PROCEEDINGS OF SCIENCE

ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Towards Understanding the Origin of Cosmic-Ray Electrons

Dimitrii Krasnopevtsev[†,*]

Massachusetts Institute of Technology, Cambridge, USA
E-mail: Dimitriy.Krasnopevtsev@cern.ch

Precision results on cosmic-ray electrons are presented in the energy range from 0.5 GeV to 1.4 TeV based on 28.1 million electrons collected by the Alpha Magnetic Spectrometer on the International Space Station. In the entire energy range the electron and positron spectra have distinctly different magnitudes and energy dependences. The electron flux exhibits a significant excess starting from 41.2 GeV compared to the lower energy trends, but the nature of this excess is different from the positron flux excess above 25.2 GeV. Contrary to the positron flux, which has an exponential energy cutoff of 810 GeV, at the 5σ level the electron flux does not have an energy cutoff below 1.9 TeV. In the entire energy range the electron flux is well described by the sum of two power law components. The different behavior of the cosmic-ray electrons and positrons measured by AMS is clear evidence that most high energy electrons originate from different sources than high energy positrons.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

[*]Presenter
[†]On Behalf of the AMS Collaboration.

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PoS(ICRC2021)111

1. Introduction

In this proceeding a precision measurements of primary cosmic-ray electrons up to 1.4 TeV with the Alpha Magnetic Spectrometer (AMS) on the International Space Station are presented. The measurements are based on 28.1 million electron events collected by AMS from May 19, 2011 to November 12, 2017. These results are crucial for providing insights into origins of high energy cosmic-ray electrons and positrons.

The description of the AMS detector is described in detail in Ref. [1] and references therein. The combination of information from the Transition radiation detector, Silicon tracker, and Electromagnetic calorimeter enables the efficient separation of the electron events from background sources. Template fit methods are used to determine the number of electrons in each energy bin. For the analysis details please refer to AMS publication in PRL [2].

2. Results.

The latest AMS results on the precision measurements of the electron spectrum together with the GALPROP [3] prediction for the secondary electrons from collision of cosmic rays are shown in Fig. 1. The spectrum is defined as the flux Φ_{e^-} scaled by $\tilde{E}^3$, where $\tilde{E}$ is the spectrally weighted mean energy [4]. As seen, the contribution of the collision of cosmic rays to the electron spectrum is negligible in the entire energy range.

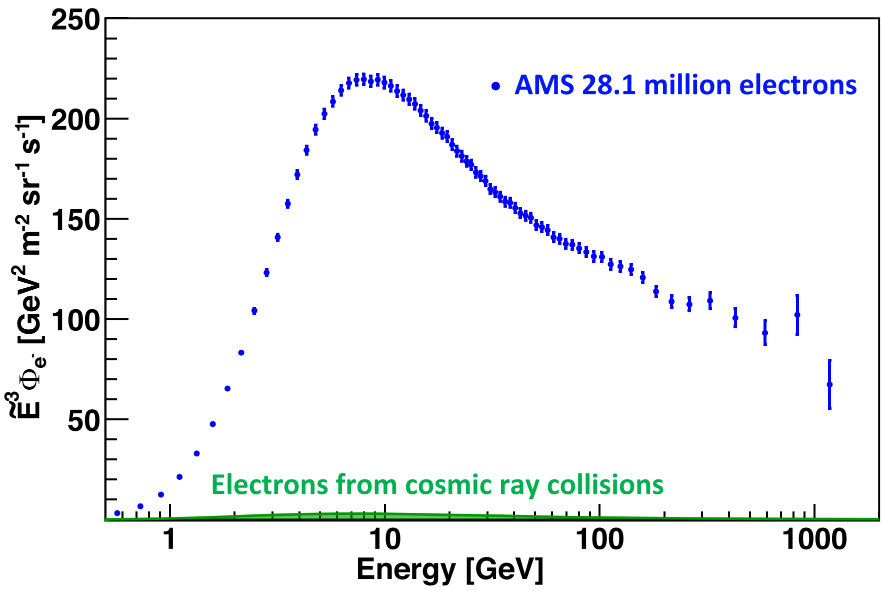

Figure 1: The AMS electron spectrum ($\tilde{E}^3\Phi_{e^-}$, blue data points) together with the GALPROP prediction for the secondary electrons from collision of cosmic rays (green shaded area).

