar modulation parameters \(\phi_e\).

3. Results

3.1. The LIS of \(e^-\) and \(e^+\)

In Fig. 1 we show the fitting spectra of \(e^+\) (upper left), \(e^-\) (upper right), \(e^- + e^+\) (lower left) and the positron fraction (lower right), compared with the AMS-02 (2014) [Aguilar et al.
Figure 1: Best-fit LIS fluxes (lines), multiplied by $E^{2.7}$, compared with the measurements of Voyager-1 (blue points; Cummings et al. 2016), and the results of AMS-02 (2014) (red points; Aguilar et al. 2014), AMS-02 (2019) (green points; Aguilar et al. 2014a,b). The green and red dashed lines are the best-fit TOA spectra for AMS-02 (2014) and AMS-02 (2019) data, respectively. The de-modulated results of the AMS-02 (2019) data are denoted by the black points, based on the fitted $\phi_+$ values. The solid lines are the best-fit LIS, with the gray bands being the 68% coverage of the fitting results.

In Fig. 2 we compare our best-fitting LIS of $e^-$ (top panel) and $e^+$ (bottom panel) with previous works with somehow different methods and assumptions (Vittino et al. 2019; Bisschoff et al. 2019; Boschini et al. 2018). For the $e^-$ spectrum, our result is very close to that of Vittino et al. (2019) and Boschini et al. (2018) at low and high energies. The main differences appear at medium energies (from 0.1 GeV to 10 GeV), which show the uncertainties of the solar modulation modelings. The result of Bisschoff et al. (2019) is higher than the others at lower energies (from 0.01 GeV to 1 GeV), with a harder spectrum, due to the use of a different data sample from Voyager-1 Stone et al. (2015), Cummings et al. (2016). The LIS of $e^+$ obtained in Vittino et al. (2019) and Bisschoff et al. (2019) shows relatively large differences from our best-fit result but is still consistent with our relatively wide uncertainty band (see Fig. 1).

The fitting results of the solar modulation potentials $\phi_-$ and $\phi_+$, and the $\chi^2$ values are given in Table 1. We find that the $\chi^2$ values for positron fluxes and positron fractions are
Figure 2: Comparison of our derived LIS with previous works (Vittino et al. 2019; Boschini et al. 2018).

Table 1: Posterior mean values and 68% credible level uncertainties of the solar modulation potentials and $\chi^2$ values of various species.

| Species | $\phi$ (GV) | $\chi^2$ |
|---------|-------------|----------|
| $e^-$ (2014) | 0.762 ± 0.039 | 31.4 |
| $e^+$ (2014) | 0.754 ± 0.039 | 45.7 |
| $e^+ + e^-$ (2014) | -- | 23.3 |
| $e^+/(e^+ + e^-)$ (2014) | -- | 124.3 |
| $e^-$ (2019) | 0.792 ± 0.038 | 26.8 |
| $e^+$ (2019) | 0.693 ± 0.039 | 40.5 |
| $e^+ + e^-$ (2019) | -- | 22.15 |
| $e^+/(e^+ + e^-)$ (2019) | -- | 83.1 |
| $e^+ + e^-$ (Voyager) | -- | 8.95 |

relatively large. As we will do below, if we multiply two renormalization factors $c_\phi$ on the 2014 data, we find $c_{e^-} = 0.997 \pm 0.004$ and $c_{e^+} = 1.038 \pm 0.005$, and the fits will be improved significantly. This result shows that the simple force-field modulation model may be not enough to describe the solar modulations at different solar conditions.

The normalized probability distributions of $\phi$ are shown in Fig. 3. The results show that the electrons were modulated more severely than positrons during the period from 2013 to 2017.

From 2011 to 2014, the electrons and positrons were modulated similarly with each other. Based on the derived modulation potentials, we de-modulate the AMS-02 (2019) electron and positron fluxes from the TOA to the LIS, as shown by the back points in Fig. 2. Note that the errors of $\phi_0$ are included in the total errors of the de-modulated fluxes via the error propagation method. The de-modulated AMS-02 data are provided in Tables 2 and 3 in the Appendix.