Figure 2 shows the AMS cosmic-ray electron spectrum together with earlier measurements [5–11]. Results from AMS have improved accuracy and extended energy range beyond 1 TeV.

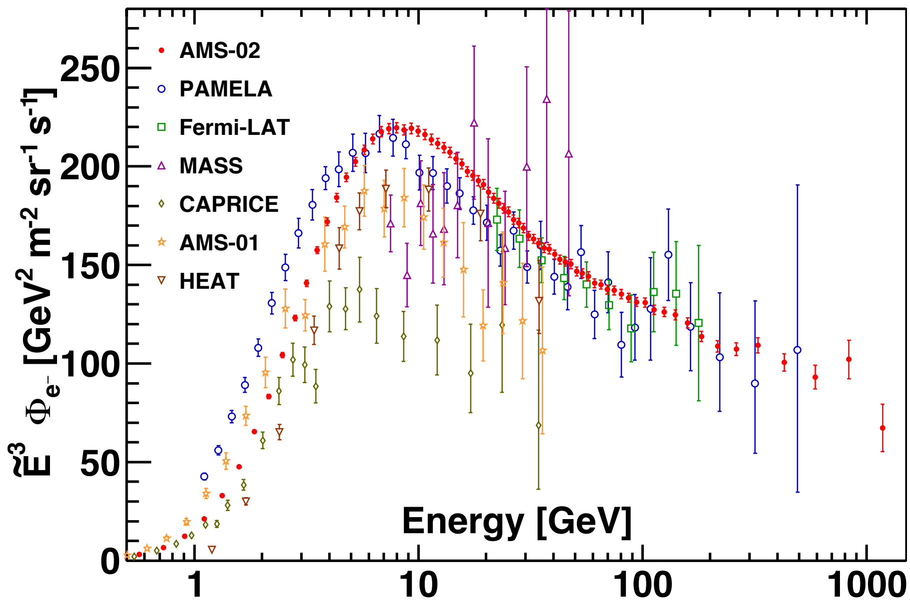

Figure 2: The AMS cosmic-ray electron spectrum. Earlier measurements from PAMELA, FermiLAT, MASS, CAPRICE, AMS-01, and HEAT are also shown.

The changing behavior of the electron flux is examined using the power law approximation, defined in Eq. (1). It is found, the electron flux exhibits a significant excess starting from $42.1^{+5.4}_{-5.2}$ GeV compared to the lower energy trends. The significance of this change is established at 7σ. The nature of this excess is different from the positron flux excess above 25.2±1.8 GeV [12].

$$\Phi_{e^-}(E) = \begin{cases} C(E/20.04\ \text{GeV})^{\gamma}, & E \leq E_0; \\ C(E/20.04\ \text{GeV})^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases} \tag{1}$$

To investigate the energy dependence of the electron flux, the entire energy range is divided into narrow intervals, assuming that the flux behavior follows a power law function in each of these intervals. The flux spectral index, defined in Eq. (2), is calculated over non-overlapping intervals which are chosen to have sufficient sensitivity. The results are presented in Fig. 3 together with the positron results. As seen, the behavior of the electron and positron spectral indices is distinctly different. Electron spectral index hardens starting from ~20 GeV and it is energy independent towards high energy contrary to positron spectral index.

$$\gamma = d[\log(\Phi)]/d[\log(E)] \tag{2}$$

The electron flux is fitted with Eq. (3) to check the existence of a finite energy cutoff E_s. At the 5σ level the electron flux does not have an energy cutoff below 1.9 TeV, contrary to the positron flux, which has an exponential energy cutoff of 810^{+310}_{-180} GeV. These results are presented in Fig. 4.

$$\Phi_{e^-}(E) = C_s(E/41.61\ \text{GeV})^{\gamma_s}\exp(-E/E_s). \tag{3}$$

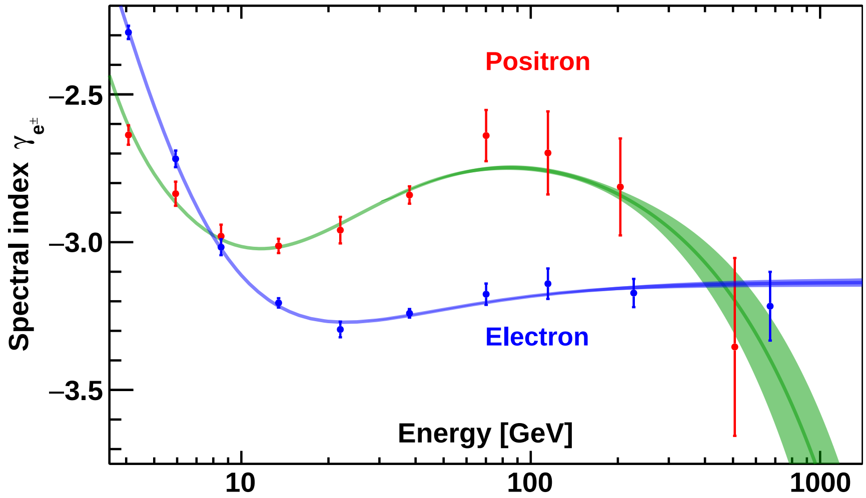

Figure 3: The spectral indices of the electron flux Φ_{e^-} and of the positron flux Φ_{e^+} as a function of AMS-02 energy. The blue band represents the 68% C.L. interval of the fit of Eq. (3) to the electron flux. The green band represents the 68% C.L. interval of a fit to the positron flux (Eq. (4) in Ref. [12]).

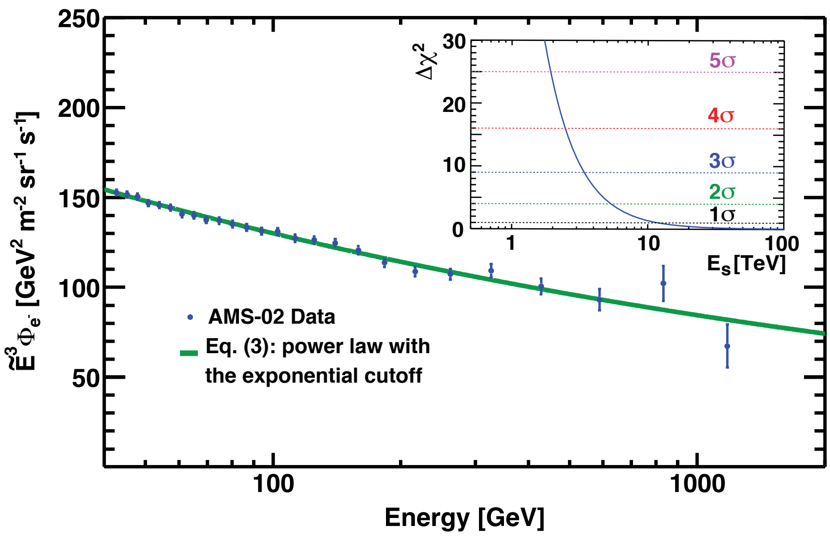

Figure 4: The fit to the electron flux data in the energy range [41.61 - 1400] GeV. The insert shows the study of the significance of the $1/E_s$ measurement by varying all three fit parameters in Eq. 3 to find the minimal $\Delta\chi^2$ corresponding to E_s values from 1 to 100 TeV. The blue curve shows the dependence of $\Delta\chi^2$ on E_s and the horizontal dashed lines show different significance levels from 1 to 5σ.