3.2. Time-dependent TOA fluxes of $e^-$ and $e^+$

Given the LIS fluxes, we can then investigate the time-evolutions of the TOA fluxes, and compare them with the long-term AMS-02 measurements (Aguilar et al. 2018c). However, we find that the direct fit (with the MCMC method) to the monthly data with the derived LIS plus a force-field modulation model can not always give a good fit. The minimum $\chi^2$ values divided by the number of degree-of-freedom (dof) are shown in the left panel of Fig. 4 with the green line. We can see that these fits typically give too large reduced $\chi^2$ values. This is perhaps due to the complicated perturbations of the interplanetary space by solar activity whose effect can not be easily accounted for by the simple force-field modulation model. To improve the fits of the time-dependent fluxes, more complicated solar modulation model and more free parameters are needed (Wang et al. 2019, Kuhlen and Mertsch 2019, Vittino et al. 2019).

Empirically we extend the force-field approximation through multiplying two renormalization factors, $c_\phi$, on the LIS as

$$J^{\text{TOA}}(E) = c_\phi \times J^{\text{LIS}}(E + \Phi) \times \frac{E(E + 2m_e)}{(E + \Phi)(E + \Phi + 2m_e)}.$$  \hspace{1cm} \text(6)$$

The fits can be improved significantly, as shown by the green line in Fig. 3. We also show the reduced $\chi^2$ for $e^-$ and $e^+$ separately in Fig. 4. Generally we see that the goodness-of-fits for positrons are better than that for electrons.

The values of $c_\phi$ are given in Fig. 5. The renormalization factors show a general correlation with the solar activity. We
expect that this is due to the mismatch between the energy-dependence of the force-field modulation model and the measurements for different time. To see these results in more details, we plot in Fig. 6 and Fig. 7 the time variations of the $e^-$ with the cases of $c_e$ is harder than the data. The renormalization factor $c_e < 1$, together with a smaller modulation potential $\phi_e$ compared with the cases of $c_e = 1$ (as can be seen in Fig. 8), can solve this discrepancy satisfactorily. Smaller $\phi_e$ gives higher low-energy fluxes, while $c_e$ suppresses high-energy fluxes when the solar modulation is weak. Therefore the model spectrum (blue solid lines) becomes softer and better match the data. Things become opposite at solar maximums, when $c_e > 1$ is required. Furthermore, we note that differences of the renormalization factors of $e^-$ and $e^+$ appear after the heliospheric magnetic field reversal. This gives a charge-sign dependence of the solar modulation effect as expected.

The correlation between $c_{\pm}$ and $\phi_{\pm}$ may be understood as the drift effect of CRs in the heliosphere. As shown in Jokipii and Kopriva (1979) and Strauss et al. (2011), the presence of drift in the Parker equation tends to give a softer TOA spectrum. In the force-field approximation, a softer TOA spectrum means a smaller $\phi_{\pm}$. To match with the data with relatively high energies (above a few GeV), a renormalization factor $c_{\pm} < 1$ is required. This case applies for the periods from 2011 to 2013, and from 2015 to 2017. For the period from 2015 to 2017, the drift effect is weak, and the modulated spectrum is thus harder. Therefore we need larger $\phi_{\pm}$ and $c_{\pm} > 1$.

3.3. The time variation of $\phi$

In this sub-section, we derive the time series of the solar modulation potentials, according to the fits to the monthly AMS-02 data discussed above, with the renormalization factors. To properly take into account the uncertainties of the LIS, we adopt a Bayesian approach with the posterior probability of $\phi_\pm$ being given by

$$p(\phi_\pm | \text{data}) \propto \int L(\phi_\pm, y, c_{\pm}) \ p(y) \ p(c_{\pm}) \ dy \ dc_{\pm}, \quad (7)$$

where $L$ is the likelihood of model parameters $(\phi_\pm, y, c_{\pm})$, $p(y)$ is the prior probability distribution of $y$ which is obtained in the fit in Sec. 3.1, and $p(c_{\pm})$ is the prior of $c_{\pm}$ which is assumed to be a flat distribution within $[0.6, 1.4]$.

Figure 4: The $\chi^2$/dof values obtained through fitting to the time-dependent spectra of AMS-02. The left (right) panel is for the fit without (with) renormalization factors.

Figure 5: The renormalization factors $c_-$ (blue) and $c_+$ (red) for different time, the dark and light color bands stand for 1σ and 2σ credible intervals. The polarity of the heliospheric magnetic field is denoted by $A < 0$ and $A > 0$, and the yellow band stands for the reversal period within which the polarity is uncertain (Sun et al. 2015).
In the left panel of Fig. 8, we compare the fitting results of $\phi_+$ for the cases without (dashed) and with (solid) renormalization factors. The overall behaviors of $\phi_+$ are similar for both cases. However, small changes of the $\phi_+$ parameters appear when including the renormalization factors. Specifically, when $c_+ < 1$ ($c_+ > 1$), $\phi_+$ become smaller (larger) than that without renormalization factors.

The right panel of Fig. 8 shows the time series of $\phi_+$ from 2011 to 2017, compared with the results derived from fitting to the B, C, and O nuclei data from ACE (Zhu et al. 2018). It is very interesting to find that the profile of $\phi_+$ results derived in this work are in good agreement with $\phi_{BCO}$. The modulation potentials for negative charge particles, $\phi_-$, show systematical differences from that of positive charge particles, especially for $A > 0$ regime. Specifically, in the $A > 0$ regime, positive charged particles are less significantly modulated than negative charged particles. This could be understood as a drift effect of particles with different charge sign. For the heliosphere magnetic field polarity of $A > 0$, positrons mainly drift from high latitudes to low latitudes, while electrons are remain confined to low latitudes and drift along the heliospheric current sheet (HCS; Strauss et al. 2011, 2012). The strength of the heliospheric magnetic field is weaker in the polar region, and thus positrons are less confined by the magnetic field and can reach the Earth more easily. As a result, the modulation potential $\phi_+$ is smaller than $\phi_-$. For the period from 2011 to 2014, the solar activity was at maximum, and the effect of drift was not important. Therefore electrons and positrons were modulated similarly (Vittino et al. 2019), with positrons being modulated a little bit more than electrons.

4. Conclusion and discussion

With the recent precise measurements of electrons and positrons from Voyager-1 at outside of the heliosphere and AMS-
Figure 7: Same as Fig. 6, but for positrons.

Figure 8: Left: Time series $\phi_-$ (blue) and $\phi_+$ (red) with (solid lines) / without (dashed lines) renormalization factors via fitting to the AMS-02 monthly data from 2011 to 2017. Right: Time series and the associated 1$\sigma$ and 2$\sigma$ uncertainty bands of $\phi_-$ (blue) and $\phi_+$ (red) via fitting to the AMS-02 monthly data from 2011 to 2017, compared with the results derived from the ACE data of nuclei (black; Zhu et al. 2018).
02 at the TOA, we study the LIS and the solar modulation effects of electrons and positions. We adopt a a non-parametric spline interpolation method to describe the LIS of $e^{-}$ and $e^{+}$, to minimize the effect of improper function form assumed. Since there are no measurements of the separate $e^{-}$ and $e^{+}$ fluxes in the Voyager-I energy window, our resulting LIS show relatively large uncertainties at low energies. Such LIS may be used further in the study of electron and positron propagation in the Milky Way [Lin et al., 2015].