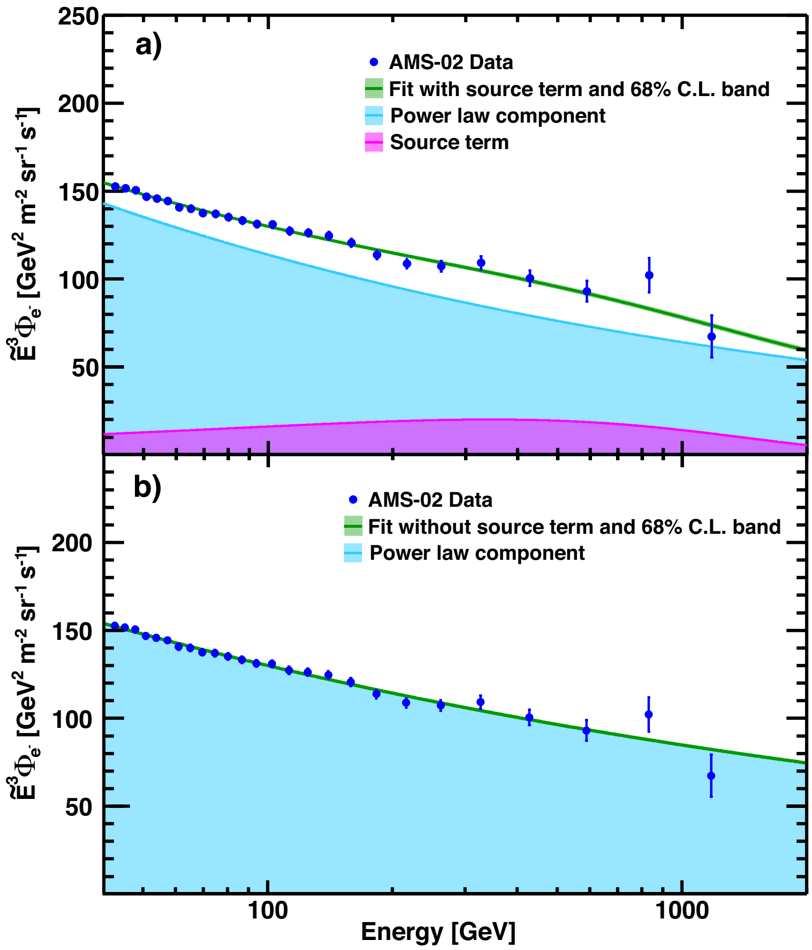

Figure 5: (a) The fit of a power law plus the positron source term ($f_{e^-} = 1$) to the electron flux data in the energy range [41.61 - 1400] GeV with the 68% C.L. (green band), $\Delta\chi^2$/d.o.f. = 15.5/24. The source term contribution, identical to that of positrons, is represented by the magenta area and the power law component by the blue area. (b) The fit of a power law ($f_{e^-} = 0$) to the electron flux data in the energy range [41.61 - 1400] GeV with the 68% C.L. (green band), $\Delta\chi^2$/d.o.f. = 15.2/24. The power law component is represented by the blue area.

New sources of high energy positrons, such as dark matter, may also produce an equal amount of high energy electrons. This hypothesis is tested using the source term from AMS positron analysis [12]. The electron flux is parametrized as a sum of a power law component and the positron source term with the exponential energy cutoff, as defined in Eq.(4). The result of the fit is presented in Fig. 5a. A similar fit to data, but with f_{e^-} fixed to 0, yields is presented in Fig. 5b. As seen in figures, the data are consistent both with the charge symmetric positron source term and also with the absence of such a term. Future AMS measurements with improved accuracy and energy reach will reveal detailed features in the electron spectrum.

$$\Phi_{e^-}(E) = C_{e^-}(E/E_1)^{\gamma_{e^-}} + f_{e^-}C_s^{e^+}(E/E_2)^{\gamma_s^{e^+}}\exp(-E/E_s^{e^+}). \tag{4}$$

In addition to a small contribution of secondary electrons produced in the collisions of ordinary cosmic rays with the interstellar medium, shown in Fig. 1, there could be several astrophysical sources of primary cosmic-ray electrons. It is assumed that there are only a few astrophysical sources of high energy electrons in the vicinity of the solar system each making a power law-like contribution to the electron flux [13, 14]. In addition, there are several physics effects which may introduce some spectral features in the original fluxes [15, 16]. Therefore, it is important to know the minimal number of distinct power law functions needed to accurately describe the AMS electron flux.

It is found, in the entire energy range [0.5 - 1400] GeV the electron flux is well described by the sum of two power law components. The two components, a and b, in Eq. (5) correspond to two power-law functions. The force-field approximation [17] is used to account for solar modulation effect. At low energy, an additional transition term is introduced to account for complex spectral behavior below ~10 GeV. A detailed discussion of the parameters and their fitted values can be found in Ref. [2].

$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}[1 + (\hat{E}/E_t)^{\Delta\gamma_t}]^{-1}[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b}]. \tag{5}$$

The fit to the data in the energy range [0.5 - 1400] GeV with Eq. (5) is presented in Fig. 6. As seen, the sum of two power-law functions with the additional transition term provides an excellent description of the data. These functions are very different in shape and in magnitude from those describing the positron flux and indicate that most cosmic-ray electrons originate from different sources than cosmic-ray positrons.

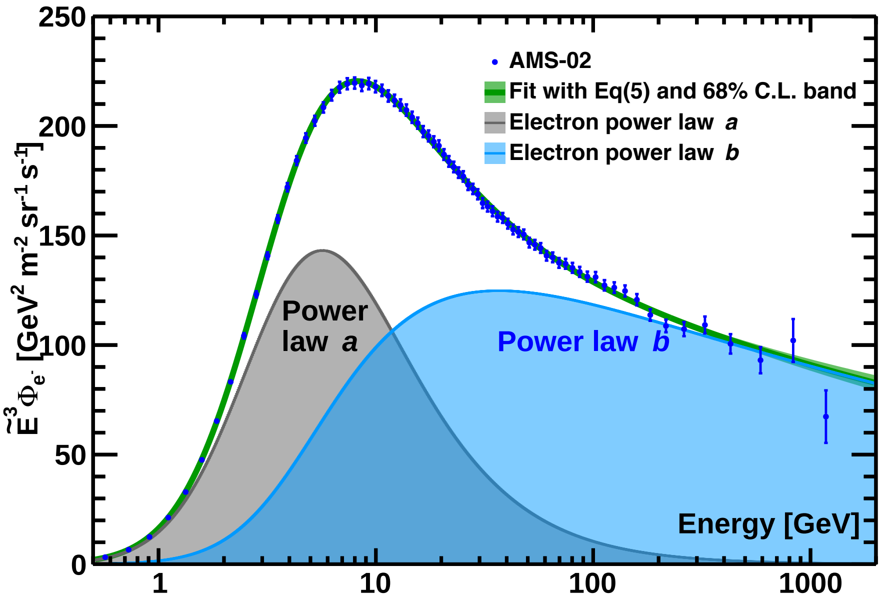

Figure 6: The two power law fit of Eq. (5) to the electron flux data in the energy range [0.5 - 1400] GeV with the 68% C.L. (green band). The two power law components a and b are represented by the gray and blue areas, respectively.

3. Conclusion.

The high statistics precision measurements of the electron flux from 0.5 GeV to 1.4 TeV, based on a data sample of 28.1×10^6 electrons were presented. In the entire energy range the electron and positron spectra have distinctly different magnitudes and energy dependences. The electron flux exhibits a significant excess starting from $42.1^{+5.4}_{-5.2}$ GeV compared to the lower energy trends, but the nature of this excess is different from the positron flux excess above 25.2±1.8 GeV. Contrary to the positron flux, which has an exponential energy cutoff of 810^{+310}_{-180} GeV, at the 5σ level the electron flux does not have an energy cutoff below 1.9 TeV. In the entire energy range from 0.5 GeV to 1.4 TeV the electron flux is well described by the sum of two power law components. The different behavior of the cosmic-ray electrons and positrons measured by AMS is clear evidence that most high energy electrons originate from different sources than high energy positrons.

Acknowledgments

This work has been supported by persons and institutions acknowledged in [1, 2].

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