We then study the time variations of the $e^{-}$ and $e^{+}$ fluxes and the modulation potentials at different time. We extend the simple force-filed approximation to fit the AMS-02 monthly modulation potentials at different time. We extend the simple force-filed approximation to fit the AMS-02 monthly and the modulation potentials at different time. We extend the simple force-filed approximation to fit the AMS-02 monthly and the modulation potentials at different time. We extend the simple force-filed approximation to fit the AMS-02 monthly and the modulation potentials at different time. We extend the simple force-filed approximation to fit the AMS-02 monthly and the modulation potentials at different time.

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Table 2: The de-modulated AMS-02 (2019) electron data.

| E (GeV) | Flux $\sigma$ (m$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-1}$) | $\sigma$ (m$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-1}$) |
|---|---|---|
| 1.56e+00 | 9.884e+00 | 6.084e+00 |
| 1.52e+00 | 7.434e+00 | 3.808e+00 |
| 1.70e+00 | 5.801e+00 | 2.516e+00 |
| 2.12e+00 | 3.541e+00 | 1.149e+00 |
| 2.37e+00 | 2.705e+00 | 7.625e-01 |
| 2.64e+00 | 2.095e+00 | 5.260e-01 |
| 2.94e+00 | 1.574e+00 | 3.546e-01 |
| 3.26e+00 | 1.203e+00 | 2.462e-01 |
| 3.61e+00 | 9.030e-01 | 1.710e-01 |
| 3.96e+00 | 6.882e-00 | 1.221e-01 |
| 4.33e+00 | 5.324e-00 | 8.943e-02 |
| 4.71e+00 | 4.131e-00 | 6.618e-02 |
| 5.11e+00 | 3.191e-00 | 4.864e-02 |
| 5.52e+00 | 2.449e-00 | 3.624e-02 |
| 6.03e+00 | 1.867e-00 | 2.701e-02 |
| 6.53e+00 | 1.430e-00 | 2.060e-02 |
| 7.05e+00 | 1.106e-00 | 1.528e-02 |
| 7.60e+00 | 8.580e-01 | 1.161e-02 |
| 8.18e+00 | 6.668e-01 | 8.916e-03 |
| 8.78e+00 | 5.206e-01 | 6.966e-03 |
| 9.41e+00 | 4.071e-01 | 5.330e-03 |
| 1.00e+01 | 3.236e-01 | 4.271e-03 |
| 1.07e+01 | 2.569e-01 | 3.313e-03 |
| 1.14e+01 | 2.186e-01 | 2.793e-03 |
| 1.22e+01 | 1.645e-01 | 2.195e-03 |
| 1.29e+01 | 1.327e-01 | 1.693e-03 |
| 1.37e+01 | 1.076e-01 | 1.405e-03 |
| 1.46e+01 | 8.775e-02 | 1.155e-03 |
| 1.54e+01 | 7.152e-02 | 9.430e-04 |
| 1.63e+01 | 5.870e-02 | 7.742e-04 |
| 1.73e+01 | 4.812e-02 | 6.407e-04 |
| 1.82e+01 | 3.998e-02 | 5.342e-04 |
| 1.92e+01 | 3.178e-02 | 4.394e-04 |
| 2.03e+01 | 2.786e-02 | 3.706e-04 |
| 2.13e+01 | 2.314e-02 | 3.143e-04 |
| 2.24e+01 | 1.938e-02 | 2.675e-04 |
| 2.36e+01 | 1.632e-02 | 2.216e-04 |
| 2.48e+01 | 1.378e-02 | 1.887e-04 |
| 2.60e+01 | 1.169e-02 | 1.669e-04 |
| 2.73e+01 | 9.795e-03 | 1.359e-04 |
| 2.87e+01 | 8.292e-03 | 1.160e-04 |
| 3.02e+01 | 6.320e-03 | 9.382e-05 |
| 3.17e+01 | 5.816e-03 | 8.179e-05 |
| 3.34e+01 | 4.915e-03 | 6.980e-05 |
| 3.52e+01 | 4.131e-03 | 5.859e-05 |
| 3.71e+01 | 3.457e-03 | 4.978e-05 |
| 3.91e+01 | 2.912e-03 | 4.238e-05 |
| 4.12e+01 | 2.436e-03 | 3.567e-05 |
| 4.35e+01 | 2.024e-03 | 3.034e-05 |
| 4.60e+01 | 1.693e-03 | 2.510e-05 |
| 4.87e+01 | 1.413e-03 | 2.136e-05 |
| 5.15e+01 | 1.154e-03 | 1.711e-05 |
| 5.47e+01 | 9.572e-04 | 1.476e-05 |
| 5.81e+01 | 7.876e-04 | 1.235e-05 |
| 6.18e+01 | 6.353e-04 | 1.012e-05 |
| 6.59e+01 | 5.199e-04 | 8.401e-06 |
| 7.04e+01 | 4.168e-04 | 6.736e-06 |
| 7.54e+01 | 3.366e-04 | 5.614e-06 |
| 8.10e+01 | 2.665e-04 | 4.473e-06 |
| 8.74e+01 | 2.080e-04 | 3.567e-06 |
| 9.48e+01 | 1.606e-04 | 2.829e-06 |
| 1.03e+02 | 1.233e-04 | 2.237e-06 |
| 1.13e+02 | 9.016e-05 | 1.688e-06 |
| 1.25e+02 | 6.542e-05 | 1.261e-06 |
| 1.40e+02 | 4.582e-05 | 9.370e-07 |
| 1.59e+02 | 3.516e-05 | 6.926e-07 |
| 1.83e+02 | 1.869e-05 | 4.380e-07 |
| 2.17e+02 | 1.083e-05 | 2.881e-07 |
| 2.62e+02 | 6.014e-06 | 1.805e-07 |
| 3.27e+02 | 3.144e-06 | 1.111e-07 |
| 3.92e+02 | 1.283e-06 | 5.657e-08 |
| 5.89e+02 | 4.572e-07 | 2.940e-08 |
| 8.33e+02 | 1.774e-07 | 1.704e-08 |
| 1.17e+03 | 4.129e-08 | 7.348e-09 |
Table .3: The de-modulated AMS-02 (2019) positron data.

| $E$ (GeV) | Flux ($m^{-2}s^{-1}sr^{-1}GeV^{-1}$) | $\sigma$ ($m^{-2}s^{-1}sr^{-1}GeV^{-1}$) |
|----------|---------------------------------|-------------------------------|
| 1.263e+00 | 1.311e+01 | 1.045e+00 |
| 1.423e+00 | 9.791e+00 | 5.696e-01 |
| 1.603e+00 | 7.052e+00 | 3.311e-01 |
| 1.803e+00 | 5.091e+00 | 2.042e-01 |
| 2.023e+00 | 3.536e+00 | 1.225e-01 |
| 2.273e+00 | 2.476e+00 | 7.476e-02 |
| 2.543e+00 | 1.746e+00 | 4.641e-02 |
| 2.843e+00 | 1.225e+00 | 2.920e-02 |
| 3.163e+00 | 8.760e-01 | 1.907e-02 |
| 3.513e+00 | 6.182e-01 | 1.248e-02 |
| 3.863e+00 | 4.491e-01 | 8.469e-03 |
| 4.233e+00 | 3.343e-01 | 6.019e-03 |
| 4.613e+00 | 2.505e-01 | 4.252e-03 |
| 5.013e+00 | 1.871e-01 | 3.051e-03 |
| 5.453e+00 | 1.403e-01 | 2.278e-03 |
| 5.933e+00 | 1.052e-01 | 1.649e-03 |
| 6.433e+00 | 7.886e-02 | 1.210e-03 |
| 6.953e+00 | 6.074e-02 | 9.165e-04 |
| 7.503e+00 | 4.722e-02 | 7.086e-04 |
| 8.083e+00 | 3.611e-02 | 5.333e-04 |
| 8.683e+00 | 2.842e-02 | 4.220e-04 |
| 9.313e+00 | 2.218e-02 | 3.306e-04 |
| 9.973e+00 | 1.767e-02 | 2.573e-04 |
| 1.065e+01 | 1.421e-02 | 2.128e-04 |
| 1.136e+01 | 1.142e-02 | 1.716e-04 |
| 1.210e+01 | 9.341e-03 | 1.428e-04 |
| 1.288e+01 | 7.727e-03 | 1.186e-04 |
| 1.368e+01 | 6.289e-03 | 9.868e-05 |
| 1.451e+01 | 5.120e-03 | 8.104e-05 |
| 1.538e+01 | 4.237e-03 | 6.774e-05 |
| 1.628e+01 | 3.559e-03 | 5.815e-05 |
| 1.721e+01 | 2.951e-03 | 4.939e-05 |
| 1.817e+01 | 2.478e-03 | 4.176e-05 |
| 1.917e+01 | 2.081e-03 | 3.517e-05 |
| 2.020e+01 | 1.786e-03 | 3.105e-05 |
| 2.127e+01 | 1.554e-03 | 2.701e-05 |
| 2.237e+01 | 1.293e-03 | 2.367e-05 |
| 2.352e+01 | 1.081e-03 | 1.974e-05 |
| 2.470e+01 | 9.506e-04 | 1.798e-05 |
| 2.594e+01 | 8.073e-04 | 1.549e-05 |
| 2.725e+01 | 7.114e-04 | 1.386e-05 |
| 2.864e+01 | 6.036e-04 | 1.289e-05 |
| 3.012e+01 | 5.304e-04 | 1.071e-05 |
| 3.169e+01 | 4.466e-04 | 9.349e-06 |
| 3.335e+01 | 3.839e-04 | 8.295e-06 |
| 3.512e+01 | 3.253e-04 | 7.175e-06 |
| 3.701e+01 | 2.860e-04 | 6.503e-06 |
| 3.902e+01 | 2.413e-04 | 5.452e-06 |
| 4.117e+01 | 2.073e-04 | 5.016e-06 |
| 4.347e+01 | 1.779e-04 | 4.426e-06 |
| 4.595e+01 | 1.491e-04 | 3.839e-06 |
| 4.861e+01 | 1.362e-04 | 3.545e-06 |
| 5.149e+01 | 1.057e-04 | 2.965e-06 |
| 5.461e+01 | 9.089e-05 | 2.608e-06 |
| 5.801e+01 | 7.742e-05 | 2.283e-06 |
| 6.172e+01 | 6.255e-05 | 1.949e-06 |
| 6.580e+01 | 5.620e-05 | 1.768e-06 |
| 7.031e+01 | 4.454e-05 | 1.475e-06 |
| 7.534e+01 | 3.897e-05 | 1.295e-06 |
| 8.098e+01 | 3.065e-05 | 1.084e-06 |
| 8.738e+01 | 2.551e-05 | 9.272e-07 |
| 9.471e+01 | 2.067e-05 | 7.762e-07 |
| 1.033e+02 | 1.481e-05 | 6.495e-07 |
| 1.134e+02 | 1.187e-05 | 5.264e-07 |
| 1.257e+02 | 8.774e-06 | 4.097e-07 |
| 1.408e+02 | 7.067e-06 | 3.311e-07 |
| 1.596e+02 | 4.635e-06 | 2.385e-07 |
| 1.838e+02 | 3.225e-06 | 1.750e-07 |
| 2.169e+02 | 1.883e-06 | 1.185e-07 |
| 2.625e+02 | 1.164e-06 | 8.170e-08 |
| 3.275e+02 | 5.986e-07 | 5.204e-08 |
| 4.592e+02 | 2.991e-07 | 3.011e-08 |
| 5.895e+02 | 8.332e-08 | 1.848e-08 |
| 8.330e+02 | 1.930e-08 | 1.176e-08 |